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Intelligence Systems in Environmental Management: Theory and Applications

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Editors

Intelligence Systems in Environmental Management: Theory and Applications

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I dedicate this book to my aunts
Seher, Sevim, and Selma.

Cengiz Kahraman

I dedicate this book to my parents Beyhan and Hasan for their continuous support and love throughout my life, to my husband Serkan for his support, encouragement, and love and to my children Can and Damla who have made my life so wonderful and more meaningful.

İrem Uçal Sarı

Preface

The increasing growth rate of industrialization, urbanization, and population negatively affects environmental quality and hence plant, animal, and human lives. An environmental management system is designed to facilitate the management of all environmental impacts related to a company's activities for continuous improvement of environmental performance.

Environmental systems are usually stochastic, multiscale, and spatial- and temporal-dependent processes and tend to comprise complex interactions among social, cultural, physical, chemical and biological processes. These processes are difficult to represent, causing considerable uncertainty. Intelligent environmental decision support systems can play a key role in the interaction of humans and ecosystems, as they are tools designed to cope with the multidisciplinary nature and high complexity of environmental problems. Intelligent techniques such as swarm optimization, neural networks, genetic algorithms, etc., are the successful tools for the solution of these complex problems.

This book handles intelligent systems in environmental management in eight main sections; namely, management, disaster response management, energy management, water resources management, sustainability, environmental economics, land-use planning, and transportation.

Chapter 1 gives an introduction to intelligent systems in environmental engineering. It summarizes environmental management fields and intelligent techniques that could be used in environmental management.

Chapter 2 examines hazardous waste management. To support the hazardous waste transportation, it proposes a systematic and integrated multi-criteria decision-making approach based on intuitionistic fuzzy TOPSIS and applies to a real case in Turkey.

Chapters 3 and 4 focus on wastewater management.

Chapter 3 develops two self-adaptive design algorithms for generating the layout and sizing of sewers. It introduces four metaheuristic methods of Genetic Algorithm (GA), Simulated Annealing (SA), Particle Swarm Optimization (PSO), and Tabu Search (TS) for optimum design of the network.

Chapter 4 presents a norm-aware multi-agent system for social simulations in a river basin for integrated wastewater management systems. The presented norms are inspired by European policies for wastewater management and can evolve through time. Moreover, the proposed method is applied to the Besòs River Basin.

Chapter 5 deals with solid waste management. It proposes a fuzzy mathematical model that, along with the cost minimizing, considers a second objective which minimizes the pollution affecting the populated districts. The model also determines the optimal locations of transfer centers and land filling areas while minimizing the total cost and pollution.

Chapter 6 applies fuzzy rules into crisis management using the data gained from the crisis management center in a Polish district. The proposed approach allows the managers to identify events with serious or even disastrous consequences, which would not have been identified otherwise.

Chapter 7 focuses on maritime environment disasters. This chapter proposes an intelligent system which consists of model-base, database, environmental disaster management actions, ship operation management actions, user interface, and environmental disaster modeling and decision support unit.

Chapter 8 analyzed changes in the solar energy generation capacity for different scenarios using fuzzy cognitive maps. The factors that affect solar energy usage and the relations among the factors are revealed based on both a comprehensive literature review and experts' opinions.

Chapter 9 proposes a model to plan efficiently natural gas consumption in a combined cycle gas turbine power plant using evolutionary algorithms. The proposed model takes the costs of natural gas, ignition and maintenance of the turbine into account and analyzes power plant with respect to the effects of market price changes to the amount of natural gas needed for production.

Chapter 10 provides a firefly algorithm-driven simulation-optimization approach for modeling water resources management problems. This approach can be used to efficiently create multiple solution alternatives to the problems containing significant stochastic uncertainties that satisfy required system performance criteria.

Chapter 11 proposes a new fuzzy neural network based model, called evolving fuzzy neural network, that extends existing artificial intelligence methods for modeling hourly dissolved oxygen concentration in river ecosystem.

Chapter 12 demonstrates a new approach for measuring sustainable development levels of the countries using a cumulative belief degrees approach. The approach enables the use of an incomplete data that is one of the critical problems in measuring sustainability of countries.

Chapter 13 describes possible supply chain risk factors in which both physical objects and information are taken into account by considering the whole e-commerce elements. In modeling process, rule-based fuzzy inference system approach is applied by the virtue of the dynamic structure of sustainable supply chain.

Chapter 14 develops engineering economy techniques under fuzziness to be employed in environmental problems. Ordinary fuzzy sets, type-2 fuzzy sets, intuitionistic fuzzy sets, and hesitant fuzzy sets are handled in the development of fuzzy environmental economy analyses.

Chapter 15 compares underground waste bins and roadside waste bins in a solid waste collection system from economic perspective using type-2 fuzzy net present worth analysis.

Chapter 16 addresses the operational planning of a forest bearing in mind that forest management involves a multiplicity of goods and services. The proposed model, which uses metaheuristic procedures, not only includes economic and sustainable development objectives but also takes into account the key role trees play in counteracting the greenhouse effect.

Chapter 17 presents a novel urban land-use planning methodology via the integration of Analytic Hierarchy Process (AHP) and Fuzzy Rule Based System (FRBS) in order to represent the uncertainty in the system in a certain level to assess urban land-use suitability.

Chapter 18 introduces a fuzzy method to define optimum allocation of the service centers for sustainable transportation networks service using base fuzzy set, antibase fuzzy set, and vitality fuzzy set definitions of fuzzy graph.

Chapter 19 develops a dynamic geoinformation model with temporal dependence of the parameters and a procedural model of routing with temporal dependence to deal with the problems of the sustainable transportation network from geographic information systems for intelligent control.

We hope that this book will provide a useful resource of ideas, techniques, and methods for research on intelligent environmental management. We are grateful to the referees whose valuable and highly appreciated works contributed to select the high quality of chapters published in this book.

Istanbul, Turkey

Cengiz Kahraman
İrem Uçal Sarı

Contents

Part I Waste Management

Chapter 1
Introduction to Intelligence Techniques in Environmental Management

Cengiz Kahraman and İrem Uçal Sarı

Abstract Environmental management is a popular interdisciplinary field which covers all the activities that have a direct or indirect impact on the environment. With the increased concerns on environmental sustainability it becomes one of the most considered issues both by the governments and industries. This chapter introduces the main concepts of environmental management and the intelligent techniques which are used to model and solve environmental management issues. Future trends on environmental management are also examined in the chapter.

1.1 Introduction

Environmental management is the management of all kind of activities which have a direct or indirect impact on environment. With increasing consuming behaviors, the sustainability of environment and critical issue to preserve the living standards for the future time have become more important. Therefore, the number of studies on environmental management have been increased. Before feeling apprehension on environmental sustainability the activities of environmental management had been focused on cost effectiveness. With the environmentally conscious people and governments the focus has been changed on the effectiveness of the activities. Nowadays, governments can afford very high budgets to prevent the environment. Environmental management covers almost all disciplines which affect ecology, but especially water resources management, solid waste management, wastewater management, forest management, air pollution management, hazardous waste management, urban planning, sustainability, and environmental transportation could be count as the most studied subjects of it.

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Intelligent systems generate representations, inference procedures, and learning strategies that automatically solve problems that were heretofore solved by humans. Some of the application areas of intelligent systems are robotics, engineering design, manufacturing, medical diagnosis, security and defense, electronic commerce, expert systems and learning systems (Schalkoff 2011). Environmental management problems include numerous biological, physical and chemical processes, which interact with each other and which are difficult to model and analyze. In addition, many earth and environmental systems present complex spatial and temporal patterns and behaviors. The complexity of the earth and environmental systems has led to the need for effective and efficient computational tools to analyze and model highly nonlinear functions and can be trained to accurately generalize when presented with new, unseen data. Intelligence techniques have some or all of these features providing an attractive alternative to developing numerical models to conventional statistical approaches, from which the new insights and underlying principles of earth and environmental sciences can be derived (Zhu 2014).

In environmental management intelligent systems have important applications due to its ability to learn and keep up the changes of the previous activities on environment. For example, in the management of a water resource, intelligent systems are able to consider the population changes or changes in the basin over time and find the best action plan which affects the ecology less. Another example of the useful applications of intelligent systems on environmental management is using intelligent algorithms on waste management. They enable researchers to forecast the waste generation and waste contamination of the citizens or industries and choose the best action plan to achieve sustainable environment goal.

In this chapter it is aimed to give a brief introduction to applications of intelligent systems in environmental management with introducing the main concepts of environmental management and the most used intelligent systems in environmental management.

The chapter is organized as follows: In Sect. 1.2 the main concepts of environmental management are introduced. In Sect. 1.3 the most used intelligent techniques are determined. In Sect. 1.4 a literature review on the applications of intelligent systems in environmental management is given. Then future trends in environmental management are defined in Sect. 1.5. Finally, the chapter is concluded with further research suggestions.

1.2 Environmental Management

Environmental management offers research and opinions on use and conservation of natural resources, protection of habitats and control of hazards. In general, environmental management involves the following topics.

1.2.1 Carbon Management

Carbon management aims to reduce carbon dioxide and other greenhouse emissions. With the increased attention on global warming, carbon management have become one of the core topics of environmental management. The main purpose of the carbon management activities which is decreasing the amount of emissions, requires a detailed analysis of the carbon dioxide and other greenhouse emissions including recording and optimization to find the best alternative carbon management plan that reduces emissions more.

Carbon management comprises activities related to the coordination of activities to achieve a resource-efficient and effective reduction of carbon emissions. Carbon management can be defined as the sum of all activities that aim to secure the success of an organisation by managing carbon emissions efficiently and effectively (Zvezdov and Schaltegger 2015). Two broad classes of carbon management can be distinguished. The first includes attempts to manipulate natural biogeochemical processes of carbon removal. The second involves preventing carbon emissions into the atmosphere and instead disposing of it in stable reservoirs (Schneider 2001).

International initiatives to reduce net greenhouse gas emissions by sequestering carbon in the terrestrial biosphere have prompted the need for an accounting framework that records changes in carbon stocks associated with changes in either land use or land management. Changes in carbon stocks following changes in land use or land management can be accounted for by either direct measurement or estimates based on similar changes measured elsewhere. Both approaches have some advantages and some disadvantages (West et al. 2004).

1.2.2 Soil Degradation and Management

Soil degradation can be described as a natural process that can be enhanced or dampened by human intervention. Driving forces of soil degradation could be divided into three facets: vulnerability of soils to degradation, physical environmental changes and human activities. Erosion is a geologic process that never stops until land surfaces, including highlands and mountains, have been leveled to the erosion basis. The physical removal of soil material by water, wind and gravity has been still going on even without human activity revolved in. A variety of physical environmental changes including global warming, sea-level variation, drought, and earth processes such as geomorphological evolution, volcanic activity, natural leaching of soils could be causative factors of degradation. Besides, natural hazards such as floods, storms, earthquakes and bushfires etc. can also cause or accelerate soil degradation (Chen et al. 2002).

Soil degradation is considered as the measurable loss or reduction of the current or potential capability of soils to produce plant materials of desired quantity and quality. Several physical, chemical, and biological processes are responsible for the degradation of soil. The physical processes include deterioration of soil structure, crusting, hardsetting, compaction, erosion, and desertification. The chemical processes include leaching, fertility depletion, acidification, salinization, and pollution. The biological processes of soil degradation include reduction in carbon and decline in soil biodiversity (Osman 2013).

1.2.3 Disaster Response and Management

Disaster management is another subject of environmental management which covers both natural disasters and man-made disasters. Comprehensive disaster management is based upon four distinct components which are mitigation, preparedness, response and recovery. Mitigation involves reducing or eliminating the consequences of hazard. Preparedness involves equipping people who may be impacted by a disaster or who may be able to help those impacted with the tools to increase their chance of survival and to minimize their losses. Response involves taking action to reduce or eliminate the impact of disasters that have occurred or are currently occurring, in order to prevent future suffering. And recovery involves returning victims' lives back to a normal state following the impact of disaster consequences (Coppola 2006).

In the environmental management perspective, the impact of a disaster (either it is natural or man-made) should be forecasted and analyzed well to determine a suitable disaster response system which will minimize the effect of the disaster. Therefore, disaster response systems have a critical importance due to its determinant characteristic for the impact of the disaster on the environment.

1.2.4 Solid Waste Management

Solid waste management covers all activities starting from the generation of the solid wastes till their disposal. There are four main strategies in solid waste management which are prevention, recycling, treatment and disposal. Prevention strategy prevents wastes from ever being formed in the first place. Recycling and reuse of materials, the recovery of certain wastes, and the conversion of certain types of waste into useful energy such as heat, electricity and hot water are strategies which recover and offset costs for overall waste management. Treatment is the strategy that focuses on stabilization of wastes, reducing toxicity or reducing volume before ultimate disposal. And the disposal is the only other strategy which is available (Cheremisinoff 2003).

Environment and human health can be affected by a poor solid waste management. With the increased human population there is an increase in demand for efficient waste management practices. A solid waste management system comprises a few or all of the following actions: formulation of policies, formulation of enforcing laws, planning and evaluating activities including formulation of financial plans, identifying environmental damages and formulation of environmental management plan, collection, transporting, treatment, disposal of waste and marketing recovered materials and creating awareness to generators and public (Chandrappa and Brown 2012).

1.2.5 Wastewater Management

Wastewater management is important since mostly the collected and treated wastewaters are disposed to rivers and seas which also could be a water resource. To maintain the sustainability of the water resources, governments pay more attention on the treatment processes and the policies which focus on the reuse of the treated wastewater.

There are three constituents and interrelated aspects of wastewater management which are collection, treatment and disposal. Collection of domestic and industrial wastewater is best achieved by a fully developed sewerage and carriage system. The planning and design of wastewater collection facilities involves the determination of wastewater flow rates, hydraulic design of sewers, and the selection of sewer appurtenances and pumping stations. Treatment of wastewater is essential in order to reduce the spread of communicable diseases and to prevent the pollution of surface and ground water. Disposal of treated wastewaters should meet the stringent regulations to protect the environment (Punmia et al. 1998).

1.2.6 Water Resources Management

Water resources planning and development is concerned with modifying the time and space availability of water for various purposes so as to accomplish certain basic national, international and local objectives (Jain and Singh 2003). Water resources management involves assessment of water resources, interaction of various locations of water (atmospheric, sea, surface and ground), drought management, flood management, impacts of catchment and river development, impact on the environment, water quality and water supply (Stephenson 2003).

The integrated water management (IWM) which is one of the modern water management approaches, is a multi-dimensional process pivoted around the need for water, the policy to meet the needs and the management to implement the policy. Water quality and quantity is the first dimension of IWM. Water uses, including agriculture, water supply, energy generation etc. is the second dimension. Third dimension of IWM is the strategy to implement the well-defined management policy. And the changing needs and objectives are the fourth dimension (Jain and Singh 2003).

1.2.7 Sustainable Transportation

Sustainable transportation addresses the question of how to shape transportation planning, policy-making and citizen activities in a direction of greater social and environmental benefit to society. It aims at promoting better and healthier ways of meeting individual and community needs while reducing the social and environmental impacts of current mobility practices by reducing resource inputs, waste outputs and minimizing transportation's often deleterious effects on the public realm (Schiller et al. 2010).

The studies on sustainable transportation mostly focus on determining and analyzing sustainability indicators for the current and possible alternative transportation systems. It is a popular research area due to the direct effects of transportation systems on air pollution, carbon management and life standards of the citizens.

1.2.8 Hazardous Waste Management

Hazardous waste is a waste that has physical, chemical or biological characteristics that can be place human health at risk or adversely affect the natural environment. Hazardous wastes can be solids, liquids or gases. They are the byproducts of a wide variety of manufacturing and service industries (Goldman et al. 1986). Environmental protection agency (EPA) has identified four characteristics which cause a waste to be regulated as a hazardous waste. Ignitability is the potential of a waste to create fires under certain conditions. Corrosivity is the capability of a waste corroding metals. Reactivity is the characteristic of a waste being unstable under "normal" conditions. Toxicity is the harmfulness of a waste when ingested or absorbed (US Environmental Protection Agency 1979).

Hazardous waste management includes storage, disposal, inspection, record keeping, and reporting of hazardous wastes which are strictly determined by the environmental regulations. Managers should take the appropriate action plan to ensure that all applicable environmental regulations are followed.

1.2.9 Air Quality Management

Air pollution is one of the most serious environmental concerns due to its adverse effects on human health. Global warming and ozone layer depletion have increased the concerns on air pollutants and air quality. Air pollution is a result of complex interactions among air pollutant emissions, meteorological conditions and a wide variety of atmospheric processes including transport, chemical transformation and deposition. To improve air quality without impairing economic development, strategies of air pollutant emission control must be carefully formulated by assessing the fate of air pollutant emissions in the atmosphere (Zhu et al. 2015).

Air pollution management programs are intended to keep air pollutants below the levels that would damage the environment and harm the health of humans. An air pollution management program should include clearly defined objectives that would meet ambient air quality standards, the identification of all air pollutants and their sources, the levels of pollutants in the ambient air, and the types of pollutants that are at risk of exceeding permissible levels (Wijetilleke and Karunaratne 1995).

1.2.10 Energy Management

Growing demand for energy and the constraints in energy supply are the main catalysts for energy management. Energy management and conservation includes all the action plans to use energy efficiently and effectively, starting from the generation process to the end user consumption. Energy management can be classified into management of energy generation, energy distribution and energy consumption. To achieve an effective energy management system, the models for selecting the energy resource and the generation processes are used to find the best energy generation strategy for governments in the energy generation phase, the models for distribution are used to have the most effective distribution networks with minimum energy losses in the distribution phase, and the policies and strategies which will reduce the energy use are handled in the consumption phase.

The direct and indirect effects of energy production and use on the environment makes energy management one of the core issues in environmental management. Most of the energy resources have environmental hazards. Mitigating the impacts of energy generation and supply by reducing demand for fossil fuels and seeking advancements in more environmentally sensitive energy forms is an important driver for energy management (Smith and Parmenter 2013).

1.3 Intelligent Systems Classification

Intelligent system (IS) is a broad term that covers approaches to design, optimization, and control of various complex systems without requiring mathematical models, in a similar way to ho humans work. IS involves many fields such as neural networks, fuzzy systems, evolutionary strategy, genetic algorithm, support vector machines, particle swarm optimization, memetic algorithms, and ant colony optimization. Effective ISs can be constructed by combining appropriate soft computing techniques based on the problems to be solved (Shin and Xu 2008).

1.3.1 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a biologically inspired computational search and optimization method developed in 1995 by Eberhart and Kennedy based on the social behaviors of birds flocking or fish schooling. PSO applies the concept of social interaction to problem solving. PSO is a simple but powerful search technique. It has been applied successfully to a wide variety of search and optimization problems.

1.3.2 Genetic Algorithms

A genetic algorithm (GA) is an approach to solving problems based on the theory of evolution that uses the survival of the fittest concept as a problem solving strategy (Stair and Reynolds 2013). Compared with traditional optimization methods, it is widely used because of its advantages such as parallelism, liability, having wider solution space, easy to discover global optimum, easy modification for different problems and performing well for large scale optimization problems (Sivanandam and Deepa 2007).

1.3.3 Fuzzy Sets

Fuzzy sets (FS) are the basic concept supporting the fuzzy set theory. The main research fields in the fuzzy set theory are fuzzy sets, fuzzy logic, and fuzzy measure. FS have the ability to realize a complex nonlinear input–output relation as a synthesis of multiple simple input–output relations. The fuzzy set theory has been used in several intelligent technologies ranging from control, automation technology, robotics, image processing, pattern recognition, medical diagnosis etc. Fuzzy logic and fuzzy set theory have been successfully applied to handle imperfect, vague, and imprecise information. Fuzzy reasoning or approximate reasoning is an application of fuzzy logic to knowledge processing. Fuzzy control which is an effective approach in nonlinear or largescale systems control, is an application of fuzzy reasoning to control devices Different generalizations and extensions of fuzzy sets have recently been introduced (Rodriguez et al. 2012): Type-2 fuzzy sets, non-stationary fuzzy sets, intuitionistic fuzzy sets, fuzzy multisets, and hesitant fuzzy sets.

1.3.4 Ant Colony Optimization

Ant Colony Optimization (ACO) is a metaheuristic approach for solving hard combinatorial optimization problems which is inspired by the foraging behavior of ant colonies, and targets discrete optimization problems. When searching for food, at first ants explore the area surrounding their nest randomly. As soon as an ant finds a food source, it evaluates it and carries some food back to the nest leaving markers (pheromones) that show the path has food. The pheromone deposited, the amount of which may depend on the quantity and quality of the food, guides other ants to the food source. Quantity of pheromone on the arc is decreased in time due to evaporating. Each ant decides to a path or way according to the quantity of pheromone which has been leaved by other ants. More pheromone trail consists in short path than long path. Because the ants drop pheromones every time they bring food, shorter paths are more likely to be stronger, hence optimizing the solution.

1.3.5 Bee Colony Optimization

Bee Colony Optimization (BCO) approach is a relatively new member of swarm intelligence. It has received increasing interest because of its simplicity, wide applicability, and outstanding performance. The BCO is inspired by bees' behavior in the nature. The basic idea of BCO is to create the multi agent system (colony of artificial bees) capable to successfully solve difficult combinatorial optimization problems. Few algorithms inspired by bees' behavior such as BCO algorithm, Artificial Bee Colony (ABC) algorithm, Marriage in Honey Bees Optimization (MBO) algorithm, Fast Marriage in Honey Bees Optimization (FMHBO) algorithm, Bees System (BS), The Bees Algorithm (BA), Honey-Bees Mating Optimization (HBMO) algorithm (Yuce et al. 2013).

1.3.6 Neural Networks

Neural network (NN) models are a broad class of nonlinear input-output models inspired by brain processes and structures at almost the lowest level, while symbolic artificial intelligence (AI) models by processes at the highest level. Artificial neural networks (ANN) have been developed as generalizations of mathematical models of biological nervous systems. In other words; ANNs, or simply neural networks, are information processing systems that roughly replicate the behavior of a human brain by emulating the operations and connectivity of biological neurons. ANN represents a promising modeling technique especially for data sets having the kind of non-linear relationships, which are frequently encountered in pharmaceutical processes. Neural networks require less formal statistical training, are able to detect complex non-linear relationships between dependent and independent variables and all possible interactions without complicated equations, and can use multiple training algorithms. In terms of model specification, artificial neural networks require no knowledge of the data source but, since they often contain many weights that are estimated, they require large training sets. In addition, ANNs can combine and incorporate both literature-based and experimental data to solve problems (Agatonovic-Kustrin and Beresford 2000).

1.3.7 Simulated Annealing

Simulated annealing (SA) is a stochastic optimization procedure which is developed by Kirkpatrick in 1984. The method models the physical process of heating a material and then slowly lowering the temperature to decrease defects, thus minimizing the system energy. SA technique generally achieves a good quality solution and it is applicable and easy to implement for all the problems which can potentially employ the iterative optimization techniques, under the condition that after each transformation the corresponding change in the objective function can be evaluated directly. It offers great flexibility as one can add new constraints easily afterwards in the program (Dreo et al. 2006).

1.3.8 Tabu Search

The basic form of Tabu Search (TS) is founded on ideas proposed by Glover (1986). The method is based on procedures designed to cross boundaries of feasibility or local optimality, instead of treating them as barriers. TS is based on the premise that problem solving, in order to qualify as intelligent, must incorporate adaptive memory and responsive exploration. The adaptive memory feature of TS allows the implementation of procedures that are capable of searching the solution space economically and effectively. TS can be directly applied to virtually any kind of optimization problem (Glover and Marti 2006).

1.3.9 Swarm Intelligence

Swarm Intelligence (SI) is an innovative distributed intelligent paradigm for solving optimization problems that originally took its inspiration from the biological examples by swarming, flocking and herding phenomena in vertebrates. Social insects work without supervision. In fact, their teamwork is largely self-organized, and coordination arises from the different interactions among individuals in the colony. Although these interactions might be primitive, taken together they result in efficient solutions to difficult problems. The collective behavior that emerges from a group of social insects has been dubbed swarm intelligence Flexibility, robustness and self-organization are the advantages of SI (Bonabeau and Meyer 2001).

1.3.10 Differential Evolution

Differential Evolution (DE) is a stochastic, population-based optimization algorithm which is introduced by Storn and Price in 1996. DE can be used to find approximate solutions to many practical problems that have objective functions which are nondifferentiable, non-continuous, non-linear, noisy, flat, multi-dimensional or have many local minima, constraints or stochasticity. DE algorithm uses mutation operation as a search mechanism and selection operation to direct the search toward the prospective regions in the search space. In addition to this, the DE algorithm uses a non-uniform crossover which can take child vector parameters from one parent more often than it does from others.

1.3.11 Evolutionary Algorithms

Evolutionary algorithms (EAs) are search and optimization algorithms that take their inspiration from natural selection and survival of the fittest in the biological world. Their main components are a population of individuals that undergoes an iterative process of fitness evaluation, variation and selection. EAs are a set of modern metaheuristics used successfully in many applications with great complexity. There are six main characteristics of EA which are representation, selection, recombination, mutation, fitness function and survivor decision. The best known EAs include genetic algorithms, evolutionary programming, evolution strategies, and genetic programming.

1.4 Literature Review

A literature research in the Scopus database including the terms *intelligent* and *environment* gave 1920 records. These records are composed of journal papers, conference papers, and book chapters. Figure 1.1 illustrates the frequencies of the papers and chapters on intelligent environmental problems with respect to their publication years. The usage of intelligent techniques in environmental works starts around the year 1985. A significant acceleration in the beginning of 2000s is observed. This acceleration leaves its place to a downward move in 2015.

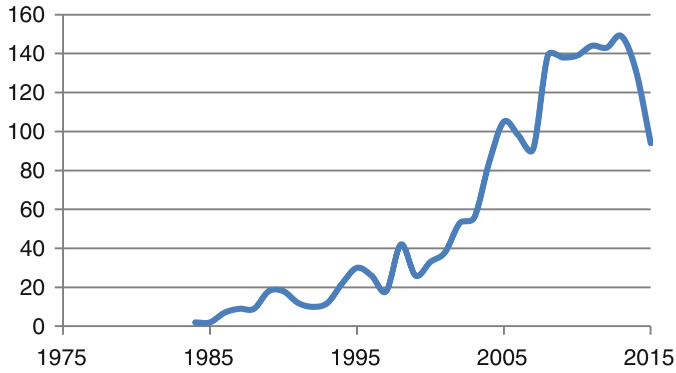

Fig. 1.1 Publication frequencies of intelligent environmental works

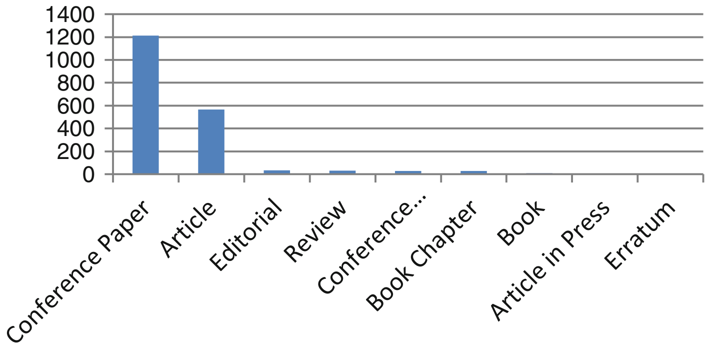

Fig. 1.2 Classification of the documents on intelligent environment

Figure 1.2 gives the types and frequencies of documents on intelligent environment. Most of these works exist in the conference proceedings since there are several international conference series on environmental theme. The second type of documents involving intelligent environmental works is articles, which is almost half of the frequency of the related conference papers. The frequencies of other types of documents publishing intelligent environmental works can be ignored.

Figures 1.3, 1.4, and 1.5 show the classifications of the publications with respect to subject areas, source countries and universities, respectively. According to Fig. 1.3, most of the intelligent environmental works are based on the areas of computer science, engineering, mathematics, social sciences, and decision sciences, respectively. The other subject areas are biochemistry, genetics, molecular biology, physics and astronomy, etc. Figure 1.4 indicates that most of the publications on intelligent environmental works come from USA, China, UK, Spain, Germany, South Korea, Japan, and others, respectively.

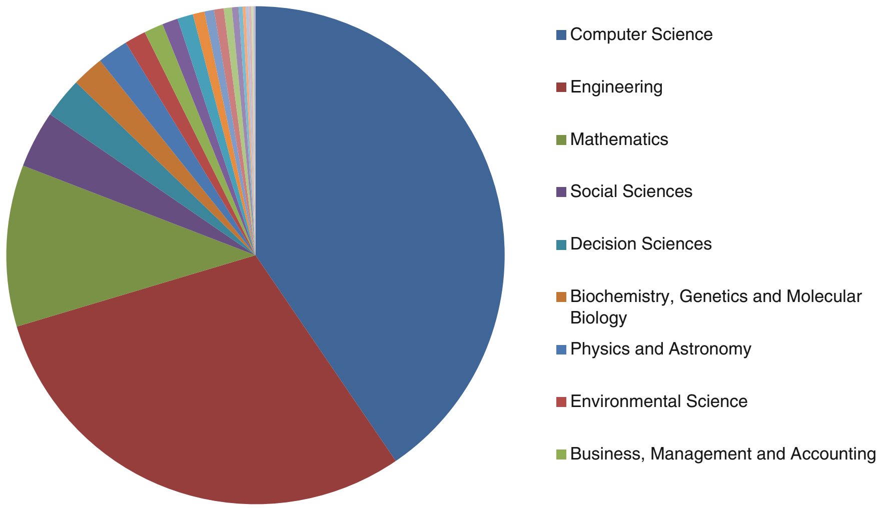

Fig. 1.3 Classification with respect to subject areas

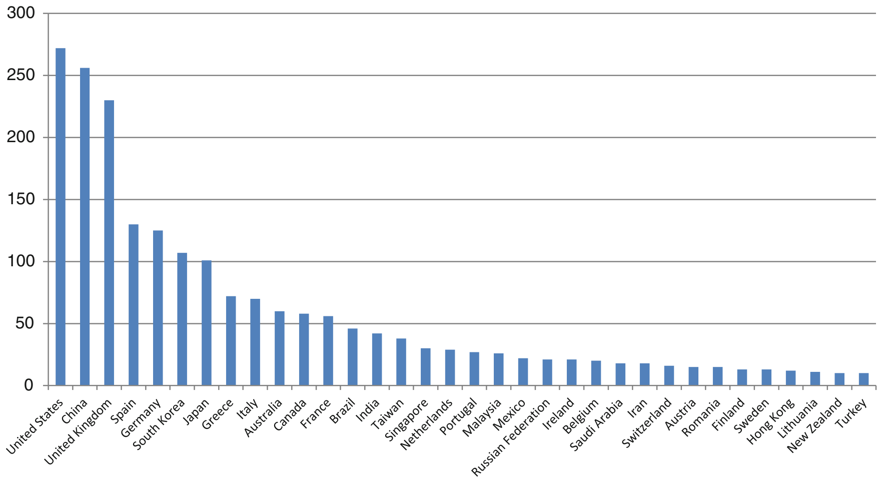

Fig. 1.4 Classification with respect to source countries

Figure 1.5 indicates that the universities most publishing works on intelligent environment are University of Essex and Ulster University from UK, Panepistimion Pireos from Greece, Universidad Politecnica de Madrid from Spain, University of Tokyo, and others, respectively. Figures 1.6 and 1.7 illustrate the frequencies of intelligent environmental works with respect to authors and journals and proceedings. Figure 1.6 indicates that H. Hagras from University of Essex is the leader in publishing intelligent environmental works. V. Callaghan from University of

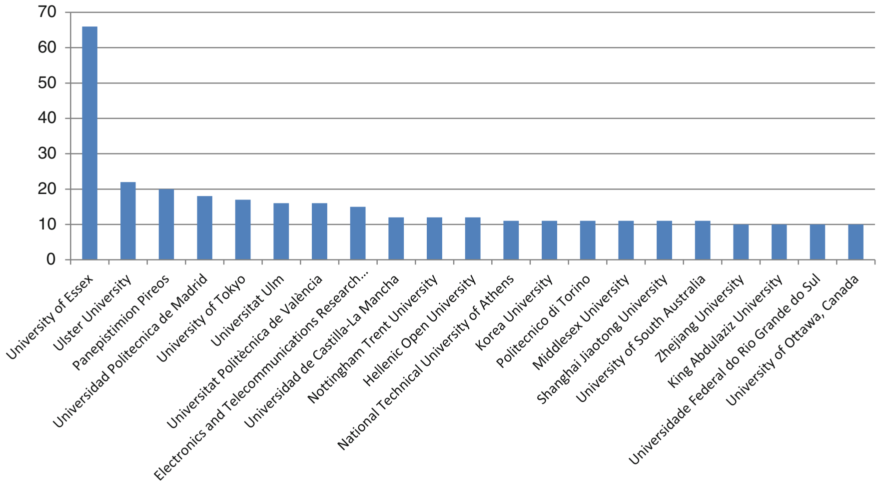

Fig. 1.5 Classification of works with respect to universities

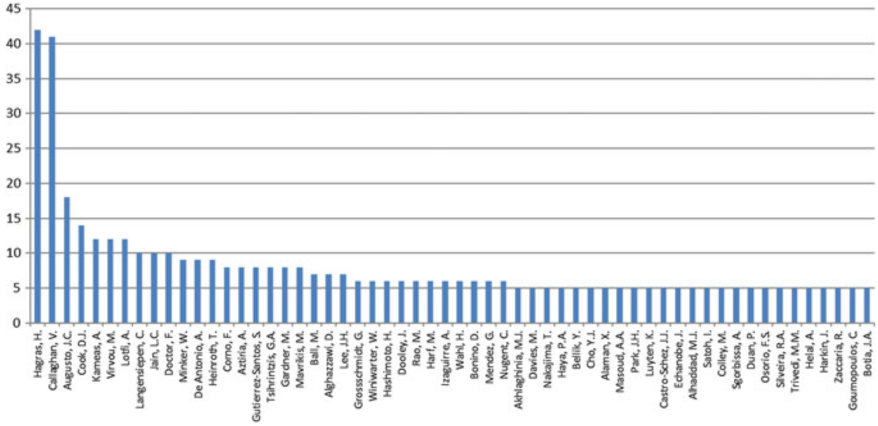

Fig. 1.6 Authors publishing intelligent environmental works

Essex; J.C. Augusto from Middlesex University; D.J. Cook from Engineering and Computer Science, USA; and A. Lotfi from School of Science and Technology, UK are the next authors most publishing intelligent environmental works. Figure 1.7 indicates that the journals or proceedings most publishing intelligent environmental works are Lecture Notes in Computer Science, Proceedings of SPIE—The International Society for Optical Engineering, Studies in Computational Intelligence, Journal of Ambient Intelligence and Smart Environments, Communications in Computer and Information Science, and others, respectively.

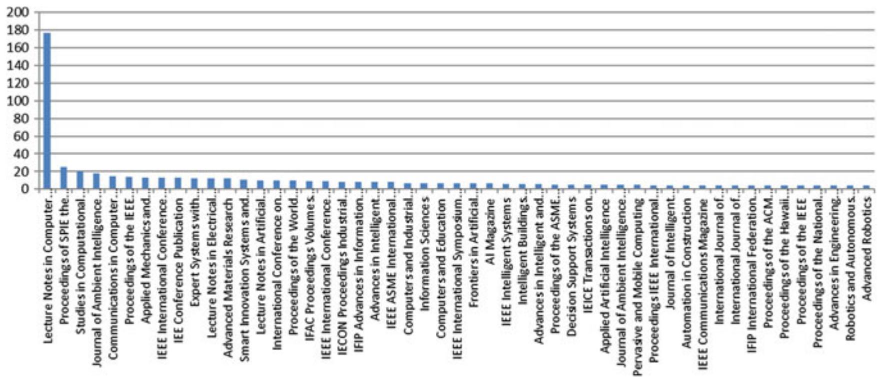

Fig. 1.7 Journals and proceedings most publishing intelligent environmental works

1.5 Future Trends

As it mentioned before, increased awareness on environmental issues makes environmental effects of the activities one of the most considered factors in management decisions. Environmental sustainability which can be defined as the maintenance of the factors and practices that contribute to the quality of environment on a long-term basis, is and will be popular to response the sensitivity of citizens on environment. To measure the environmental performance of nations environmental sustainability index was determined in 1999 which is part of a large project called The Environmental Performance Measurement project, an initiative of the Yale Center for Environmental Law and Policy and the Center for International Earth Science Information Network of Columbia University, in collaboration with the World Economic Forum and the Joint Research Centre of the European Commission. The ESI measures the overall progress of nations toward environmental sustainability. As a composite index it tracks a set of environmental, socioeconomic, and institutional indicators that characterize and influence environmental sustainability at a national level (Schmiedeknecht 2013).

The ESI was published between 1999 and 2005 by Yale University. Then a new index was developed which is called Environmental Performance Index (EPI) by the same team. The EPI ranks countries' performance on high-priority environmental issues in two areas: protection of human health and protection of ecosystems. Within these two policy objectives the EPI scores national performance in nine issue areas comprised of more than 20 indicators. EPI indicators measure country proximity to meet internationally established targets or, in the absence of agreed targets, how nations compare to one another (Hsu et al. 2016). The issue areas scored by EPI which could be desired as the main drivers of future trends on environmental management are health impacts, air quality, water and sanitation, biodiversity and habitat, climate and energy, water resources, agriculture, forests and fisheries. The managers and analysts should focus on the activity plans which will increase the sustainability of these main drivers.

To meet the environmental sustainability goal of the nations, industries are being forced to be more environmental friendly by governments. They are also encouraged by the customers' expectations to provide more environmental friendly products and services. With these leading forces, industries are paying more attention to decrease their impacts on environment. In waste generation management which is the one of core issues of environmental management, zero waste philosophy has become popular among industries. Zero waste is a whole-system approach that aims to eliminate rather than 'manage' waste. As well as encouraging waste diversion from landfill and incineration, it is a guiding design philosophy for eliminating waste at source and at all points down the supply chain (Curran and Williams 2012). Under the zero waste philosophy, both product design and waste management principles are considered simultaneously to eliminate potential threats to the environment caused by human consumption and behavior. The zero waste product design ensures that the discarded zero waste product would easily be reused and repaired for extended product lifespan or remanufactured to produce a secondary product. If not, the zero waste management ensures that the discarded waste would be either recycled, recovered or easily be nourished through natural process, without polluting natural environment (Zaman 2014). Trends show that recycling, reusing and remanufacturing will be more popular in future to minimize waste generation.

Energy management is also a popular issue both for the governments and industries. Governments seek new alternative energy resources which are less harmful to the environment. They invest more on renewable energy resources which are biofuel, biomass, geothermal, hydropower, solar energy, wave power and wind power. It is forecasted that the researches on the energy production technologies for the renewable energy resources will be increased to make the production more efficient and common. On the other hand, industries try to use energy more efficiently and effectively by changing their production systems. Also self-production of the energy becomes popular both for the industries and citizens. The number of solar-powered homes are increasing day by day. Therefore, it is clear that researches on energy solutions will be more trendy in the future.

The complexity and nonlinearity of most earth and environmental problems have led to the increased use of computational intelligence techniques. There are several applications of intelligent techniques on environmental problems, but as it is seen from the literature review, most of the conventional modelling frameworks have not been integrated with intelligent techniques yet. The environmental sustainability goals of the nations led the researchers develop innovative approaches which adapt intelligent techniques to existing modelling frameworks in environmental management. Also new intelligent techniques have been developing rapidly to model complex systems in a better way. In future, there will be more applications of intelligent techniques on environmental management to model complex environmental problems and ecological systems.

1.6 Conclusion

Environmental management is a broad and rapidly developing interdisciplinary field which includes the protection, conservation and sustainable use of the various elements or components of the environment. Limited environmental resources which are effected badly by pollution and overpopulation, global warming, deforestation and public health issues makes environmental management more important and critical for survival of the earth and living species.

In this chapter it is aimed to give general information on environmental management and the intelligent techniques which are useful to model and solve environmental problems. Intelligent techniques are essential for environmental management to model and solve complex environmental problems. Most of the environmental problems have parameters which are unpredictable or have interactions among each other. Intelligent techniques which are explained in the chapter are useful for analyzing data, providing forecasts, quantifying uncertainty, providing information and suggesting a suitable action strategy for environmental management issues. Future trends on environmental management are also examined to guide the researchers and practitioners.

References

Agatonovic-Kustrin, S., & Beresford, R. (2000). Basic concepts of artificial neural network (ANN) modeling and its application in pharmaceutical research. *Journal of Pharmaceutical and Biomedical Analysis, 22*(5), 717–727.

Bonabeau, E., & Meyer, C. (2001). Swarm intelligence: A whole new way to think about business. *Harvard Business Review, 79*(5), 106–115.

Chandrappa, R., & Brown, J. (2012). *Solid waste management: Principles and practice*. Berlin: Springer.

Chen, J., Chen, J.-Z, C., Tan, M.-Z, & Gong, Z.-T. (2002). Soil degradation: A global problem endangering sustainable development. *Journal of Geographical Sciences, 12*(2): 243–252.

Cheremisinoff, N. P. (2003). *Handbook of solid waste management and waste minimization technologies*. Oxford: Butterworth-Heinemann.

Coppola, D. P. (2006). *Introduction to international disaster management*. Oxford: Butterworth-Heinemann.

Curran, T., & Williams, I. D. (2012). A zero waste vision for industrial networks in Europe. *Journal of Hazardous Materials, 207*, 3–7.

Dreo, J., Petrowski, A., Siarry, P., & Taillard, E. (2006). *Metaheuristics for hard optimization: Methods and case studies*. Berlin: Springer.

Eberhart, R. C., & Kennedy, J. (1995). A new optimizer using particle swarm theory. In *Proceedings of the Sixth International Symposium on Micro Machine and Human Science, 1*, 39–43.

Environmental Protection Agency (EPA). (1979). *Siting of hazardous waste management facilities and public opposition*. Washington D.C.: EPA.

Glover, F. (1986). Future Paths for integer programming and links to artificial intelligence. *Computers & Operations Research, 13*, 533–549.

Glover, F., & Marti, R. (2006). Tabu search. In *Metaheuristic procedures for training neutral networks* (pp. 53–69). US: Springer.
Goldman, B., Hulme, J. A., Johnson, C., Marlin, A. T., & Ross, S. S. (1986). *Hazardous waste management: Reducing the risk*. Washington, D.C.: Island Press.
Hsu, A., Alexandre, N, Cohen, S., Jao, P., Khusainova, E., & Mosteller, D., et al. (2016). *2016 Environmental performance index*. New Haven, CT: Yale University. Available: www.epi.yale.edu
Jain, S. K., & Singh, V. P. (2003). *Water resources systems planning and management*. Amsterdam: Elsevier Science.
Kirkpatrick, S. (1984). Optimization by simulated annealing: Quantitative studies. *Journal of Statistical Physics, 34*(5–6), 975–986.
Osman, K. T. (2013). *Soil degradation, conservation and remediation*. Berlin: Springer.
Punmia, B. C., Jain, A. K., & Jain, A. K. (1998). *Waste water engineering*. New Delhi: Firewall Media.
Rodriguez, R. M., Martinez, L., & Herrera, F. (2012). Hesitant fuzzy linguistic term sets for decision making. *IEEE Transactions on Fuzzy Systems, 20*(1), 109–119.
Schalkoff, R. J. (2011). *Intelligent systems: Principles, paradigms and pragmatics*. Burlington: Jones & Bartlett Publishers.
Schiller, P. L., Bruun, E. C., & Kenworthy, J. R. (2010). *An introduction to sustainable transportation: Policy, planning and implementation*. London: Earthscan.
Schmiedeknecht, M. H. (2013). Environmental sustainability index. In *Encyclopedia of corporate social responsibility* (pp. 1017–1024). Berlin, Heidelberg: Springer.
Schneider, S. H. (2001). Earth systems engineering and management. *Nature, 409*(6818), 417–421.
Shin, Y. C., & Xu, C. (2008). *Intelligent systems: Modeling, optimization, and control* (Vol. 30). Boca Raton: CRC press.
Sivanandam, S. N., & Deepa, S. N. (2007). *Introduction to genetic algorithms*. Berlin: Springer.
Smith, C. B., & Parmenter, K. E. (2013). *Energy, management, principles: Applications, benefits, savings*. Amsterdam: Elsevier.
Stair, R., & Reynolds, G. (2013). *Principles of information systems*. Boston: Cengage Learning.
Stephenson, D. (2003). *Water resources management*. Netherlands: Swets & Zeitlinger B.V.
Storn, R., & Price, K. V. (1996). Minimizing the real functions of the ICEC'96 contest by differential evolution. In *International Conference on Evolutionary Computation* (pp. 842–844).
West, T. O., Jain, A. K., & Andrasko, K. (2004). Carbon management response curves: Estimates of temporal soil carbon dynamics. *Environmental Management, 33*(4), 507–518.
Wijetilleke, L., & Karunaratne, S. A. (1995). *Air quality management: Considerations for developing countries* (Vol. 23). Washington, D.C.: World Bank Publications.
Yuce, B., Packianather, M. S., Mastrocinque, E., Pham, D. T., & Lambiase, A. (2013). Honey bees inspired optimization method: the bees algorithm. *Insects, 4*(4): 646–662.
Zaman, A. U. (2014). Identification of key assessment indicators of the zero waste management systems. *Ecological Indicators, 36*, 682–693.
Zhu, X. (2014). Computational intelligence techniques and applications. In *Computational intelligence techniques in earth and environmental sciences* (pp. 3–26). Netherlands: Springer.
Zhu, Y., Lao, Y., Jang, C., Lin, C. J., Xing, J., Wang, S., et al. (2015). Development and case study of a science-based software platform to support policy making on air quality. *Journal of Environmental Sciences, 27*, 97–107.
Zvezdov, D., & Schaltegger, S. (2015). Decision support through carbon management accounting—A framework-based literature review. In *Corporate carbon and climate accounting* (pp. 27–44). Berlin: Springer.

Part I
Waste Management

Chapter 2
An Intuitionistic Fuzzy MCDM Approach for Effective Hazardous Waste Management

Gülçin Büyüközkan and Fethullah Gocer

Abstract Improperly handled hazardous waste can pose significant threat to human health and the environment. Safety of waste transportation is an important aspect of hazardous waste management. This makes the evaluation and selection of the most suitable hazardous waste transportation firm (HWTF) a crucial problem for hazardous waste generators. A number of factors affect the selection of the proper HWTF, which need to be addressed with usually vague and imprecise data provided by a team of experts from different backgrounds. This chapter proposes a systematic and integrated multi criteria decision making (MCDM) approach to support the HWTF selection process. This approach is based on the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method in an intuitionistic fuzzy (IF) environment. A Group Decision Making (GDM) approach is utilized by the means of IF to minimize the bias stemming from experts' fuzzy evaluations and to better manage the associated uncertainties and partiality. A real case application from Turkey is presented to illustrate the use of the proposed methodology.

2.1 Introduction

In modern societies, almost all materials, devices and objects sooner or later turn into waste (Gumus 2009). Waste can be classified as hazardous or non-hazardous, depending on whether they exhibit particular characteristics. Hazardous waste has been defined for the first time in the USA in early 1980s (Marinković et al. 2008) as unwanted flammable, oxidizing, poisonous, radioactive, toxic or explosive materials which pose a threat to humans or environment when handled improperly. Sources of hazardous waste are various; it may be produced in hospitals, by metal finishing or timber treatment processes, petrol storage, paint manufacture etc.

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Economic growth and industrial prosperity globally undergone in recent decades has accelerated the generation of hazardous waste (Duan et al. 2008), putting hazardous waste concerns into agenda of many developed or developing countries, which has led to the exploration of alternative ways for proper hazardous waste management and handling.

Considering associated dangers, it presents to humans and environment, prevention of contamination by hazardous waste is vital, underlining the importance of its safe transportation. However, hazardous waste generators believe that safe transportation regulations are particularly enforced by policy makers because other parties handle those processes (Gumus 2009; Orford 2007). For these reasons, generators explore safe and cost-effective solutions in hazardous waste management (HWM), presenting a problem with several different objectives. For a commercial firm, for instance, the most feasible HWM solution might be the option with the minimum cost, whereas a public authority might look for the solution with lowest spillage or leakage risk. Therefore, a hazardous waste transportation firm (HWTF) must have a certain level of quality, safety, service and responsibility at the same time, in an environment where it is expected to comply with legislation and act correctly (Ho 2011).

In this chapter, a Group Decision Making (GDM) approach is implemented for the selection of the most suitable HWTF. At first, the literature about HWM and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods under Intuitionistic Fuzzy (IF) environment will be reviewed. Following that, the proposed methodology structure will be explained and a real case from Turkey will be presented. Then, procedural IF TOPSIS steps and related calculations will be provided to introduce the technique. A numerical application of the case study will be illustrated at the final stage in order to display how the proposed method functions.

2.2 Literature Review

2.2.1 Hazardous Waste Management

Hazardous waste with explosive, ignitable/flammable, oxidizing, poisonous, corrosive, radioactive or toxic characteristics can be generated during petrol storage, metal finishing, paint manufacturing, dry cleaning and hospitals, beside others.

If handled poorly, hazardous waste will cause significant damage to both humans and environment, putting specific emphasis on choosing the right transportation and disposal firm for hazardous waste. Hsu et al. (2008) selected the most suitable medical hazardous waste disposal firm with the help of AHP and a modified Delphi technique. They suggested that their method reduced overhead costs and thus enhanced the management of hazardous waste. Ho (2011) suggested a fuzzy AHP method for this kind of evaluation with which medical and health care institutions could objectively and systematically choose appropriate infectious medical waste disposal firms. Using a MCDA approach, Feo and Gisi (2014) developed a hazardous waste minimization procedure with geographical information. In their study, AHP is used to define the priorities of evaluation criteria for its ease and usefulness. A HWM case study in the USA is done using DEA-TOPSIS techniques by Ali et al. (2015). In another study, Mohsin et al. (2015) made an assessment of HWM proposal using AHP. Abessi and Saeedi (2014) presented an approach for siting hazardous waste landfill in large areas using site screening method and AHP. Alidi (1996) suggested a multi objective optimization model for the proper management of hazardous waste. They combined AHP with a goal programming approach to prioritize conflicting goals.

To the extent of our knowledge, the most recent studies about HWTF are presented by Gumus, Kabir and Sumi. Kabir (2015) extended VIKOR method under fuzzy environment for the selection of HWTF. Kabir and Sumi (2015) also proposed a method for selecting HWTF by using AHP and PROMETHEE. Gumus (2009) evaluated a two-step methodology for HWTF by using fuzzy AHP and TOPSIS.

In this study, an IF TOPSIS method is used in order to decide on the most appropriate HWTF. It must be underlined that this technique is applied for the problem evaluation and the results of IF TOPSIS show the ranking order of the HWTFs. To the best of our knowledge, this kind of a study has not appeared in related literature in earlier publications, differentiating itself by integrating TOPSIS and IF with a GDM approach for a real case HWTF selection problem.

2.2.2 IF TOPSIS Literature

In this section, literature related to the TOPSIS technique under IF set is reviewed.

This literature survey in the HWT context revealed that key aspects have been, for the most part, overlooked by researchers, indicating a research gap for selecting suitable HWTF. Fuzzy TOPSISI is commonly used in HWM to obtain the effective ranking of HWTF. GDM is often preferred to avoid the bias and minimize the partiality in this kind of decision process. From literature, however, it is observed that in some situations classical fuzzy sets can be inadequate and even defective in handling the ambiguity of the concepts that are associated with human beings' subjective judgments. IF sets, on the other hand, are useful tools to investigate the fuzziness in decision makers' (DMs') judgments in the complexity of socio-economic environment and the lack of knowledge or data about the problem. A fusion of GDM with DMs' assessments is considered as one uniform group decision by means of IF set.

Table 2.1 displays a summary of the TOPSIS literature under IF or Interval Valued IF (IVIF) environment with an emphasis on the focus and the employed technique.

Table 2.1 IF TOPSIS literature

Author	Aim of the study	Applied technique	GDM	Illustrative or case study
Boran et al. (2009)	Supplier selection	IF TOPSIS	X	Illustrative
Boran (2011)	Supplier selection	IF TOPSIS	X	Illustrative
Park et al. (2011)	Equipment selection	IVIF TOPSIS	X	Illustrative
Wang et al. (2011)	Supplier selection	IVIF TOPSIS	–	Illustrative
Boran et al. (2012)	Technology evaluation	IF TOPSIS	–	Illustrative
İntepe et al. (2013)	Forecasting method	IVIF TOPSIS	X	Illustrative
Yue and Jia (2013)	Partner selection	IF TOPSIS	X	Illustrative
Aloini et al. (2014)	Machine selection	IF TOPSIS	X	Case study
Kucukvar et al. (2014)	Sustainability performance	IF TOPSIS	X	Illustrative
Li et al. (2014)	Module partitioning evaluation	IVIF TOPSIS	X	Case study
Long and Geng (2015)	Module selection	IVIF TOPSIS	–	Case study
Wu (2015)	Supplier selection	IF TOPSIS	X	Illustrative
Wan et al. (2015)	Technology selection	IF TOPSIS	X	Case study
Wang et al. (2015)	E-tendering	IF TOPSIS	–	Illustrative
Yang et al. (2015)	Method proposal for deriving weights	IF TOPSIS	X	Illustrative
Zhang and Xu (2015)	Soft computing technique	IVIF TOPSIS	X	Illustrative
Joshi and Kumar (2016)	Personnel selection	IVIF TOPSIS	X	Illustrative
Wan et al. (2016)	Logistics outsourcing	IF TOPSIS	X	Illustrative

2.3 IF TOPSIS Methodology

This section presents the IF TOPSIS multi criteria GDM method. Let us denote, $D = \{D_1, D_2, \ldots, D_k)$ be a set of DMs, assume that the importance of DM D_k is λ_k, where $\sum_{\mathrm{k}=1}^{K} \lambda_k = 1$, and $C = \{C_1, C_2, \ldots, C_n\}$ be a set of criteria, $w = \{w_1, w_2, \ldots, w_n\}$ the weight vector of criteria, where $w_j \geq 0$, $j = 1, 2, \ldots, n$, $\sum_{\mathrm{j}=1}^{n} w_j = 1$. The set of alternatives: $A = \{A_1, A_2, \ldots, A_m\}$ in the form of TIFN.

2.3.1 Intuitionistic Fuzzy Sets

In this section, the basic concept of intuitionistic fuzzy sets will be briefly introduced. The Intuitionistic Fuzzy Set (IFS) is developed by Atanassov (1986) and constitutes an extension of Zadeh's fuzzy set. It assigns a degree of membership to each element and defines a (crisp) set E, with A $\subset$ E be a fixed set. An IFS A in E is an object of the following form:

$$A = \{\mathrm{x}, \mu_\mathrm{A}(\mathrm{x}), \nu_\mathrm{A}(\mathrm{x}) | x \in E\},$$

The functions μ_A: E $\rightarrow$ [0, 1] and ν_A: E $\rightarrow$ [0, 1] define the degree of membership and the degree of non-membership of the element $x \in$ E to the set A, respectively. For every $x \in$ E:

$$0 \leq \mu_\mathrm{A}(\mathrm{x}) + \nu_\mathrm{A}(\mathrm{x}) \leq 1.$$
$$\{\langle \mathrm{x}, \mu_\mathrm{A}(\mathrm{x}), 1 - \mu_\mathrm{A}(\mathrm{x}) | \mathrm{x} \in \mathrm{E} \rangle\}$$

If

$$\pi_\mathrm{A}(\mathrm{x}) = 1 - \mu_\mathrm{A}(\mathrm{x}) - \nu_\mathrm{A}(\mathrm{x}),$$

then $\pi_\mathrm{A}(\mathrm{x})$ is the degree of non-determinacy (uncertainty) of the membership of element $x \in$ E to set A. In the case of ordinary fuzzy sets, $\pi_\mathrm{A}(\mathrm{x}) = 0$ for every $x \in$ E.

2.3.2 Proposed Computational Steps

In this section, computational steps for IF TOPSIS method is presented. This integrated method is quite suitable for solving MCDM problems. The alternatives are ranked using IF TOPSIS method, as adapted from the studies of Boran et al. (2011) and Boran (2011). The evaluation of the study, which is based on our method, is given in Fig. 2.1 as a schematic diagram.

The steps of the method for IF TOPSIS MCDM are as follows.

Step 1: Construct a hierarchy for the evaluation of the problem.

Define the goal, objective, attributes and alternatives for resolving the problem.

Step 2: Determine the weights of Experts.

Importance of experts is considered as linguistic variables. The defined TIFNs seven-point linguistic variable scale is introduced to estimate the weight of each DM in the GDM process. In order to express DMs' individual assessments more precisely, the linguistic variable scale, which is adapted from the five-point scale of Boran et al. (2009) is improved with a minor addition to intermediate values. The new seven-point scale used in DMs' assessment stages ranges from Very Unimportant to Very Important, as presented in Table 2.2.

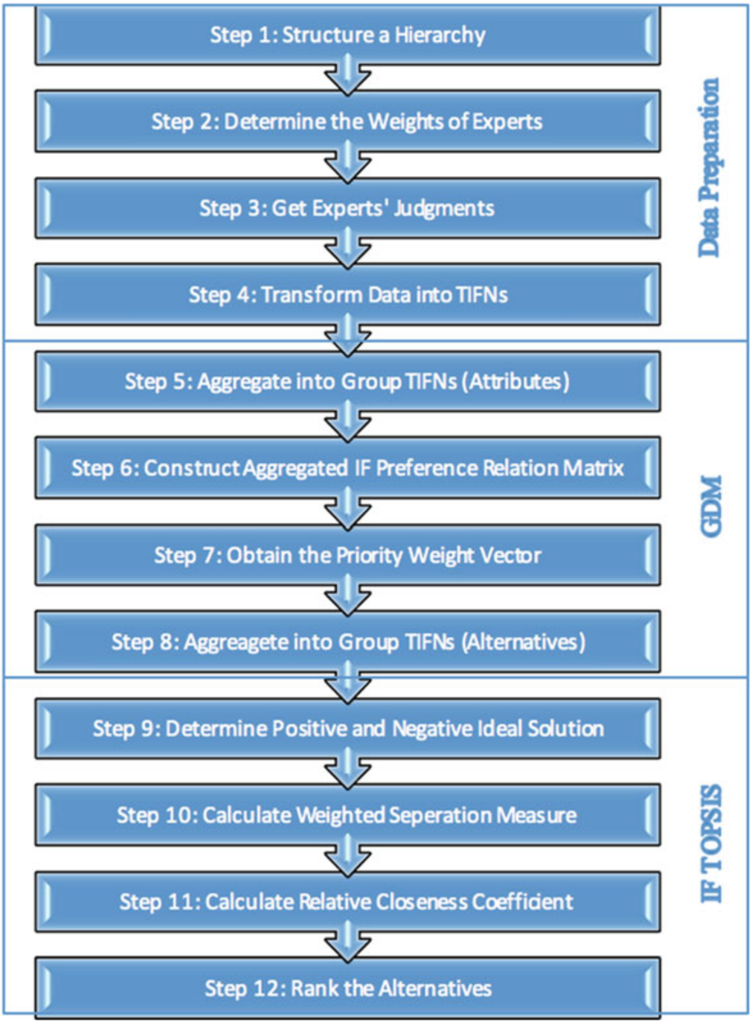

Fig. 2.1 The proposed IF TOPSIS MCDM methodology to determine the best alternative for a HWTF

Let Dk $= (\mu_k, v_k, \pi_k)$ be an IF number for rating of the kth DM. The weights of the kth DM are obtained using the following Eq. (2.1) which is adapted from the study of Boran et al. (2009).

$$\lambda_k = \frac{\left[\mu_k + \pi_k \left[\frac{\mu_k}{1-\pi_k}\right]\right]}{\sum_{k=1}^{K} \left[\mu_k + \pi_k \left[\frac{\mu_k}{1-\pi_k}\right]\right]}, \quad where \ \sum_{k=1}^{K} \lambda_k = 1 \tag{2.1}$$

Table 2.2 Linguistic variable for the importance of each DM

Linguistic variables	TIFNs		
	μ	υ	Π
Very important	0.90	0.05	0.05
Important	0.75	0.20	0.05
Somewhat important	0.60	0.30	0.10
Medium important	0.50	0.40	0.10
Somewhat unimportant	0.30	0.60	0.10
Unimportant	0.25	0.60	0.15
Very unimportant	0.10	0.80	0.10

Step 3: Based on prior knowledge and expertise on their specific topics, experts are required to provide their judgments.

In this step, assume that each expert provides his/her judgments on each factor in linguistic terms.

Step 4: Transform Data into TIFNs.

Construct the preference relation matrix for attributes and alternatives.

After forming the hierarchy, the preference relation matrix is structured. During the preference relation, a TIFNs preference scale is used for the evaluation. Since the linguistic terms are not mathematically operable, the next step is to make a standardization of experts' evaluations by converting them to TIFNs, once all linguistic assessments of factors from each expert are obtained. The scale used in TOPSIS stage for preparing the preference relation matrix ranges from 1 (Extremely Unimportant) to 9 (Extremely Important), as presented in Table 2.3. The linguistic scale is adapted from Abdullah and Najib (2014).

Step 5: Aggregate individual TIFNs into group TIFNs for the attributes.

In this step, each individual experts' opinion is aggregated into IF environment. It has been decided to use the intuitionistic fuzzy weighted averaging (IFWA) operator which is used to aggregate the matrix assessment of DMs into a group

Table 2.3 Linguistic variable for the importance of factors (Abdullah and Najib 2014)

Linguistic variable		μ	υ	π
Extremely unimportant	EU	0.02	0.18	0.80
Very strong unimportance	VSU	0.06	0.23	0.70
Strongly unimportant	SU	0.13	0.27	0.60
Moderately unimportant	MU	0.22	0.28	0.50
Equally important	EI	0.33	0.27	0.40
Moderately important	MI	0.47	0.23	0.30
Strongly important	SI	0.62	0.18	0.20
Very strong importance	VSI	0.80	0.10	0.10
Extremely important	EMI	1.00	0.00	0.00

opinion due to Xu (2011) since IFWA weights only the IF arguments but not the ordered position and practical in use.

Step 6: Construct the aggregated IF preference relation matrix

$$B = \begin{bmatrix} \hat{b}_{11} & \hat{b}_{12} & \dots & \hat{b}_{1n} \\ b_{21} & \hat{b}_{21} & \dots & \hat{b}_{2n} \\ & & \cdot & \\ & & \cdot & \\ & & \cdot & \\ \hat{b}_{m1} & \hat{b}_{m2} & \dots & \hat{b}_{mn} \end{bmatrix}$$

where $\tilde{b}_{ij} = (\mu_{ij}, \upsilon_{ij})(i = 1, 2, \dots, n;\ j = 1, 2, \dots, n)$ and satisfies the following Eqs. (2.2) and (2.3).

$$(\mu_{ij})^* = \max\left\{\mu_{ij}, \max_p\left\{\frac{\mu_{ip}\mu_{pj}}{\mu_{ip}\mu_{pj} + (1 - \mu_{ip})(1 - \mu_{pj})}\right\}\right\} \tag{2.2}$$

$$(\upsilon_{ij})^* = \max\left\{\upsilon_{ij}, \max_p\left\{\frac{\upsilon_{ip}\upsilon_{pj}}{\upsilon_{ip}\upsilon_{pj} + (1 - \upsilon_{ip})(1 - \upsilon_{pj})}\right\}\right\} \tag{2.3}$$

Step 7: Obtain the priority vector of criteria:

$$w = (w_1, w_2, \dots, w_n)^T$$

Weights of the criteria can be estimated with the help of the equation proposed by Genç et al. (2010).

$$w_j = \left[w_j^L, w_j^U\right] = \left(\frac{1}{\sum_{j=1}^{n}\left(\frac{(1-\tilde{\mu}_{ij}^*)}{\tilde{\mu}_{ij}^*}\right)}, \frac{1}{\sum_{j=1}^{n}\left(\frac{(1-\tilde{v}_{ij}^*)}{\tilde{v}_{ij}^*}\right)}\right) \tag{2.4}$$

Step 8: Aggregate individual TIFNs into group TIFNs for the alternatives.

In this step, each individual expert's opinion is aggregated into IF environment and the aggregated IF decision matrices for each expert is constructed:

Assume that R is the group decision making matrix where

$$R = \left(R_{ij}^k\right) = \begin{bmatrix} R_{11}^k & \cdots & R_{1n}^k \\ \vdots & \ddots & \vdots \\ R_{m1}^k & \cdots & R_{mn}^k \end{bmatrix}, \quad k\epsilon K$$

where $R_{ij}^k = \left(\mu_{ij}^{\mathrm{k}}, \upsilon_{ij}^{\mathrm{k}}, \pi_{ij}^*\right)$. Use the following Eq. (2.5) for individual aggregation of each expert's opinions.

$$R_{ij} = IFWA_\lambda\left(R_{ij}^{(k)}\right) = \lambda_k r_{ij}^{(k)} \tag{2.5}$$

Step 9: Determine the positive ideal solution and the negative ideal solution.

A^* is the positive ideal solution, and A^- is the negative ideal solution,

$$A^* = \left(\tilde{r}_1^*, \tilde{r}_2^*, \ldots, \tilde{r}_n^*\right), \tilde{r}_j^* = \left(\mu_j^*, \upsilon_j^*, \pi_j^*\right), \quad j = 1, 2, \ldots, n \tag{2.6}$$

$$A^- = \left(\tilde{r}_1^-, \tilde{r}_2^-, \ldots, \tilde{r}_n^-\right), \tilde{r}_j^- = \left(\mu_j^-, \upsilon_j^-, \pi_j^-\right), \quad j = 1, 2, \ldots, n \tag{2.7}$$

where

$$\begin{aligned} \mu_j^* &= \left\{\left(\max_i\{\mu_{ij}\} | j \in J_1\right)\right\}, \left\{\left(\min_i\{\mu_{ij}\} | j \in J_2\right)\right\} \\ \upsilon_j^* &= \left\{\left(\min_i\{\upsilon_{ij}\} | j \in J_1\right)\right\}, \left\{\left(\max_i\{\upsilon_{ij}\} | j \in J_2\right)\right\} \\ \mu_j^- &= \left\{\left(\min_i\{\mu_{ij}\} | j \in J_1\right)\right\}, \left\{\left(\max_i\{\mu_{ij}\} | j \in J_2\right)\right\} \\ \upsilon_j^- &= \left\{\left(\max_i\{\upsilon_{ij}\} | j \in J_1\right)\right\}, \left\{\left(\min_i\{\upsilon_{ij}\} | j \in J_2\right)\right\} \end{aligned}$$

Step 10: Calculate the weighted separation measures.

The weighted Hamming distance is utilized to calculate the separation measures (Xu 2011).

$$\left(S_i^*\right)^L = \frac{1}{2}\sum_{j=1}^n w_j^L\left[\left|\mu_{ij} - \mu_j^*\right| + \left|v_{ij} - v_j^*\right| + \left|\pi_{ij} - \pi_j^*\right|\right] \tag{2.8}$$

$$\left(S_i^*\right)^U = \frac{1}{2}\sum_{j=1}^n w_j^U\left[\left|\mu_{ij} - \mu_j^*\right| + \left|v_{ij} - v_j^*\right| + \left|\pi_{ij} - \pi_j^*\right|\right] \tag{2.9}$$

$$\left(S_i^-\right)^L = \frac{1}{2}\sum_{j=1}^{n} w_j^L \left[\left|\mu_{ij} - \mu_j^-\right| + \left|v_{ij} - v_j^-\right| + \left|\pi_{ij} - \pi_j^-\right|\right] \tag{2.10}$$

$$\left(S_i^-\right)^U = \frac{1}{2}\sum_{j=1}^{n} w_j^U \left[\left|\mu_{ij} - \mu_j^-\right| + \left|v_{ij} - v_j^-\right| + \left|\pi_{ij} - \pi_j^-\right|\right] \tag{2.11}$$

Step 11: Calculate the relative closeness coefficients.

$$\left(C_i^*\right)^L = \left(\frac{\left(S_i^-\right)^L}{\left(S_i^*\right)^U + \left(S_i^-\right)^U}\right) \tag{2.12}$$

$$\left(C_i^*\right)^U = \left(\frac{\left(S_i^-\right)^U}{\left(S_i^*\right)^L + \left(S_i^-\right)^L}\right) \tag{2.13}$$

Step 12: Rank the alternatives in ascending order of the relative closeness coefficients.

The best alternative is selected in ascending order of the relative closeness coefficient. The possibility degree formula, which is proposed by Xu and Da (2002), is used to rank the alternatives as shown in Eqs. (2.14) and (2.15).

$$p(a \geq b) = \max\{1 - \max\left(\frac{b^U - a^L}{b^U - b^L + a^U - a^L}, 0\right), 0\} \tag{2.14}$$

$$p(b \geq a) = \max\{1 - \max\left(\frac{a^U - b^L}{b^U - b^L + a^U - a^L}, 0\right), 0\} \tag{2.15}$$

2.4 Case Study

2.4.1 Company Background

The proposed method has been implemented in a chemical company registered in Turkey. Due to privacy concerns, the identity of the firm is kept anonymous. In this chapter, the company is referred as ABC Company from now on.

The ABC Company is established in 1924 to deal with chemicals trading with recognized international suppliers, mainly polymer emulsions and specialty chemicals. The first polymer emulsions and textile auxiliaries investment of ABC had a plant capacity of 6000 tons. As of 2007, over the last 28 years this production capacity grew more than 30-fold to 200,000 tons per year, thanks to 5 plant expansions with an ambition to grow and passion for its business.

Environment is a key concern for ABC, not only in production, but also in new product development, both at individual and corporate levels. ABC is well aware that reducing the use of Polyethylene (PE) adds up to sizable benefits for the environment. ABC's goal is to improve the production performance by analyzing each step in the production, logistics and transport and determine the way for decreasing energy consumption, raw material use, equipment wear and tear and byproducts and increasing the customer satisfaction, hygiene, environmental safety and the wellbeing of its workers and community. For this reason, ABC is willing to find a suitable HWTF for all its hazardous waste.

2.4.2 Implementation of the Proposed Methodology

ABC's main objective is to select the most suitable HWTF that can satisfy its needs. There are 5 HWTF alternatives with which ABC has worked in the past for hazardous waste material transportation. At this stage, experts' earlier works done with the company's existing firms is taken as reference. These 5 firms, referred as A_1, A_2, A_3, A_4 and A_5 from now on, are assessed in the following case study.

The criteria determined for the purpose of evaluating and ranking alternative transportation firms are taken from similar studies in literature (Gumus 2009; Kabir and Sumi 2015; Kabir 2015) and experts' opinions. Three experts are designated for evaluation; the logistics and distribution manager, the sales coordination manager and the health-safety and environment specialist. ABC's logistic director has been employed since 1990 to manage stock levels, delivery times and negotiations with customers and suppliers, etc. He is one of the most experienced and longest serving staff of the company. ABC's sales coordination manager is working for the company since 1999. He has worked in different departments in the company in the past and currently works as a manager for coordinating the sales team, assessing the progress of the department and developing sales strategies. Health-safety and environmental specialist works for the company in order to ensure that environmental regulations and workplace safety standards are fully met to protect the wellbeing of the public and the environment. She is employed in ABC since 2005.

The details of the HWTF selection process for ABC Company is illustrated below.

Step 1. The hierarchical structure is constructed.

The goal of finding the best suitable HWTF and 5 transportation firm alternatives for resolving the problem is defined. The evaluation criteria that are grouped under 10 categories for evaluating transportation firms are given as follows:

C_1 Economic Capability (EC)
C_2 Cost of Service (CS)

C_3 Financial Stability (FS)
C_4 Service Capability (SC)
C_5 Service Time (ST)
C_6 Experience and Qualification (E&Q)
C_7 Technical Capability (TC)
C_8 Environmental and Safety (ES)
C_9 Hygiene and Safety (HS)
C_{10} Taking Care of Human Health (TCH)

Step 2. Weights of the DMs are determined.

Importance weights of the experts are calculated, as seen in Table 2.4.

Step 3. Experts' judgments are collected for each HWTF.

Table 2.5 shows the judgment matrix of the first DM as an example. Table 2.6 shows the judgment matrix for all alternatives for each DM.

Step 4. Linguistic data are transformed into TIFNs.

The sample of the transformed TIFNs is shown in Table 2.7 for the first alternative.

Step 5. Individual data are aggregated into group TIFNs.

Table 2.8 displays B matrix, the group TIFNs for attributes.

Table 2.4 Importance weights of the experts

	DM-1	DM-2	DM-3
Linguistic terms	Very important	Important	Medium important
Weight	0.4133	0.3444	0.2423

Table 2.5 Judgment matrix of criteria for DM1

	EC	CS	FS	SC	ST	E&Q	TC	ES	HS	TCH
EC	EU	EI	SU	SI	EI	EI	SU	SU	VSU	SU
CS	EI	EU	EI	MU	SI	MI	MU	MU	SU	VSU
FS	MI	EI	EU	EI	SU	EI	SU	VSU	MU	VSU
SC	VSU	MI	EI	EU	MU	VSU	MU	SU	SU	SU
ST	EI	SI	MI	SI	EU	MU	EI	VSU	VSU	VSU
E&Q	EI	MU	EI	VSI	SI	EU	MU	SU	MU	SU
TC	MI	SI	MI	SI	EI	SI	EU	VSU	SU	VSU
ES	MI	SI	VSI	MI	VSI	MI	VSI	EU	VSU	SU
HS	VSI	MI	SI	MI	VSI	SI	MI	VSI	EU	VSU
TCH	MI	VSI	VSI	MI	VSI	VSI	VSI	MI	VSI	EU

Table 2.6 Judgment matrix of alternatives

Criteria	A_1			A_2			A_3			A_4			A_5		
	DM1	DM2	DM3	DM1	DM2	DM3	DM1	DM2	DM3	DM1	DM2	DM3	DM1	DM2	DM3
EC	SI	VSI	MI	MI	EI	VSI	MI	EI	MU	MI	EI	VSI	MI	MI	MI
CS	MI	SI	SI	MI	MU	SI	EI	SI	EI	EI	MI	EU	EI	SI	EI
FS	MI	EI	VSI	SI	EI	VSI	MU	MI	MU	SI	EI	VSI	EI	EI	EI
SC	MU	EI	MU	MU	MI	MU	EI	EI	EI	MU	MI	MU	MU	SU	MU
ST	EI	MI	MI	MI	MU	MU	SI	MU	EI	MI	MU	MU	SI	MU	EI
E&Q	MU	SI	MI	SU	VSU	EI	MI	EI	MU	MI	MU	SI	EI	MI	EI
TC	MI	MU	EI	SI	VSU	EI	MU	VSU	SU	EI	SI	MI	SI	EI	EI
ES	VSI	VSI	VSI	MI	EI	EI	EI	MI	SI	MI	EI	EI	EI	MI	SI
HS	SI	MI	SI	EI	SI	MI	SI	MI	EI	VSU	EI	MU	MU	MI	MU
TCH	SI	SI	VSI	MI	MI	MI	MI	MI	MI	MI	MI	MI	MI	EI	MU

Table 2.7 TIFNs for the first alternative

		DM1			DM2			DM3		
		μ	υ	π	μ	υ	π	μ	υ	π
A1	EC	0.62	0.18	0.2	0.8	0.1	0.1	0.47	0.23	0.3
	CS	0.47	0.23	0.3	0.62	0.18	0.2	0.62	0.18	0.2
	FS	0.47	0.23	0.3	0.33	0.27	0.4	0.8	0.1	0.1
	SC	0.22	0.28	0.5	0.33	0.27	0.4	0.22	0.28	0.5
	ST	0.33	0.27	0.4	0.47	0.23	0.3	0.47	0.23	0.3
	E&Q	0.22	0.28	0.5	0.62	0.18	0.2	0.47	0.23	0.3
	TC	0.47	0.23	0.3	0.22	0.28	0.5	0.33	0.27	0.4
	ES	0.8	0.1	0.1	0.8	0.1	0.1	0.8	0.1	0.1
	HS	0.62	0.18	0.2	0.47	0.23	0.3	0.62	0.18	0.2
	TCH	0.62	0.18	0.2	0.62	0.18	0.2	0.8	0.1	0.1

Table 2.8 Aggregated TIFNs for attributes (B)

	EC		CS		FS		SC		ST	
	μ	υ	υ	μ	μ	υ	μ	υ	μ	υ
EC	0.02	0.18	0.48	0.23	0.23	0.27	0.5	0.22	0.36	0.26
CS	0.23	0.45	0.02	0.18	0.24	0.27	0.41	0.24	0.59	0.19
FS	0.27	0.2	0.27	0.22	0.02	0.18	0.36	0.26	0.15	0.26
SC	0.26	0.24	0.24	0.35	0.26	0.34	0.02	0.18	0.24	0.27
ST	0.26	0.34	0.19	0.58	0.27	0.13	0.27	0.22	0.02	0.18
E&Q	0.26	0.31	0.22	0.5	0.27	0.3	0.25	0.08	0.27	0.22
TC	0.27	0.2	0.28	0.22	0.26	0.1	0.27	0.28	0.27	0.3
ES	0.26	0.11	0.28	0.19	0.26	0.1	0.26	0.15	0.2	0.11
HS	0.24	0.08	0.25	0.09	0.28	0.19	0.25	0.09	0.25	0.1
TCH	0.25	0.09	0.26	0.12	0.26	0.1	0.26	0.11	0.2	0.11
	E&Q		TC		ES		HS		TCH	
	μ	υ	μ	υ	μ	υ	μ	υ	μ	υ
EC	0.33	0.26	0.23	0.27	0.11	0.26	0.08	0.24	0.09	0.25
CS	0.51	0.22	0.22	0.28	0.2	0.28	0.09	0.25	0.14	0.26
FS	0.3	0.27	0.11	0.26	0.1	0.25	0.2	0.28	0.1	0.25
SC	0.09	0.25	0.29	0.27	0.19	0.26	0.09	0.25	0.11	0.26
ST	0.24	0.27	0.3	0.27	0.08	0.23	0.12	0.25	0.08	0.23
E&Q	0.02	0.18	0.25	0.28	0.15	0.27	0.17	0.27	0.15	0.27
TC	0.28	0.24	0.02	0.18	0.12	0.25	0.09	0.23	0.11	0.25
ES	0.27	0.15	0.25	0.1	0.02	0.18	0.05	0.22	0.11	0.26
HS	0.27	0.16	0.24	0.07	0.19	0.08	0.02	0.18	0.06	0.24
TCH	0.26	0.11	0.25	0.09	0.26	0.11	0.18	0.07	0.02	0.18

Step 6. Aggregated IF preference relation matrix is constructed.

After taking the judgments of experts about all criteria, the aggregated preference relation matrix is formed and then using the Eqs. (2.2) and (2.3), the consistent IF preference relation matrix is constructed, as shown in Table 2.9.

Step 7. Obtain the priority vector.

The priority vector of criteria is estimated using Eq. (2.4). Table 2.10 displays the calculated data.

Step 8. Alternatives are aggregated into group TIFNs.

Table 2.11 displays the aggregated IF decision matrix for each alternative.

Step 9. Positive and negative ideal solutions are calculated.

The positive and negative ideal solutions are calculated by considering ranking values and Eqs. (2.6) and (2.7) (Table 2.12). Economic capability, cost of service and financial stability criteria are considered as cost criteria and the rest are considered as benefit criteria.

Table 2.9 IF preference relation matrix for attributes (consistent B*)

	EC		CS		FS		SC		ST	
	μ	υ	μ	υ	μ	υ	μ	υ	μ	υ
EC	0.260	0.191	0.479	0.324	0.258	0.272	0.499	0.220	0.568	0.258
CS	0.333	0.447	0.254	0.246	0.340	0.272	0.413	0.238	0.588	0.219
FS	0.272	0.204	0.272	0.331	0.164	0.180	0.359	0.258	0.348	0.264
SC	0.261	0.300	0.245	0.347	0.259	0.338	0.260	0.180	0.316	0.274
ST	0.259	0.527	0.243	0.580	0.265	0.341	0.274	0.302	0.254	0.246
E&Q	0.264	0.449	0.248	0.503	0.272	0.299	0.263	0.240	0.285	0.223
TC	0.272	0.204	0.280	0.371	0.258	0.165	0.274	0.279	0.357	0.299
ES	0.262	0.162	0.278	0.194	0.256	0.098	0.262	0.151	0.354	0.106
HS	0.244	0.081	0.250	0.163	0.278	0.194	0.250	0.087	0.322	0.099
TCH	0.250	0.097	0.259	0.140	0.256	0.098	0.262	0.110	0.333	0.106
	E&Q		TC		ES		HS		TCH	
	μ	υ	μ	υ	μ	υ	μ	υ	μ	υ
EC	0.490	0.263	0.286	0.272	0.190	0.261	0.092	0.243	0.127	0.249
CS	0.511	0.224	0.385	0.280	0.199	0.278	0.175	0.249	0.159	0.258
FS	0.305	0.272	0.183	0.257	0.117	0.255	0.199	0.278	0.104	0.255
SC	0.253	0.247	0.287	0.274	0.191	0.261	0.092	0.249	0.115	0.261
ST	0.240	0.276	0.305	0.349	0.082	0.346	0.122	0.314	0.077	0.324
E&Q	0.226	0.219	0.248	0.282	0.153	0.280	0.168	0.274	0.153	0.272
TC	0.289	0.243	0.141	0.180	0.122	0.250	0.094	0.235	0.105	0.245
ES	0.287	0.148	0.251	0.099	0.087	0.180	0.079	0.220	0.115	0.261
HS	0.274	0.162	0.240	0.077	0.188	0.083	0.087	0.180	0.065	0.235
TCH	0.268	0.111	0.246	0.087	0.262	0.110	0.180	0.065	0.059	0.180

Table 2.10 Priority weight vector

	Lower	Upper
EC	0.030	0.033
CS	0.039	0.035
FS	0.024	0.033
SC	0.024	0.036
ST	0.020	0.051
E&Q	0.028	0.040
TC	0.021	0.031
ES	0.021	0.017
HS	0.020	0.013
TCH	0.023	0.012

Table 2.11 IF decision matrix

	EC		CS		FS		SC		ST	
	μ	υ	μ	υ	μ	υ	μ	υ	μ	υ
A_1	0.670	0.156	0.564	0.199	0.546	0.199	0.260	0.277	0.416	0.246
A_2	0.546	0.199	0.441	0.232	0.605	0.179	0.317	0.262	0.335	0.258
A_3	0.369	0.255	0.449	0.235	0.317	0.262	0.330	0.270	0.441	0.231
A_4	0.546	0.199	0.322	0.232	0.605	0.179	0.317	0.262	0.335	0.258
A_5	0.470	0.230	0.449	0.235	0.330	0.270	0.190	0.277	0.441	0.231
	E&Q		TC		ES	HS	TCH		E&Q	
	μ	υ	μ	υ	μ	υ	μ	υ	μ	υ
A_1	0.446	0.229	0.359	0.256	0.800	0.100	0.574	0.196	0.675	0.156
A_2	0.163	0.257	0.406	0.218	0.392	0.253	0.479	0.226	0.470	0.230
A_3	0.369	0.255	0.147	0.261	0.461	0.232	0.511	0.216	0.470	0.230
A_4	0.441	0.232	0.479	0.226	0.392	0.253	0.202	0.257	0.470	0.230
A_5	0.330	0.270	0.511	0.216	0.461	0.232	0.317	0.262	0.369	0.255

Table 2.12 The negative and positive ideal solutions

	A^*			A^-		
EC	0.369	0.255	0.376	0.670	0.156	0.174
CS	0.322	0.235	0.443	0.564	0.199	0.237
FS	0.317	0.270	0.413	0.605	0.179	0.216
SC	0.330	0.262	0.408	0.190	0.277	0.533
ST	0.441	0.231	0.327	0.335	0.258	0.407
E&Q	0.446	0.229	0.325	0.163	0.270	0.567
TC	0.511	0.216	0.273	0.147	0.261	0.591
ES	0.800	0.100	0.100	0.392	0.253	0.355
HS	0.574	0.196	0.230	0.202	0.262	0.536
TCH	0.675	0.156	0.169	0.369	0.255	0.376

Step 10. Weighted separation measures are calculated.

Negative and positive separation measures, based on the weighted lower and upper hamming distance for each alternative, have been calculated using the Eqs. (2.8), (2.9), (2.10), and (2.11) (Table 2.13).

Step 11. Relative closeness coefficient is calculated.

The distances of each alternative to the ideal solutions and the closeness coefficient are calculated as given in Table 2.14.

Step 12. Alternatives are ranked.

Five candidate HWTF have been ranked in descending order of the relative closeness coefficients. The candidates are ranked by using the possibility degree formula, thus the matrix in Table 2.15 is created. The ranking of the alternatives is $A_2 > A_1 > A_3 > A_4 > A_5$. Finally, A_2 is selected as the best alternative for ABC Company.

Table 2.13 Separation measures

	S_i*		S_i^-	
	Upper	Lower	Upper	Lower
A1	0.035	0.030	0.042	0.040
A2	0.051	0.045	0.026	0.026
A3	0.028	0.028	0.049	0.042
A4	0.037	0.037	0.040	0.034
A5	0.031	0.034	0.046	0.036

Table 2.14 Closeness coefficient

Lower	Upper
0.528	0.596
0.333	0.374
0.545	0.693
0.438	0.566
0.466	0.655

Table 2.15 Possibility degree matrix

A_1	0.500	1.000	0.765	0.197	0.494	2.956	2
A_2	0.000	0.500	1.000	1.000	1.000	3.500	1
A_3	0.235	0.000	0.500	0.923	0.674	2.333	3
A_4	0.803	0.000	0.077	0.500	0.683	2.063	4
A_5	0.506	0.000	0.326	0.317	0.500	1.649	5

2.5 Conclusion

MCDM methods are used for comparing, ranking and selecting multiple alternatives with multiple criteria. When there are several alternatives available, MCDM can be used, since a decision needs to be taken that is favorable over others. The HWTF selection problem is often influenced by vagueness and uncertainty in practice since DMs' judgments cannot be explained precisely in numerical values. Therefore, DMs' preferences and evaluations are very often expressed in linguistic terms. Some of researchers extend the typical MCDM methods to the fuzzy environment. A fuzzy MCDM is used in case of uncertainty and vagueness in DMs' perceptions. A variety of different MCDM/fuzzy MCDM approaches have been proposed by researchers (such as AHP, ANP, TOPSIS, ELECTRE, etc.). From literature, it is observed that in some situations Fuzzy Sets can be insufficient for dealing with subjectivity and ambiguity which is an unavoidable aspect of human statements. IF sets, however, are useful tools to investigate the fuzziness in DMs' judgments in the lack of knowledge or data about the problem. This study proposes integrated IF TOPSIS as a MCDM technique with a group decision making approach for a real case HWTF selection problem in order to decide on the most appropriate HWTF. Our approach is used to obtain the effective ranking of HWTF alternatives. IF TOPSIS approach is a flexible and robust way for DMs to better understand a decision problem in case of uncertainty and vagueness in DMs perceptions.

There are several future research directions to follow this study. Only ten criteria are used for this analysis. More HWTF evaluation criteria can be used to improve the effectiveness of the decision making process. Also, the present approach only considers IF sets. Another promising future work would be to consider the regular fuzzy logic and to compare the results by a sensitivity analysis. Another area to be studied could be the use of other MCDM methods in integration with fuzzy or IF, AHP, TOPSIS or VIKOR, etc. in order to resolve these problems effectively and satisfactorily.

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References

Abdullah, L., & Najib, L. (2014, December). Sustainable energy planning decision using the intuitionistic fuzzy analytic hierarchy process: Choosing energy technology in Malaysia. *International Journal of Sustainable Energy*, 1–18.

Abessi, O., & Saeedi, M. (2014). Hazardous waste landfill siting using GIS technique and analytical hierarchy process. *Environment Asia, 7*(2), 104–111.

Ali, M., Yadav, A., & Anis, M. (2015a). Assessment of hazardous waste management proposal: Using the analytic hierarchy process. *International Journal of Economics, Commerce and Management, III*(7), 315–327.

Ali, M., Yadav, A., Anis, M., & Sharma, P. (2015b). Multiple criteria decision analysis using Dea-TOPSIS method for hazardous waste management: A case study of the USA. *International Journal of Managing Information Technology, 7*(3), 1–17.

Alidi, A. S. (1996). A multiobjective optimization model for the waste management of the petrochemical industry. *Applied Mathematical Modelling, 20*(12), 925–933.

Aloini, D., Dulmin, R., & Mininno, V. (2014). A peer IF-TOPSIS based decision support system for packaging machine selection. *Expert Systems with Applications, 41*(5), 2157–2165.

Atanassov, K. T. (1986). Intuitionistic fuzzy sets. *Fuzzy Sets and Systems, 20*(1), 87–96.

Boran, F. E. (2011). An integrated intuitionistic fuzzy multi criteria decision making method for facility location selection. *Mathematical and Computational Applications, 16*(2), 456–466.

Boran, F. E., Boran, K., & Menlik, T. (2012). The evaluation of renewable energy technologies for electricity generation in Turkey using intuitionistic fuzzy TOPSIS. *Energy Sources, Part B: Economics, Planning and Policy, 7*(1), 81–90.

Boran, F. E., Genc, S., & Akay, D. (2011). Personnel selection based on intuitionistic fuzzy sets. *Human Factors and Ergonomics in Manufacturing, 21*(5), 493–503.

Boran, F. E., Genç, S., Kurt, M., & Akay, D. (2009). A multi-criteria intuitionistic fuzzy group decision making for supplier selection with TOPSIS method. *Expert Systems with Applications, 36*(8), 11363–11368.

De Feo, G., & De Gisi, S. (2014). Using MCDA and GIS for hazardous waste landfill siting considering land scarcity for waste disposal. *Waste Management, 34*(11), 2225–2238.

Duan, H., Huang, Q., Wang, Q., Zhou, B., & Li, J. (2008). Hazardous waste generation and management in China: A review. *Journal of Hazardous Materials, 158*, 221–227.

Genç, S., Boran, F. E., Akay, D., & Xu, Z. (2010). Interval multiplicative transitivity for consistency, missing values and priority weights of interval fuzzy preference relations. *Information Sciences, 180*(24), 4877–4891.

Gumus, A. T. (2009). Evaluation of hazardous waste transportation firms by using a two step fuzzy-AHP and TOPSIS methodology. *Expert Systems with Applications*, *36*(2 PART 2), 4067–4074.

Ho, C. C. (2011). Optimal evaluation of infectious medical waste disposal companies using the fuzzy analytic hierarchy process. *Waste management (New York, N.Y.)*, *31*(7), 1553–1559.

Hsu, P.-F., Wu, C.-R., & Li, Y.-T. (2008). Selection of infectious medical waste disposal firms by using the analytic hierarchy process and sensitivity analysis. *Waste management (New York, N.Y.)*, *28*(8), 1386–1394.

İntepe, G., Bozdag, E., & Koc, T. (2013). The selection of technology forecasting method using a multi-criteria interval-valued intuitionistic fuzzy group decision making approach. *Computers & Industrial Engineering, 65*(2), 277–285.

Joshi, D., & Kumar, S. (2016). Interval-valued intuitionistic hesitant fuzzy choquet integral based TOPSIS method for multi-criteria group decision making. *European Journal of Operational Research, 248*(1), 183–191.

Kabir, G. (2015). Selection of hazardous industrial waste transportation firm using extended VIKOR method under fuzzy environment Golam Kabir. *International Journal of Data Analysis Techniques and Strategies, 7*(1), 40–58.

Kabir, G., & Sumi, R. S. (2015). Hazardous waste transportation firm selection using fuzzy analytic hierarchy and PROMETHEE methods. *International Journal of Shipping and Transport Logistics, 7*(2), 115–136.

Kucukvar, M., Gumus, S., Egilmez, G., & Tatari, O. (2014). Ranking the sustainability performance of pavements: An intuitionistic fuzzy decision making method. *Automation in Construction, 40*, 33–43.

Li, Y., Chu, X., Chu, D., Geng, X., & Wu, X. (2014). An integrated approach to evaluate module partition schemes of complex products and systems based on interval-valued intuitionistic fuzzy sets. *International Journal of Computer Integrated Manufacturing, 27*(7), 675–689.

Long, S., & Geng, S. (2015). Decision framework of photovoltaic module selection under interval-valued intuitionistic fuzzy environment. *Energy Conversion and Management, 106*, 1242–1250.

Marinković, N., Vitale, K., Holcer, N. J., Dzakula, A., & Pavić, T. (2008). Management of hazardous medical waste in Croatia. *Waste Management, 28*(6), 1049–1056.

Orford, P. (2007). Hazardous waste—A UK compliance overview. *Reinforced Plastics, 51*(3), 55–58.

Park, J. H., Park, I. Y., Kwun, Y. C., & Tan, X. (2011). Extension of the TOPSIS method for decision making problems under interval-valued intuitionistic fuzzy environment. *Applied Mathematical Modelling, 35*(5), 2544–2556.

Wan, S.-P., Wang, F., & Dong, J.-Y. (2016). A novel group decision making method with intuitionistic fuzzy preference relations for RFID technology selection. *Applied Soft Computing, 38*(168), 405–422.

Wan, S.-P., Wang, F., Lin, L.-L., & Dong, J.-Y. (2015). Knowledge-based systems an intuitionistic fuzzy linear programming method for logistics outsourcing provider selection. *Knowledge-Based Systems, 82*, 1–15.

Wang, Z., Li, K. W., & Xu, J. (2011). A mathematical programming approach to multi-attribute decision making with interval-valued intuitionistic fuzzy assessment information. *Expert Systems with Applications, 38*(10), 12462–12469.

Wang, Y., Xi, C., Zhang, S., Zhang, W., & Yu, D. (2015). Combined approach for government E-tendering using GA and TOPSIS with intuitionistic fuzzy information. *PLoS ONE, 10*(7), e0130767.

Wu, J. (2015). A SD-IITFOWA operator and TOPSIS based approach for MAGDM problems with intuitionistic trapezoidal fuzzy numbers. *Technological & Economic Development of Economy, 21*(1), 28–47.

Xu, Z. (2011). *Intuitionistic preference modeling and interactive decision making*. Berlin: Springer.

Xu, Z. S., & Da, Q. L. (2002). The uncertain OWA operator. *International Journal of Intelligent Systems, 17*(6), 569–575.

Yang, W., Chen, Z., & Zhang, F. (2015). New group decision making method in intuitionistic fuzzy setting based on TOPSIS. *Technological and Economic Development of Economy, 4913* (November), 1–21.

Yue, Z., & Jia, Y. (2013). An application of soft computing technique in group decision making under interval-valued intuitionistic fuzzy environment. *Applied Soft Computing, 13*(5), 2490–2503.

Zhang, X., & Xu, Z. (2015). Soft computing based on maximizing consensus and fuzzy TOPSIS approach to interval-valued intuitionistic fuzzy group decision making. *Applied Soft Computing, 26*, 42–56.

Chapter 3
Intelligent Optimization of Wastewater Collection Networks

Ali Haghighi

Abstract Design of a wastewater collection network is consisting of (1) generating the network's layout and (2) sizing its hydraulic components. These two sub-problems are nonlinear and discrete in nature and include many complex constraints from hydraulics, technical criteria and regional limitations. This chapter introduces a comprehensive sewer design model possible to be coupled to a variety of intelligent optimization models. For this purpose, two self-adaptive design algorithms are developed for generating the layout and sizing of sewers. Through these algorithms, all constraints of the problem are systematically met and hence, there is no need for any constraint handling strategy into the applied optimization solvers. For optimum design of the network four metaheuristic methods of Genetic Algorithm (GA), Simulate Annealing (SA), Particle Swarm Optimization (PSO) and Tabu Search (TS) are introduced.

3.1 Introduction

Wastewater collection networks are of the most important infrastructure of any modern city; they directly influence public health and are essential for environmental protection. Annually, governments spend a lot of money on development and operation of sewer systems, especially for those in flat areas. However, the affiliated costs and operational problems could be somewhat managed and optimized during the design process. In this regard, the development and application of optimization models to design of sewer networks is quite helpful. Through the optimization, it would be possible to gain a cost-effective design while all hydraulic and technical constraints associated with the sewer systems are systematically met.

The design of a wastewater collection network needs to solve two successive sub-problems: (1) generating the layout and (2) sizing the network's components.

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The latter involves sewer diameters and installation depths, as well as the pumping facilities if required (Haghighi and Bakhshipour 2015a). These sub-problems are nonlinear and discrete in nature and include many complex constraints coming from the hydraulics principles, technical criteria, and regional limitations. In general, three approaches may be used to solve the aforementioned problems:

1. Full enumeration, in which all layout alternatives first are generated and then are hydraulically designed. The best of the existing designs is finally chosen (Pereira 1988; Diogo and Graveto 2006). This approach is very promising to reach the global optimum; however, it is practical only for small networks.
2. A separate design, in which the layout is designed manually or by defining a simplified objective function; in this, the two sub-problems are disconnected and individually optimized (Liebman 1967; Bhave 1983; Tekeli and Belkaya 1986; Walters and Lohbeck 1993; Walters and Smith 1995; Pan and Kao 2009; Afshar 2010; Haghighi and Bakhsipour 2012; Haghighi 2013; Karovic et al. 2014). In practice, this approach is very useful, especially for large networks; however, it is difficult to determine the global optimum design.
3. Simultaneous design, through which the two sub-problems, layout generation and sewer sizing, are implicitly optimized together (Li and Matthew 1990; Haghighi and Bakhsipour 2015b; Steele et al. 2016). This integrated approach is the only way to attain the global optimum design of large sewer systems. Nevertheless, integrating the two sub-problems into a model and coupling an optimization solver to that requires tough formulations and specific design algorithms.

The two sub-problems of sewer system design are very different from each other mathematically. In fact, the layout sub-problem belongs to a difficult class of combinatorial optimization in graph theory. Meanwhile, sewer sizing is a nonlinear discrete program that also can be viewed as a hierarchy decision-making problem. Both of these problems are nonlinear and highly constrained, and they could be highly multimodal depending on the cost function formulation. Currently, great advances in personal computers as well as in nature-inspired metaheuristics would help to overcome many of the complicated engineering problems. Despite this, the metaheuristics are generally unconstrained optimization methods and slowly converge. Therefore, applying them efficiently to design a sewer network needs to pay a careful attention to handling the problem constraints and dimensionality. For this purpose, this chapter introduces several computational algorithms. First, two self-adaptive algorithms are developed for solving the layout generation and sewer sizing sub-problems. Using these algorithms, all constraints of the sewer network design are systematically satisfied, and there is no need for any constraint handling e.g., penalty functions into the applied optimization solver. For the least-cost design of the network three scholastic metaheuristics of Genetic Algorithm (GA), Simulate Annealing (SA) and Particle Swarm Optimization (PSO) as well as a deterministic metaheuristic of Tabu Search (TS) are introduced. Furthermore, the concept of reliability in design and management of sewer networks in flat regions is discussed.

3.2 Sewer Layout Design

The word “network” has a special meaning in life and is frequently used in various fields of science and engineering. In every network structure, there are nodes connected by links for a certain purpose. In wastewater collection networks, nodes are manholes and links are sewer lines. Sewage flows are laterally gathered by secondary sewers to intermediate manholes and longitudinally conveyed by primary sewers toward the outlet of the system. The configuration of layouts is highly dependent on the problem size, location of the outlet, and extent and topography of the area. Finding the best layout among too many alternatives is the first step in designing of a new sewer network.

Sewers are supposed to gravitationally collect sewage flows. Consequently, as a basic rule, the designer relies on the topography of the area to follow natural ground slopes toward the outlet of the network. Depending on the designer’s experiences and the steepness of the area, a nearly optimum layout can be obtained in which sewers are in compliance with the natural ground. In other words, in the case of steep areas, based on engineering judgments, it is almost possible to design a cost-effective layout. Because of the proper natural slopes, this layout results in reducing the diameter sizes and excavation volumes of the sewers and the need for pumping facilities, and consequently, the construction cost of the system.

In flat areas, the problem is totally different and difficult to solve. There is no significant change in topography elevations; consequently, the designer cannot see and trace obvious natural ground slopes to a distinguished outlet. In such areas, there are often many possibilities for the connectivity of the sewers and for the outlet location of the network. In contrast with steep areas, engineering judgments and experiences are not enough to design the sewer layout of flat areas, where the number of feasible layouts exponentially increases with the number of sewers. Because the network lacks enough natural slopes, its design specifications and its construction and operational costs are greatly sensitive to the configuration of the layout. As a result, the inclusion of such hydraulic factors as flow rate, sizes and gradients of pipes, and the effect of online pumping stations is very important to the layout selection of urban drainage systems (Li and Matthew 1990). For this purpose, it is very helpful to utilize optimization methods, at least for flat areas where the conventional approaches are not very efficient.

As explained, the layout sub-problem belongs to a hard class of combinatorial mathematics, which needs some background knowledge about the graph theory and nonlinear discrete optimization.

3.2.1 Basic Graph Theory

A sewer network layout is mathematically a graph with specific properties. Before addressing this issue it is necessary to review some basic notions and terminologies in the graph theory. As a main branch of discrete mathematics, the graph theory studies the principles of mathematical expression of graphs. Focusing on the scope of this chapter, some principles of the graphs, mostly taken from Fournier (2009), are summarized as follows:

- Undirected graph: An undirected graph G is defined by two finite sets: a non-void set X of elements called vertices, a set E of elements called edges (Fig. 3.1a). Herein, the vertices are manholes and the edges are sewer lines. Also, the number of X and E is respectively denoted by n and m.
- Directed graph: A directed graph, abbreviated to a digraph is defined by two finite sets: a non-empty set X of vertices and a set A of directed edges, with an ordered pair (x, y) where y is called the head and x is called the tail (Fig. 3.1b). In a classification, digraphs may be defined as cyclic digraphs (including loops or double edges) and acyclic digraphs (in the absence of loops). The latter is also referred to as the tree digraph (Fig. 3.1c).
- Connected and Disconnected Graph: A G graph is said to be connected if any two vertices of this graph are linked by a path in G (Fig. 3.1a–c). Otherwise, the graph is disconnected.
- Spanning Trees: A spanning tree of graph G is a tree sub-graph, including all vertices. By definition, a connected graph G has (at least) one spanning tree.
- Root: The root of a digraph G is a vertex r, like vertex 3 in Fig. 3.1c, such that there is for any vertex x of G a directed path from x to r. In general, a digraph may have several roots.
- Arborescence: An arborescence is a digraph which has one root and of which the underlying graph is a tree (Fig. 3.1c).

With these definitions, the layout of a wastewater collection network is a sub-graph extracted from a pre-defined base graph. Depending on the method applied to create the layout sub-graphs, the base graph can be initially considered to be directed (Walters and Lohbeck 1993) or undirected (Walters and Smith 1995; Diogo and Graveto 2006; Haghighi 2013). In a base graph, all drainage possibilities

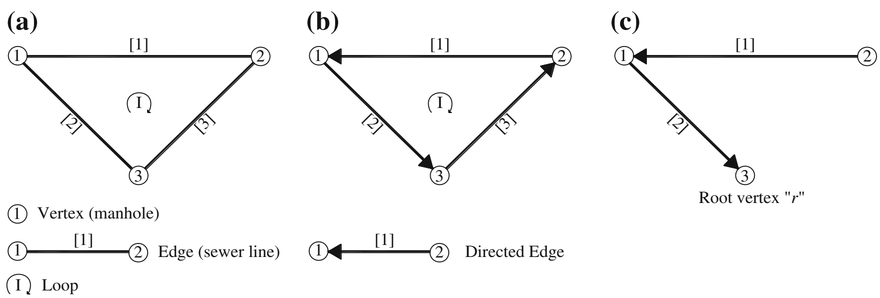
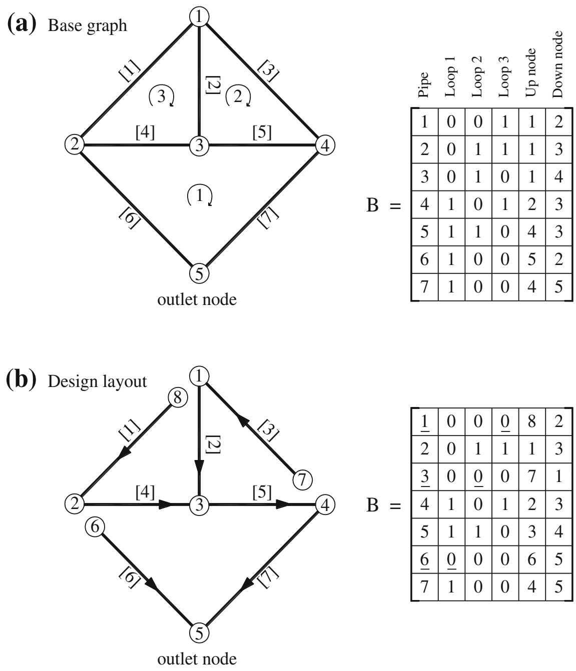


Fig. 3.1 Sample graphs. **a** Undirected graph. **b** Cyclic graph. **c** Acyclic graph



(a) B =

Pipe	Loop 1	Loop 2	Loop 3	Up node	Down node
1	0	0	1	1	2
2	0	1	1	1	3
3	0	1	0	1	4
4	1	0	1	2	3
5	1	1	0	4	3
6	1	0	0	5	2
7	1	0	0	4	5

(b) B =

1	0	0	0	8	2
2	0	1	1	1	3
3	0	0	0	7	1
4	1	0	1	2	3
5	1	1	0	3	4
6	0	0	0	6	5
7	1	0	0	4	5

Fig. 3.2 **a** Example base graph; its representative matrix B and **b** the resulted layout

are so included that manholes (vertices) and sewers (edges) constitute a connected cyclic graph. With respect to the street alignments, topology, barriers, watercourses, location of the outlet and existing sewers in the city, an undirected base graph can be drawn like Fig. 3.2a. Each manhole in the base graph is potentially possible to be linked with its adjacent manholes toward which the sewage flow is directed.

3.2.2 *Sewer Layout Constraints*

For generating a feasible layout from a base graph the following basic constraints need to be fulfilled:

1. No cycle is accepted. The layout is therefore, a tree,
2. All manholes (vertices) must be involved in the tree. It means that the layout is a spanning tree,
3. All sewers (edges) must be involved in the tree since each of them drains a certain street,
4. There is an outlet (root) in the system toward which the spanning tree must be directed, and
5. Several sewers can flow into a manhole. But, except for the root node exactly one sewer leaves every non-root manhole in the direction of the root.

As a result, a feasible layout is an arborescence spanning tree with a root which is finally connected to a wastewater treatment plant or a main sewer collection line. In cases with more than one outlet, *nr* roots, a forest of *nr* arborescences represents the layout.

Searching for the best spanning tree of a base graph with respect to a fitness criterion and subject to the aforementioned constraints is known as the shortest-path problem in the graph theory. Generally, a linear objective function is defined based on some weights or cost values assigned to edges in the base graph which is then referred to as the weighted graph. After that, several methods could be employed to solve the raised linear problem as found in Rosen (2003) and Fournier (2009). Herein, the sewer layout sub-problem seems to be similar to the shortest-path problems. However, because of the following fundamental differences, the layout sub-problem is more complex and intractable to be solved by means of common linear methods,

1. In urban drainage systems, weight of each edge is the construction cost of its sewer line which is a function of the sewer diameter and installation depth and pump stations all of which are still unknown. In simplified cost functions, like what was proposed by Walters and Lohbeck (1993), edge weights are defined by a non-linear concave function of sewer length and discharge. Even if such these simplifications are adopted, the accumulated discharges of sewers are not initially known before designing the layout. In other words, the system cost is implicitly obtained with the layout configuration. As a result, the layout sub-problem is nonlinear and typical linear optimization models cannot be therefore utilized.
2. In common spanning tree problems, it is only necessary to connect all vertices of the base graph in the form of a tree sub-graph. For this purpose, one edge of each loop in the base graph must be inevitably omitted to make a connected tree (e.g., edge 3 in Fig. 3.1c). This is while; every edge in a sewer network is responsible to drain a certain sub-area. Therefore, all edges as well as all vertices must be kept in the extracted trees. It means that instead of removing edges, they must be cut which results in appearing new vertices in the incision locations.

For handling the above constraints, some graph-based algorithms have been so far developed. For instance, Behave (1983) considered a same weight for all sewers in the network and then designed the layout by means of minimum spanning tree method in the graph theory. Takel and Belkaya (1986) defined three kinds of weights including; the reciprocal of ground surface gradient, pipe length and the excavation corresponding to minimum hydraulic gradient for self-cleaning velocity. They then applied the shortest path spanning tree method to each of the mentioned assumptions. Li and Matthew (1990) developed a robust model for complete optimization of urban drainage systems. Through an iterative procedure, in one sub-problem the layout is considered to be fixed while pipe diameters and slopes and location of pumping stations are optimized using the DDDP method. Then, through the next sub-problem the layout is optimized while the other variables are kept constant from the previous solution. For solving the layout sub-problem in that work, an algorithm namely searching direction method was introduced. That algorithm works based on Dijkstra method (Minieka 1978) which is used to generate the shortest spanning tree of a graph. The sewer weights were considered to be the production of sewer lengths and average installation depths available from the first sub-problem solution. As explained, the two sub-problems are successively solved until the results do not change.

Later on, to overcome the nonlinearity of the problem, researchers used metaheuristic methods which are mostly inspired by nature. In this context, Walters and Lohbeck (1993) proposed two alternative genetic algorithms for optimal selection of the layout of pipe networks from an initially directed base graph. They showed that the directed base graph substantially reduces the number of possible trees which can form a network. However, it was emphasized that a great attention is required to define the initial base graph for considering all pipes connectivity and sewer layout restrictions. Walters and Smith (1995) developed a genetic algorithm with new specific features of evolution for the layout optimization. An efficient method named as the tree growing algorithm was incorporated within the main solver to produce the spanning trees on a random basis. By defining the root node and the connectivity decision variables, the tree growing algorithm starts to form a spanning tree in such a way that the resultant tree converges to the root. Diogo and Graveto (2006) showed that if specific restrictions of the problem are appropriately exploited the optimum layout can be achieved in a deterministic way, of course for small to medium systems. On this basis, they proposed an adaptive algorithm to select the layout from an undirected base graph. Using that method, spanning trees of a base graph are extracted while many infeasible trees are systematically avoided. The optimum network is finally obtained by means of a simple economical comparison of all plan solutions having optimized design. For large dimension networks, where the full enumeration algorithm is not practicable, those investigators suggested the simulated annealing method. Haghighi (2013) introduced a self-adaptive layout generator called the loop-by-loop cutting algorithm. Using this algorithm, the undirected base graph is opened with a step-by-step procedure while the layout constraints are systematically met. This algorithm is simply implemented and can solve the problem's complexities efficiently. By this approach, the problem becomes quite unconstrained and possible to connect to any metaheuristic easily. Because of these benefits, this algorithm is adopted here and explained through the next section.

3.2.3 Loop by Loop Algorithm

To generate possible layouts of a network, an undirected base graph is initially provided for the network under deign as for example shown in Fig. 3.2a. Every pipe, manhole and loop in the base graph is named with a number. The base graph is then mathematically represented by a matrix named as B. The matrix B is consisting of m rows and $NL + 3$ columns where m and NL are respectively the number of sewers (network size) and the number of loops. In this matrix, column 1 contains the sewer names, columns 2 to $NL + 1$ are sewer-in-loop indicators which determine that a sewer is either in a loop (value 1) or not (value 0). Columns $NL + 2$

and $NL+3$ also include the names of sewer ends which are arbitrarily assigned since the graph is undirected. For example the matrix of the base graph of Fig. 3.2a has been presented next to it.

To create a feasible layout from the base graph, all loops must be opened. To this end, one pipe from each loop must be cut, which may be done either from its upstream or its downstream manhole. Thus, there are two decision variables for opening each loop including name of the selected pipe to be cut and name of its truncation end. These variables are respectively characterized by α and β in the algorithm. α is a real-valued number in (0, 1) that indirectly points to the pipe to be cut whereas, β is a binary number (0 or 1) to show from where the selected pipe is cut, 0 means the upstream and 1 means the downstream end.

For each loop, variable β explicitly determines the cut location while, α is a coded variable that needs to be firstly decoded. On basis of a given real-valued α on (0, 1) the pipe to be cut for loop i is determined by the following relationship:

$$\mu_i = \text{round}\left(1 + \alpha_i\left(\sum_{j=1}^{m} \mathrm{B}_{j,i+1} - 1\right)\right) \tag{3.1}$$

where subscript i indicates the loop number in the base graph; m is the number of sewers;$\sum_{j=1}^{m} \mathrm{B}_{j,i+1}$ is the total number of pipes in loop i, which are possible to be cut. For loop i at hand, the corresponding column in matrix B, column $i+1$, is taken into account. From the top of this column, the row of the μth nonzero member indicates the pipe to be cut. For example, suppose that for opening loop 1 in the base graph of Fig. 3.2a, random values of 0.6 and 1 are respectively given to α_1 and β_1. Column 2 in matrix B represents the pipes those are possible to be cut for opening loop 1, which are in the rows with non-zero members. As seen there are three pipes in loop 1 and it is found from matrix B that $\sum_{j=1}^{7} \mathrm{B}_{j,2} = 4$. Consequently, $\alpha_1 = 0.6$ results in $\mu_1 = \text{round}(1 + 0.6(4-1)) = 3$ meaning that pipe 6 as the third pipe of loop 1 in matrix B is chosen to be cut. Also, $\beta_1 = 1$ determines that pipe 6 must be cut from its downstream end, which is node 2 in matrix B (Fig. 3.2b).

When a loop was opened, the base graph changes; hence, the previous matrix B needs to be updated before other loops are opened. Subject to the previously addressed constraints of the layout sub-problem, the updates of matrix B are applied step by step as the network is opened loop by loop. For this purpose, matrix B is modified after each loop opening to meet the following criteria:

1. The new manhole: As a pipe is cut for opening loop i, a new manhole appears at the truncation end, which is named $n+i$, where n is the number of manholes in the base graph. The new manhole is located in this matrix instead of the previous one. For example, in Fig. 3.2b, after loop 1 was opened by cutting pipe 6 from manhole 2, the new manhole 6 appears in the graph and is substituted for manhole 2 in $\mathrm{B}_{6,6}$.

2. The flow direction: The flow direction of the cut pipe is from its new manhole, $n+i$, toward its next end. This update is done by changing the location of the cut pipe's ends in matrix B so that the new manhole $n+i$ is placed on column $NL+2$ if it is not already there.
3. Once pipe is cut: If a pipe has been cut to open a loop, it is no longer possible to be cut for other loops. This constraint is met by switching all nonzero sewer-in-loop members in the row of the cut pipe to zero. For example, in Fig. 3.2b, since pipe 6 is cut for opening loop 1, all members of $B_{6,2}$ to $NL+1$ become zero. This update does not let pipe 6 be selected again for the remaining loops in the rest of the process.
4. Network integrity: Suppose all pipes in a manhole can be cut for different loops, like sewers 4, 5, and 2 in Fig. 3.2b, which are common in manhole 3. In such cases, at least one link must not be cut to drain the common manhole and to keep the network integrity. To satisfy this issue, the downstream manhole of the cut pipe is checked. If there is exactly one intact pipe (i.e., not previously cut) connected to this manhole, it must not be cut for the next loops. For this purpose, all the sewer-in-loop members of matrix B in the row of the aforementioned intact pipe are changed to zero.

When these updates complete, matrix B is ready to use for opening the next loops on the basis of the given α and β variables. This procedure is continued until all NL loops are opened and a feasible layout results, which has m pipes and $n+NL$ manholes, while $m=n+NL-1$. Then the sewers in the obtained layout can be easily directed toward the outlet node following the principle that except for the outlet, exactly one sewer leaves every manhole (Fig. 3.2b). The sewer directions are also introduced to the final version of matrix B by changing the location of the sewer ends in columns $NL+2$ and $NL+3$ if they are not already correct. After the direction of all pipes are updated, every manhole appears only once in column $NL+2$.

3.3 Sewer Sizing

After generating a feasible sewer layout, the second sub-problem is to size its hydraulic components including sewer diameters, installation depths and pump stations. This sub-problem is a consequence decision making, which can deterministically be solved using the method of Discrete Differential Dynamic Programming (DDDP) as an extension of classical dynamic programming (Heidari et al. 1971; Mays and Yen 1975; Mays et al. 1976; Li and Matthew 1990). For many years DDDP was the best approach for solving many complex decision making problems such as the sewer networks design. Through a DDDP model, it is required first to define the DDDP's stages manually subject to the problem constrains. Then, an optimum design is sought among the discrete solutions appear in successive stages. However, the curse of dimensionality makes the DDDP computationally inefficient for large problems. An alternative approach is to use the metaheuristic direct search methods such as GA, PSO, SA and TS. These methods are simple in concept and implementation and promising to find the global optimum of the problem. Nevertheless, they are inherently unconstrained and mostly stochastic with some special random-based operators, which need to be calibrated carefully. To exploit metaheuristic methods efficiently for solving the highly constrained problem of sewer design, Haghighi and Bakhshipour (2012) introduced a self-adaptive hydraulic design procedure. Through this method, all hydraulic and technical constraints of the sewer design with a given layout are systematically met and therefore, there is no need for any constraint handling into the optimization process. In what follows, the sewer hydraulics are first briefly reviewed and then, the self-adaptive sewer sizing algorithm is introduced in details.

3.3.1 Sewer Hydraulics

The steady flow in sewer lines is expressed by Manning's equation:

$$V = \frac{1}{n} R^{2/3} S^{1/2} \tag{3.2}$$

where V is flow velocity; A is flow cross-sectional area, n is Manning's coefficient, R is hydraulic radius, and S is sewer slope. The geometrical specifications of circular sections commonly used in sewer design are obtained from the following equations:

$$\frac{d}{D} = \frac{1}{2} \times \left(1 - \cos\frac{\theta}{2}\right) \tag{3.3}$$

$$\frac{A}{A_0} = \left(\frac{\theta - \sin\theta}{2\pi}\right) \tag{3.4}$$

$$R = \frac{D}{4} \times \left(\frac{\theta - \sin\theta}{\theta}\right) \tag{3.5}$$

where D is pipe diameter; A_0 is pipe cross-sectional area, d/D is proportional water depth, and θ is central angle from the center of the section to the water surface (Fig. 3.3).

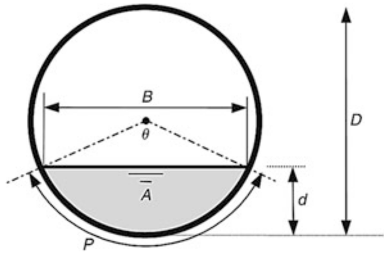


Fig. 3.3 Sewer cross section

3.3.2 Self-adaptive Sewer Sizing Algorithm

For a sewer network having m pipes and a given layout, the design variables of the second sub-problem are m pipe diameters $[D]$, m pipe slopes $[S]$, and m pump indicators $[P]$. Herein, a vector having $3m$ members in the range of (0, 1) named as the normal design vector is introduced to the model. This vector indirectly represents pipe diameters (the first m members) and slopes (the second m members) and directly gives the pump indicators (the third m members). If a pipe's pump indicator $P = 1$, there is a lift station at its upstream manhole; otherwise, if $P = 0$, there is no pump.

The normal pipe diameters and slopes in the normal design vector are denoted by $[\hat{d}]$ and $[\hat{s}]$, respectively. These variables need to be decoded to obtain the meaningful design values $[D]$ and $[S]$, such that the following criteria are met.

For every sewer:

1. The flow velocity must be kept within a permissible limit for self-cleaning capability (minimum velocity) and prevented from scouring (maximum velocity).
2. The proportional water depth must be kept below a specified maximum level.
3. Pipe diameters must be chosen from a commercially available list.
4. A minimum buried depth needs to be kept to prevent damages from the surface activates.

For every manhole:

1. Inlet pipes need to be no lower than the outlet pipe.
2. The outlet pipe's diameter must be equal to or greater than the upstream inlet pipes.

A normal design vector can be either randomly or systematically produced on interval (0, 1) by an optimization solver. To extract a feasible design from a given normal alternative subject to these constraints, the following adaptive algorithm is proposed.

Step 1: For every sewer diameter, there is a normal real value $\hat{d}$ between 0 and 1. The corresponding design diameter D is obtained as the following:

$$D = D_{\min} + (D_{\max} - D_{\min}) \times \hat{d} \tag{3.6}$$

where $D_{\max}$ is the largest commercially available size and $D_{\min}$ is the minimum allowable size for the pipe under consideration. $D_{\min}$ is determined with respect to two limitations. First, the pipe must be capable of conveying the design flow rate Q and consequently be true for the following constraint (Pan and Kao 2009):

$$\frac{Q}{V_{\max}} \leq \left(\frac{\pi D^2}{4}\right) \times \left(\frac{A}{A_0}\right)_{(d/D)_{\max}} \tag{3.7}$$

where $V_{\max}$ = maximum permissible flow velocity and $(d/D)_{\max}$ is maximum permissible proportional water depth. Substituting $(d/D)_{\max}$ in Eq. (3.3), $\theta_{\max}$ is explicitly obtained as follows:

$$\theta_{\max} = 2\cos^{-1}(1 - 2 \times (d/D)_{\max}) \tag{3.8}$$

Substituting Eq. (3.8) in Eq. (3.4), the proportional area (A/A_0) is also calculated. Then, a $D_{\min}$ is obtained from Eq. (3.8).

Second, the diameter of every pipe must be equal to or greater than that of its upstream pipes, which means that

$$D \geq \max[DU] \tag{3.9}$$

where $[DU]$ contains pipe diameters connected to the upstream end of the pipe at hand. $[DU]$ is available from the previous calculations. Between the diameters obtained by Eqs. (3.8) and (3.9), the greater size is assigned to $D_{\min}$ in Eq. (3.6). This equation results in a real diameter size that needs to be finally rounded up in the commercial list for assigning the design diameter D to the pipe. The described procedure is applied step by step to all pipes in such a way that at first, the network's upstream pipes' so-called chord links (which have no pipe at their upstream) are considered. Then the remaining upstream pipes, which have been already sized using Eq. (3.6), are taken into account. This continues until the normal vector $[d]$ is interpreted in the design diameter vector $[D]$ for the whole network.

Step 2: For every sewer slope, there is also a normal real value $\hat{S}$ between 0 and 1. Similar to the previous step, the corresponding design slope S is obtained as follows:

$$S = S_{\min} + (S_{\max} - S_{\min}) \times \hat{s} \tag{3.10}$$

where $S_{\min}$ and $S_{\max}$ are the minimum and maximum permissible slopes for the pipe, respectively. $S_{\min}$ is determined so that three following constraints are met.

First, the sewer slope needs to be greater than the minimum constructional value of S_c, and hence

$$S \geq S_c \tag{3.11}$$

Second, associated with the pipe discharge and its diameter size from the previous step, the pipe slope must satisfy the constraint of the maximum proportional water depth. For the pipe at hand, $\theta_{\max}$ was already obtained from Eq. (3.8). Therefore, it is expected that

$$S \geq (nQ)^2 \times \left[(AR^{2/3})_{\theta_{\max}}\right]^{-2} \tag{3.12}$$

Third, the pipe flow velocity always must be greater than the minimum velocity $V_{\min}$ which leads to the following by substituting $V_{\min}$ into Manning's equation:

$$S \geq (nV_{\min})^2 \times \left[(R^{2/3})_{\theta_{\min}}\right]^{-2} \tag{3.13}$$

Thereafter, each of these three constraints, Eqs. (3.11)–(3.13), returns the greatest value selected as the lower bound of pipe slope, $S_{\min}$, in Eq. (3.10). Meanwhile there is only one restriction for $S_{\max}$, which is associated with the maximum velocity $V_{\max}$. This constraint is also taken into account as follows:

$$S \leq (nV_{\max})^2 \times \left[(R^{2/3})_{\hat{\theta}_{\max}}\right]^{-2} \tag{3.14}$$

where $\hat{\theta}_{\max}$ is obtained by substituting $V_{\max}$ into Manning's equation, similar to what was done to obtain $\theta_{\min}$ in Eq. (3.13). The right hand side of Eq. (3.14) is used as the upper bound of pipe slope $S_{\max}$ in Eq. (3.10). Step 2 is repeated for all pipes, eventually resulting in the design pipe slopes $[S]$ from the initial normal vector $[\hat{s}]$.

Step 3: At this point, the installation depths of the pipes are determined with respect to their slope, diameter size, and pump station status, as well as the least cover depth that the pipe requires. The least cover depth, $C_{\min}$, is a user-defined constraint that is decided based on the mechanical properties of soil and pipe material, as well as on the surface activities and traffic loads. This constraint is satisfied by placing the sewers, which now have a design diameter, slope, and pump indicator, at the proper elevations. To this end, initially, the installation elevations of upstream branches in the network, like cut pipes 1, 3, and 6 in Fig. 3.2b, are determined. For an upstream branch, the minimum cover depth is assigned to its upstream end as

$$EU = GU - C_{\min} \tag{3.15}$$

in which EU and GU are the pipe's upstream crown and ground surface elevations, respectively. Then, the downstream crown elevation ED is obtained from

$$ED = EU - L \times S \tag{3.16}$$

where L is the pipe length. The least cover depth is also checked at the pipe's downstream end so that if $GD - ED < C_{\min}$, then

$$ED = GD - C_{\min} \tag{3.17}$$

Accordingly

$$EU = ED + L \times S \tag{3.18}$$

After that, the installation elevations were computed for all upstream branches, the remaining upstream inlet pipes, which were already placed, are taken into account. For a pipe in this group, the following is the case:

- If the pump indicator $P = 1$, a lift station is allocated at the pipe's upstream manhole. If so, the installation elevations are obtained using Eqs. (3.15)–(3.18). On the other hand, the lift station on a pipe makes that an upstream branch.
- Otherwise ($P = 0$), the pipe's upstream crown is placed at the lowest downstream crown of its inlet pipes. Then Eqs. (3.16)–(3.18) are used to calculate the downstream crown elevation, as well as to control the minimum cover depth.

This procedure is continued until for all pipes and manholes, the installation depths are determined.

It is worth mentioning that this approach assumes that the ground slope is constant along a sewer line between its nodes. In reality, there may be local high and low points along a sewer line, which means that the ground slope is not necessarily constant along a sewer. Although this issue can be neglected in many flat regions, but in some projects, it might be significant. To solve this problem, it is required to add more manholes to the initial base graph and break long pipes into shorter pieces.

By means of the proposed algorithm, every random normal design alternative is acceptable since all hydraulic and technical constraints are systematically met. Similar to the loop-by-loop cutting algorithm, the sewer sizing algorithm does not need any constraint handling trick into the optimization solver and always returns a feasible design.

3.4 Design Objective Functions

When the two sub-problems of sewer networks design are integrated into a model, a large and hard class of nonlinear combinatorial optimization is formed. Fortunately, the described self-adaptive design algorithms for layout generation and sewer sizing make the problem easier so it can be solved efficiently by a variety of heuristics methods. For the optimization of a sewer network design, different objective functions can be taken into account. In what follows, some frequently used objective functions are introduced.

Table 3.1 Cost functions (in Yuan) for a sewer design project in China (Li and Matthew 1990)

CP (Sewer cost)	
$(4.27 + 93.59D^2 + 2.86D \times H + 2.39H^2) \times L$	$D \le 1$ m, $H \le 3$ m
$(36.47 + 88.96D^2 + 8.70D \times H + 1.78H^2) \times L$	$D \le 1$ m, $H > 3$ m
$(20.50 + 149.27D^2 - 58.96D \times H + 17.75H^2) \times L$	$D > 1$ m, $H \le 4$ m
$(78.44 + 29.25D^2 + 31.80D \times H - 2.32H^2) \times L$	$D > 1$ m, $H > 4$ m
CM (Manhole cost)	
$136.67 + 166.19D^2 + 3.50D \times H + 16.22H^2$	$D \le 1$ m, $H \le 3$ m
$132.67 + 790.94D^2 - 280.23D \times H + 34.97H^2$	$D \le 1$ m, $H > 3$ m
$209.04 + 57.53D^2 + 10.93D \times H + 19.88H^2$	$D > 1$ m, $H \le 4$ m
$210.66 - 113.04D^2 + 126.43D \times H - 0.60H^2$	$D > 1$ m, $H > 4$ m
CL (Pump cost)	
$270.021 + 316.42Q - 0.1663Q^2$	Q (l/s)

(a) **The total construction cost**: The main objective of a sewer network optimization is to gain its least-cost design. Accordingly, the main objective function of the problem is the total construction cost of the network as the following.

$$C(\alpha, \beta, \hat{d}, \hat{s}, P) = \sum_{1}^{m}(CP_i + P_i \times CL_i) + \sum_{1}^{m+1} CM_i \tag{3.19}$$

where C is the cost function that evaluates each design alternative according to the given layout design parameters (α, β) and sewer sizing parameters $(\hat{d}, \hat{s}, P)$; CP and CM are the sewer and manhole construction costs estimated as a function of pipe diameter D and length L, respectively, as well as its buried depth H; and CL are the construction costs of the pump station, which are generally estimated with respect to the pumping head and flow rate. The functions CP, CM and CL are required to be estimated for each project according to the regional tariffs. For example, Li and Matthew (1990) estimated these functions as presented in Table 3.1 for a sewer system in China. To optimize a sewer network using the objective function of Eq. (3.19) the layout and sizing sub-problems must be simultaneously solved as schematically shown in Fig. 3.4. This integrated optimization would result in the global optimum design of the network. However, sometimes, for the sake of simplicity or to consider other aspects of sewer system design, the sewer sub-problems may be solved individually as explained in the following.

(b) **The simplified objective function**: to separate the layout sub-problem from the sewer sizing sub-problem, Walters and Smith (1995) proposed an objective function reflecting the layout cost in terms of the length and concave function of flow rate of each link as the following:

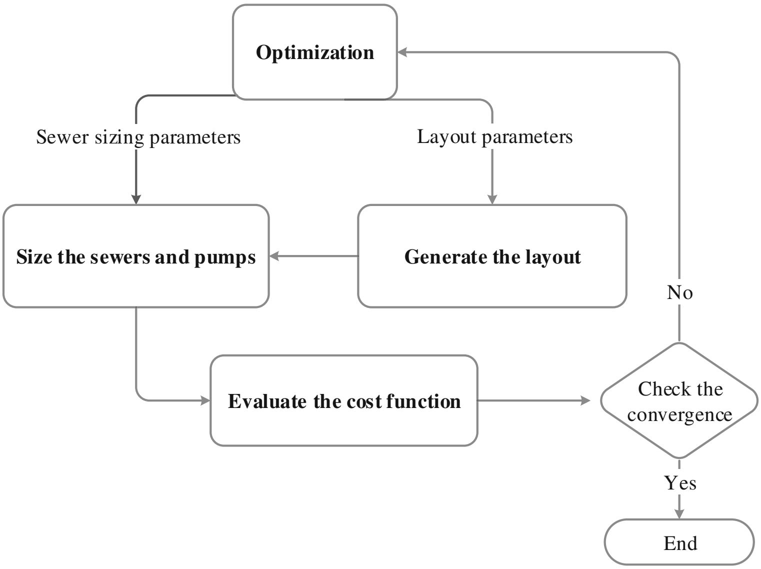


Fig. 3.4 The integrated optimization model for sewer networks design

$$E(\alpha, \beta) = \sum_{1}^{m} L_i \times \sqrt{Q_i} \tag{3.20}$$

where E = layout objective function; L = sewer length; and Q = accumulated sewer flow rate that is implicitly obtained with the configuration of the layout. After an optimum layout was obtained by minimizing the above objective function, the sewer sizing sub-problem can be optimized individually for the least construction cost, Eq. (3.19).

(c) **Reliability-based objective function**: the construction cost of a sewage collection network, specifically in flat regions, is highly influenced by the layout configuration and the pipe slopes. In such areas, sewers are designed with the least slope and velocity according to the design criteria. This may result in low and in some cases inadequate velocities required for self-cleaning. This particularly happens in the primary years of operation and in low discharge sewers. In practice, deposition and clogging in low-slope sewers are very common and pose serious environmental problems and costs to the operating companies. These issues become more troublesome and costlier when the clogging occurs in a main sewage collector. In this condition, all sewers upstream of the clogged line are affected by the clogging event, and this could be a serious threat to the public health of a large sub-area. Through a common design approach for flat areas, all sewers are designed based on the cleaning velocity and will have almost the same velocity in operation. In this condition, if the system reliability is defined as a function of the sewer velocity, there would not be a significant difference between the low and high discharge sewer lines. Also, when designing a sewer layout, the system's hydraulic properties, including the sewer diameters, slopes and velocities are still unknown and cannot therefore be used to evaluate the system's reliability. To quantify the clogging consequences in sewer networks this study proposes a simple but meaningful criterion that only uses the layout design properties.

This criterion is able to indirectly evaluate how well a sewer system can react to a sewage flow blockage. The main idea comes from the following definition: "*Averagely, less population affected by a pipe clogging the sewer network would be more reliable*." If it is supposed that the probability of simultaneous sewer clogging in the network is extremely low, one-at-a-time clogging is adopted here to evaluate the reliability of the system's performance. On this basis, the reliability of every individual sewer is mathematically measured by the following index.

$$R_i = 1 - \frac{Q_i}{Q_{total}} \tag{3.21}$$

And for the entire network the averaged reliability index (ARI) is measured as follows (Haghighi and Bakhshipour 2015a, b).

$$AR_i = \overline{R}_i = 1 - \frac{\sum_{i=1}^{m} Q_i}{m \times Q_{total}} \tag{3.22}$$

in which, R_i is the reliability index of sewer i and Q_{total} is total sewage flow of the network toward the outlet. The objective function (3.22) is also used to design the network layout separately. Then, for the given layout the network hydraulic characteristics are optimized with respect to the construction cost, Eq. (3.19).

The reliability concept, especially in flat areas, can play a remarkable role in the design of sewer networks besides the technical and economic concerns. However, it is worth noting that, the concept of reliability in designing of sewers layout includes some important considerations to be noticed. For more detailed discussions on this issue please refer to (Haghighi and Bakhshipour 2015a, b).

3.5 Optimization Methods

In last two decades, many intelligent meta-heuristic methods have been developed and widely used for optimization of complicated engineering problems. These methods are easy to understand and implement; able to solve mixed-integer non-linear problems and, are very promising to find the global optimum of multimodal search spaces. Nevertheless, intelligent methods are inherently unconstrained. Consequently, to exploit these methods efficiently a careful attention must be paid to handling the problem constraints. This chapter introduced two self-adaptive design procedures for designing the layout and sizing the sewers and pumps of wastewater collection networks. Since all the technical constraints of the problem are systematically satisfied into the aforementioned procedures, the sewer network optimization problem becomes quite unconstrained (Fig. 3.4). Hence, any unconstrained meta-heuristic method can be efficiently applied to the problem to minimize the network construction cost. For this purpose, four meta-heuristic algorithms are introduced here, which have been previously used for optimization of sewer networks. Of the following methods, the Genetic Algorithm (GA), Simulated Annealing (SA) and Particle Swarm Optimization (PSO) are stochastic, while the Tabu Search is a deterministic direct search method. It is worth mentioning that, in all algorithms presented in the following it is supposed that the problem objective function is the network's total construction cost Eq. (3.19) and each design alternative $X = (\alpha, \beta, \hat{d}, \hat{s}, P)$ contains all design variables of the layout and sizing sub-problems. Accordingly, the optimization solver aims at finding the best X that minimizes total cost function $C(X)$.

3.5.1 Genetic Algorithm (GA)

Genetic algorithms are based on the principles of natural genetics and natural selection. The GAs are inspired by Darwin's evolution theory and first presented by Holland (1975). Since then, the GAs were highly developed (Goldberg 1989; Mitchell 1996; Coley 1999) and widely used to solve many complicated engineering problems. In the following, a standard continuous GA is introduced to be coupled with the sewer design sub-problems according to the flow-diagram of Fig. 3.4.

1. An initial population of NP chromosomes is randomly generated within the feasible search space. Each chromosome contains a design alternative X and, each design variable into it is called gene.
2. The self-adaptive sewer layout and sizing models are run against all chromosomes and the corresponding construction costs (from Eq. 3.19) are evaluated.
3. A tournament selection method is used to select the parents in such a way that, for each parent two chromosomes y and z are randomly picked up from the population. y wins the tournament if it has a cheaper cost value otherwise, z wins the tournament. The number of parents is a user-defined parameter generally considered to be half of the initial population size ($NP/2$). After all parents were selected, they are transferred to the mating pool to generate new offsprings.
4. The blend crossover method (BLX-α) proposed by Eshelman and Shaffer (1993), is applied to each couple in the mating pool resulting in two children.

When the crossover operator is applied to all couples, the population of children with NP size is created.

5. A few genes in the new population are mutated according to a user-defined mutation ratio.
6. The children population is introduced to the design models and their construction costs are evaluated.
7. The old and new populations are combined resulting in a population with $2NP$ size. The combined population is sorted from the lowest to highest cost function values. The top NP chromosomes with lower cost values form the new generation. Since the new generation is extracted from the combination of parents and children, the elitism is systematically preserved in this algorithm.
8. The convergence criteria are checked. If no further improvement was seen in the results the optimization is terminated otherwise, the algorithm with new population is repeated from step 2.

3.5.2 Simulated Annealing (SA)

The simulated annealing method is inspired by the simulation of thermal annealing of critically heated solids. This method was originally introduced by Kirkpatrick et al. (1983) based on the Metropolis criterion (Metropolis et al. 1953). When a solid (metal) is brought into a molten state by heating it to a high temperature, the atoms in the molten metal move freely with respect to each other. However, the movements of atoms get restricted as the temperature is reduced. As the temperature reduces, the atoms tend to get ordered and finally form crystals having the minimum possible internal energy. When the temperature of the molten metal is reduced at a very fast rate, it may not be able to achieve the crystalline state. In engineering applications, rapid cooling may introduce defects inside the material. Thus the temperature of the heated solid needs to be reduced at a slow and controlled rate to ensure proper solidification with a highly ordered crystalline state that corresponds to the lowest energy state (internal energy). This process of cooling at a slow rate is known as annealing (Rao 2009).

The above procedure is exploited to develop the simulated annealing method for the mathematical optimization. In what follows, a standard algorithm of SA for optimization of sewer networks is introduced.

1. The SA parameters including the initial temperature T, cooling rate c and the number of isothermal iterations e are decided.
2. An initial design alternative X_0 is randomly generated within the feasible search space and set the iteration number $i = 1$ and the cycle number $j = 1$. Then, X_0 is introduced to the design models and its construction cost is evaluated.
3. A new design alternative X_i in vicinity of the current alternative X_{i-1} is randomly generated. X_i is introduced to the design models and its cost value $C(X_i)$

is evaluated. The difference between the current and new design costs is also evaluated as $\Delta C = C(X_{i-1}) - C(X_i)$.

4. According to the Metropolis criterion, the probability of accepting the next design is calculated using the Boltzmann's probability distribution.

$$P_a = \min\left\{1, e^{-\Delta C/KT}\right\} \tag{3.23}$$

where P_a is the probability of accepting X_i and K is Boltzmann's constant which serves as a scaling factor in the SA. Equation (3.23) implies that if $\Delta C \leq 0$ then $P_a = 1$ and the new design alternative is certainly accepted otherwise, it may be accepted with probability $P_a < 1$. If so, a random number r within $(0, 1)$ is generated. If $P_a \geq r$ the new design X_i is accepted otherwise, it is rejected and the algorithm goes back to step 3.
5. If the convergence criteria are met terminate the optimization otherwise, set $i = i + 1$.
6. If $i > j \times e$ set $j = j + 1$ (update the number of cycle) and decrease the temperature as $T = c \times T$. Then, go to step 3.

3.5.3 Particle Swarm Optimization (PSO)

Particle swarm optimization is a biologically inspired intelligent optimization method originally introduced by Kennedy and Eberhart (1995) and then developed by other researchers (Clerc 2006; Olsson 2011). The main idea behind the PSO is inspired by the behavior of birds flocking or fish schooling when seeking out food into a search space. The PSO is a population-based optimization. Each design alternative in the PSO is called particle and the population of particles is called swarm. Each particle having a position and a velocity vector wanders around in the problem search space and memorizes the best visited position with respect to the objective function value. During the search, the particles communicate information and adjust their individual positions and velocities based on the information received on the good positions of other particles in the swarm. To optimize sewer networks according to the integrated model of Fig. 3.4. a standard PSO algorithm is introduced as the following.

1. The swarm size NP is decided. For NP particles in the swarm the initial position vectors X are randomly generated in the feasible search space. The particle position vectors represent the sewer network design alternatives. All particles are considered to be initially stagnant and therefore their initial velocity $V = 0$.
2. The particles are introduced to the design models and their corresponding construction costs are evaluated.

3. For each particle j the best historical position $P_{\text{best},j}$ with respect to the objective function is identified. Also, for the entire swarm the best ever visited position G_{best} is identified.
4. For each particle j the velocity vector is updated using the following relationship:

$$V_j^{\text{new}} = V_j^{\text{old}} + c_1 r_1 (P_{\text{best},j} - X_j^{\text{old}}) + c_2 r_2 (G_{\text{best}} - X_j^{\text{old}}) \tag{3.24}$$

where V_j^{new} and V_j^{old} are respectively the new and old velocity vectors of particle j; X_j^{old} is the current position vector of particle j; c_1 and c_1 are respectively the cognitive and social learning rates generally $c_1 = c_1 = 2$ and, r_2 and r_2 are two random number within $(0, 1)$.

5. For each particle j the position vector is updated as the following:

$$X_j^{\text{new}} = X_j^{\text{old}} + V_j^{\text{new}} \tag{3.25}$$

where X_j^{new} is the new position vector of particle j

6. After the above update, some particles may be shot outside of the feasible search space. For the reposition of the errant particles the following method was proposed by Formato (2007):

$$\begin{cases} \text{if } x_{i,j}^{\text{new}} > x_i^{\max}, x_{i,j}^{\text{new}} = x_i^{\max} - F_{rep}(x_i^{\max} - x_{i,j}^{\text{old}}) \\ \text{if } x_{i,j}^{\text{new}} < x_i^{\min}, x_{i,j}^{\text{new}} = x_i^{\min} + F_{rep}(x_{i,j}^{\text{old}} - x_i^{\min}) \end{cases} \tag{3.26}$$

where $x_{i,j}^{\text{old}}$ and $x_{i,j}^{\text{new}}$ are respectively the old and new quantities of the ith direction (decision variable) of particle j position and, $x_i^{\min}$ and $x_i^{\max}$ are respectively the lower and upper bounds of the ith direction. Also, F_{rep} is a reposition factor in the range $(0, 1)$, generally considered to be 0.5.

7. The convergence criteria are checked. If no further improvement was seen in results the PSO is terminated otherwise, go to step 2.

3.5.4 Tabu Search (TS)

Tabu search optimization method was originally introduced by Hertz and Werra (1987) and also Glover (1989). It was then developed by Glover (1990, 1995) and popularized by Hertz and Werra (1990). Later, this method was applied to solve many combinatorial optimization problems in various fields of engineering and economics. The distinguished advantages of TS compared to other metaheuristics is that TS is a deterministic search, meaning that there is no randomness in it. As a consequence, TS is generally found to be computationally efficient.

Simply phrased, TS initiates the exploration of a decision space with an arbitrary starting point. In the vicinity of the current point, the best solution is sought with respect to the given objective function. Whether the best neighbor point is better than the current point or not, it is adopted as the new solution and the search is continued. This is the main difference between the TS and local search algorithms, in which worse neighbors are unacceptable, and this is why they quickly fall into a local optima. This feature helps the TS be a metaheuristic and not be easily stopped by local optima; however, there are two concerns with this issue. First, it may significantly increase the number of objective function evaluations and takes a lot of time to complete the search of the decision space. Second, it is very probable that the search becomes trapped in a loop of successive solutions that periodically leads to the same results. To overcome these issues, TS systematically uses the memory of the search in such a way that the exploration route so far traveled is remembered and exploited to decide new points and search directions. For this purpose, the best solution at each iteration or the move toward it is sent to a tabu list. The length of the tabu list is a user-defined parameter in TS upon which a long or short memory search is formed. Throughout the search, TS is forbidden to pick points from the tabu list, even if those points are superior to other neighbors. With this idea, no visited point is revisited again; consequently, the search does not fall in a loop of solutions anymore. Furthermore, there are some other features in TS that control a search's accuracy and efficiency. For instance, the diversification, intensification, and aspiration are the most common phases in a conventional TS. If all these features are appropriately programmed and exploited in a search, TS would be a serious rival to stochastic metaheuristics. Herein, a TS algorithm is introduced as follows to be coupled to the sewer design optimization models.

1. An initial design alternative $X = (\alpha, \beta, \hat{d}, \hat{s}, P)$ is arbitrarily generated with respect to the decision variable limits on interval $(0, 1)$. This solution is termed K, and let $K^* = K$, where K^* is the best answer so far visited.
2. Set the cycle number $j = 1$.
3. Set the iteration number $i = 1$.
4. Solution K is sent to the tabu list T with a user-specified length $|T|$.
5. For solution K, a neighborhood zone $N(K)$ in the problem's decision space is generated. The structure and production strategy of $N(K)$ play a great role in the efficiency and accuracy of a TS run. For the sewer design problem, the univariate search direction method has been found efficient and easy to use for producing neighborhood points (Haghighi and Bakhshipour 2015a, b).
6. The allowable neighborhood, named V^*, is obtained by extracting the tabu solutions from the generated neighbors such that $V^* = N(K) - N(K) \cap T$. For all points in V^*, the problem is solved and the cost function is evaluated. With no comparison with the current solution, the best solution in V^* is found and termed as U. Set $K = U$, and if the cost function $C(K) < C(K^*)$, let $K^* = K$. Also, let $i = i + 1$ and go to step 4 until all directions are once sought.
7. Set the cycle number $j = j + 1$. At this point, TS has partially sought the decision space in all directions. Now, it is said that a search cycle has been done.

If the user-defined stopping criteria are met the search is terminated, otherwise go back to step 3.

3.6 Summary and Conclusion

Design of a new sewer network is consisting of solving two sub-problems respectively for producing the sewers layout and sizing of pipes diameter and slope as well as pumps if required. For each sewer system, the number of layout alternatives increases exponentially with the number of pipes. In flat areas, it is not practically easy to find a cost-effective layout explicitly. This chapter introduced several optimization models for systematically solving the sewer design sub-problems. The loop-by-loop cutting algorithm was introduced for adaptive layout generation. Then, for the sewer network with a given layout, an adaptive design algorithm was presented to size the pipes and pumps. Through the proposed self-adaptive analysis and design algorithms, all hydraulic and technical constraints of sewer design sub-problems are automatically met and therefore, no constraint remains to be handled in optimization.

For optimization of the sewer network design, four well-known metaheuristic methods including the genetic algorithm; simulated annealing; particle swarm optimization and tabu search were introduced. Coupling the aforementioned models for the layout generation and sewer sizing to each metaheuristic method makes it computationally efficient, unconstrained and promising to find the global optimum.

It was also argued that in flat areas, sewers are rationally designed with minimum slopes. In such designs, sediment deposition and clogging is very common. This issue highly affects the network performance and public health as well as poses significant cost on operating companies. To address this issue, a new criterion to generate sewers layout according the concept of reliability was introduced. This criterion averagely determines that if a sewer line was blocked, in what extent the upstream lines and population are involved.

For more investigations in future, application of other evolutionary methods like the bees algorithm (Pham et al. 2005), central force optimization (Formato 2007) and harmony search (Geem et al. 2001) to the sewer systems design are suggested. Furthermore, the challenges between the cost and reliability of sewers layout can be systematically handled by multi-objective optimization models. Consideration of operational costs is also quite important to the sewer systems design which needs more attention in future studies. Furthermore, design of sewers layout needs a deep understanding of graph theory. There are several methods in the graph theory that could be efficiently used and developed for this purpose. This issue would be very interesting and useful for the sewer systems designers and software developer.

References

Afshar, M. H. (2010). A parameter-free continuous ant colony optimization algorithm for the optimal design of storm sewer networks. *Advanced Engineering Software, 41*(2), 188–195.

Behave, P. R. (1983). Optimization of gravity-fed water distribution systems: Theory. *Journal of Environmental Engineering, 109*(1), 189–205.

Clerc, M. (2006). *Particle swarm optimization*. London: Wiley-ISTE.

Coley, D. A. (1999). *An introduction to genetic algorithms for scientists and engineers*. Singapore: World Scientific Publishing.

Diogo, A. F., & Graveto, V. M. (2006). Optimal layout of sewer systems: A deterministic versus a stochastic model. *Journal of Hydraulic Engineering Division of the American Society of Civil Engineers, 132*(9), 927–943.

Eshelman, L. J., & Shaffer, D. J. (1993). Real-coded genetic algorithms and intervalschemata. In D. L. Whitley (Ed.), *Foundations of genetic algorithms 2* (pp. 187–202). San Mateo, CA: Morgan Kaufman.

Formato, R. A. (2007). Central force optimization: A new metaheuristic with applications in applied electromagnetics. *Journal of Progress In Electromagnetics Research, 7*(1), 425–449.

Fournier, J. C. (2009). *Graph theory and applications* (2nd ed.). Hoboken, NJ: Wiley.

Geem, Z. W., Kim, J. H., & Loganathan, G. V. (2001). A new heuristic optimization algorithm: Harmony search. *Simulation, 76*, 60–68.

Glover, F. (1989). Tabu search—Part I. *ORSA Journal on Computing, 1*(3), 190–206.

Glover, F. (1990). Tabu search—Part II. *ORSA Journal on Computing, 2*(1), 4–32.

Glover, F. (1995). Tabu thresholding: Improved search by nonmonotonic trajectories. *ORSA Journal on Computing, 7*(4), 426–442.

Goldberg, D. E. (1989). *Genetic algorithms in search, optimization, and machine learning*. Reading, MA: Addison-Wesley.

Haghighi, A. (2013). Loop-by-loop cutting algorithm to generate layouts for urban drainage systems. *Journal of Water Resources Planning and Management, 139*(6), 693–703.

Haghighi, A., & Bakhshipour, A. E. (2012). Optimization of sewer networks using an adaptive genetic algorithm. *Water Resources Management, 26*(12), 3441–3456.

Haghighi, A., & Bakhshipour, A. E. (2015a). Deterministic integrated optimization model for sewage collection networks using tabu search. *Journal of Water Resources Planning and Management, 141*(1), 04014045.

Haghighi, A., & Bakhshipour, A. E. (2015b). Reliability-based layout design of sewage collection systems in flat areas. *Urban Water Journal*. doi:10.1080/1573062X.2015.1036085

Heidari, M., Chow, V. T., Kokotovi´c, P. V., & Meredith, D. D. (1971). Discrete differential dynamic programming approach to water resources system optimization. *Water Resources Research, 7*(2), 273–282.

Hertz, A., & Werra, D. (1987). Using tabu search techniques for graph coloring. *Computing, 39*(4), 345–351.

Hertz, A., & Werra, D. (1990). The tabu search meta-heuristic: How we used it. *Annals of Mathematics and Artificial Intelligence, 1*(1–4), 111–121.

Holland, J. H. (1975). *Adaptation in natural and artificial systems*. Ann Arbor: University of Michigan Press.

Karovic, O., & Larry, W. M. (2014). Sewer system design using simulated annealing in Excel. *Water Resources Management, 28*(13), 4551–4565.

Kennedy J., & Eberhart R. C. (1995). Particle swarm optimization. In *Proceedings of the 1995 IEEE International Conference on Neural Networks*. IEEE Service Center, Piscataway, NJ.

Kirkpatrick, S., Gelatt, C. D., & Vecchi, M. P. (1983). Optimization by simulated annealing. *Science, 220*, 671–680.

Li, G., & Matthew, R. G. S. (1990). New approach for optimization of urban drainage system. *Journal of Environmental Engineering, 116*(5), 927–944.

Liebman, J. C. (1967). A heuristic aid for the design of sewer networks. *Journal of the Sanitary Engineering Division, American Society of Civil Engineers, 93*(4), 81–90.

Mays, L. W., Wenzel, H. G., & Liebman, J. C. (1976). Model for layout and design of sewer systems. *Journal of the Water Resources Planning Management Division, 102*(2), 385–405.

Mays, L. W., & Yen, B. C. (1975). Optimal cost design of branched sewer system. *Water Resources Research, 11*(1), 37–47.

Metropolis, N., Rosenbluth, A., Rosenbluth, M., Teller, A., & Teller, E. (1953). Equation of state calculations by fast computing machines. *Journal of Chemical Physics, 21*(6), 1087–1092.

Minieka, E. (1978). *Optimization algorithms for network and graphs*. New York: Dekker Marcel.

Mitchell, M. (1996). *An introduction to genetic algorithms*. Cambridge, MA: MIT press.

Olsson, A. E. (2011). *Particle swarm optimization: Theory, techniques and applications*. Hauppauge, NY: Nova Science Pub Inc.

Pan, T. C., & Kao, J. J. (2009). GA-QP model to optimize sewer system design. *Journal of Environmental Engineering, 135*(1), 17–24.

Pereira, D. J. (1988). *Redes Urbanas de drenagem—Projecto assistido por computador com optimização tridimensional*. Ph.D. thesis, Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa, Lisboa, Portugal.

Pham, D.T., Ghanbarzadeh A., Koc, E., Otri S., Rahim, S., & Zaidi, M. (2005). The bees algorithm. Technical Note, Manufacturing Engineering Centre, Cardiff University, UK.

Rao, S. S. (2009). *Engineering optimization theory and practice*. Hoboken, NJ: Wiley.

Rosen, K. H. (2003). *Discrete mathematics and its applications* (5th ed.). New York: McGraw-Hill.

Steele, J. C., Mahoney, K., Karovic, O., & Mays, L. W. (2016). Heuristic optimization model for the optimal layout and pipe design of sewer systems. *Water Resources Management, 30*(5), 1605–1620.

Tekel, S., & Belkaya, H. (1986). Computerized layout generation for sanitary sewers. *Journal of Environmental Engineering, 112*(4), 500–515.

Walters, G. A., & Lohbeck, T. (1993). Optimal layout of tree networks using genetic algorithms. *Engineering Optimization, 22*(1), 27–48.

Walters, G. A., & Smith, D. K. (1995). Evolutionary design algorithm for optimal layout of tree networks. *Engineering Optimization, 24*(4), 261–281.

Chapter 4
A Norm-Aware Multi-agent System for Social Simulations in a River Basin

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Abstract Wastewater management is a complex task involving a wide range of technical environmental and social factors. Furthermore, it typically requires the coordination of a heterogeneous society of actors with different goals. Regulations and protocols can be effectively used to tackle this complexity. In this chapter we present a norm-aware multi-agent system for social simulations in a river basin. The norms we present are inspired in European policies for wastewater management and they can evolve through time.

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4.1 Introduction

In this chapter we will study the effect of regulations in the administration of wastewater fluxes in a river basin. Wastewater management is a difficult task, requiring the simultaneous consideration of a wide range of factors: technical, environmental, economical, social, legal, etc. When applied to a scenario such as a river basin, wastewater management requires to coordinate a wide range of activities performed by a society of actors with different goals (sometimes not aligned with the holistic goal of the society). The combination of these factors results in the fact that wastewater management in river basin is a complex process. One of such scenarios, for instance, involve the well-known dilemma of the *Tragedy of the Commons* (Hardin 1968), where rational agents use fresh water as part of their operations thus generating wastewater. Left alone, these agents would overpass wastewater treatment plants capacity until river gets too polluted and, hence, no longer usable by anybody.

Regulations and protocols are one of the possible solutions we can apply to tame complexity. However, due to the implicit complexity of the scenario it is hard for policy makers to tailor the exact set of regulations that will govern the system. On the one hand, several interacting factors have to be taken into account when designing the regulations. On the other hand, such regulations cannot be tested in real scenarios due to the cost of their application and its environmental implications.

We present a norm-aware multi-agent system (MAS) for social simulations in a river basin. Our system allows studying the effect of regulations in the behaviour of the different actors involved in a scenario based on the Tragedy of the Commons, as well as analysing different agents' behaviours under such scenario. The idea is using a norm-aware simulator where policies encourage the alignment of agents' behaviour to the common objective of the system, effectively detecting and sanctioning free-raiders and misbehaving actors, thus trying to prevent the Tragedy. The policies we present are inspired in European policies for wastewater management practice. Furthermore, policies in our system can evolve through time as a result of agents' behaviour and adapt to unexpected situations such as heavy rains or river pollution. Information technologies applied to environmental issues show potential in a wide range of fields, among others, decision support systems (Poch et al. 2004) and simulations (Hamilton 1969). However, the complexity of environmental problems introduces several challenges that information technologies should tackle. The first one is the fact that environmental issues must be considered in terms of complex systems, mainly due to the amount of variables to be considered and their dependencies. Also the high degree of uncertainty associated to the system and the potential impact (and therefore, risk) of the decisions taken *w.r.t.* these systems. The second issue is the fact that, in environmental systems, the scenario should often reflect conflicting goals, and we need to take into account a set of heterogeneous (sometimes conflicting) views and perspectives. These complex scenarios, where a wide variety of actors with different (sometimes conflicting) goals interact between them, can benefit from norm-aware electronic distributed systems based on agent technologies. Such systems can ensure compliance with the different actors to the expected behaviours and environmental policies, where environmental policies are designed to guide the overall system to a common higher goal, such as the preservation of the environment while keeping an active economy.

Our proposal is a norm-aware agent-based model for integrated Wastewater Management Systems. We apply this to the Besòs River Basin. The idea of using Autonomous Agents to cope with the problem has been done in view of the various, sometimes conflicting, goals that the identified actors have to fulfil their private interests. In this scenario each actor requires its own system *view* with customized privileges and access to differing control tools, either managerial or operational.

The system proposed aims at managing the treatment capabilities of Wastewater Treatment Plants (WWTPs), allowing coordination among them and with the different actors in the scenario. Plants treat wastewater coming from various sources before discharging it to the river, treated and with the appropriate ecologic conditions. To ensure river's ecological quality, water sensors measuring different parameters (e.g., temperature, acidity, suspended solids on water, river oxygen demand, etc.) are located along the river in interesting points, such as water discharge points for WWTPs. Plants are connected to various elements providing wastewater with different characteristics, including: towns providing household wastewater with a steady flow of quantity and variable pollutant concentrations; rain retaining tanks providing lightly polluted meteo wastewater, which comes in very high quantities during short periods of time; industries providing industrial wastewater with high variability both in quantity and pollutant concentrations. Some of the elements (e.g., towns) are connected directly to the plant, effectively providing a steady flow of wastewater. Some elements have a retainer tank between the wastewater source and the plant (e.g., meteorological wastewater). Finally, some elements present both options, they can discharge wastewater directly to the plant or store it on a retention tank (e.g., industries). The different elements are connected using pipes that form a sewage network. Some points in the network (e.g., where industrial wastewater is mixed with household wastewater) might be observed by sewage inspectors. Finally, a competent authority oversees the whole system taking decisions to ensure both the ecological quality of the water and the economic sustainability of the society.

Our agent-based model is built on top of the *ALIVE* (Aldewereld et al. 2010) framework. This *Chapter* focuses on the specification of *ALIVE*'s organisational model, putting special emphasis on the norms and how they evolve due to organisational, technological, social and contextual changes.

The rest of this chapter is organized as follows. Section 4.2 describes the process followed, and the case study. It is an urban wastewater system inspired on the actual Besós river basin which is fully described in Sect. 4.2.1. In Sect. 4.3 we introduce the Tragedy of the Commons. Section 4.4 explores the objectives, roles and social structure of the system with the communication links. In Sect. 4.5 we introduce the basis and elements for the decision making from a wastewater management perspective. Later, Sect. 4.6 introduces the norms governing the system and provides examples of how they can evolve dynamically. Finally, Sect. 4.7, presents a discussion and the main conclusions of this chapter.

4.2 Methodology

In the *ALIVE* organizational model roles are the central concept. Roles identify the activities necessary to achieve organizational objectives and enable abstraction from the specific actors that perform them (Dignum et al. 2009). Based on these conceptualizations, the modelling process follows an iterative application of the following steps:

- identify the stakeholders in the system
- formally define the roles, identifying their goals and their dependencies
- model the interaction scenes between roles. Scenes are used to manage role dependencies via interaction protocols
- organize the scenes into a coherent interaction structure
- identify the way agents will enact roles at run-time.

All this process is supported by the OperettA Tool (Aldewereld and Dignum 2010), this is one of the results of the *ALIVE* FP7 funded project (Vázquez-Salceda et al. 2010).

4.2.1 Schema of Wastewater Flows in the Case Study

The case study is a River Basin composed by elements generating both wastewater (a set of households $[\kappa_1, \ldots \kappa_k] \in$K and a set of industries $[I_1, \ldots I_i] \in$ I) and polluted water (meteorological events that generate runoff). For simplicity we will consider both wastewater and polluted water to be wastewater. There are also elements storing wastewater (a set of retention tanks $[T_1, \ldots T_l] \in T$), treating wastewater (a set of Urban Wastewater Treatment Plants $[W_1, \ldots W_j] \in$W), and receiving waters (e.g. a River).

Also, there is a graph $s_i \in$ S that represents the sewerage infrastructure in a urban sector or city. It encompasses components such as receiving drains, manholes, pumping stations, storm overflows, and screening chambers of the combined sewer or sanitary sewer. s_i ends at the entry to a W_j. In turn every W_j is connected with the receiving waters. In our model as in many European countries all elements in K and I are obliged to connect their sanitation and/or wastewater discharge to s_i where possible.

The wastewater is characterized by the flow (or volume) and the pollutant concentrations of: Total Suspended Solids (*TSS*), Biochemical Oxygen Demand (*BOD*), Chemical Oxygen Demand (*COD*), Total Nitrogen (*TN*) and Total Phosphorus (*TP*), which are defined as the set of pollutants x_r with (TSS, DBO, COD, TN, TP) = $(x_1, x_2, x_3, x_4, x_5)$ (Verdaguer et al. 2012). All concentrations related to these pollutants are indicated with a supra-index r, with $r = 1, \ldots, 5$. For subsequent paragraphs, this specification is not repeated in the text in order to avoid many repetitions.

The household generates a wastewater mass $M_D \in$ M with a particular volume $volume(M_D) = V_D$, and a concentration for each pollutant $O_j \in$ O *concentration* $(M_D, O_j) = C_D^j$, which is discharged in a plant $W_k \in$ W. Analogously, the runoffs retention tank has a wastewater mass stored $M_M \in$ M with volume $volume(M_M) = L_M$ and pollutant concentration $concentration(M_M, O_j) = C_M^j$. The tanks has a volumetric discharge to W_k and feasible volumetric bypass to receiving waters when the retention tank has an overflow. It means the tank can bypass a water mass $M_{DM} \in$ M with a volume $volume(M_{DM}) = V_{DM}$. These two discharge possibilities allow adapting the sewer performance of separative or combined run-off collection. Each industrial activity has its own retention tank, with a water mass $M_i \in$ M with volume $volume(M_i) = L_i$ and pollutant concentration $concentration(M_i, O_j) = C_i^j$. Its volumetric discharge to the treatment is $volume(M_i) = V_i$. The plant W_k is capable of accepting a water mass as influent $M_T \in$ M with volume $volume(M_T) = V_T$ and pollutant concentration $concentration(M_T, O_j) = C_T^j$. It provides a water mass as effluent $M_e \in$ M with volume $volume(M_e) = V_e$ and pollutant concentration $concentration(M_e, O_j) = C_e^j$ to receiving waters.

Additionally, the treatment has the possibility to bypass wastewater. The bypass consists in a water mass $M_b \in$ M with volume $volume(M_b) = V_b$ and pollutant concentration $concentration(M_b, O_j) = C_b^j$. The upstream provides a water mass $M_U \in$ M with volume $volume(M_U = V_U)$ and pollutant concentration *concentration* $(M_U, O_j) = C_U^j$ to receiving waters. The receiving waters correspond to a section of river basin, which has a water mass $M_{RW} \in$ M with volume $volume(M_{RW}) = V_{RW}$ and pollutant concentration $concentration(M_{RW}, O_j) = C_{RW}^j$.

4.3 Tragedy of the Commons

The *Tragedy of the Commons* was described by Hardin (1968), inspired by the lectures of Lloyd (1833) about population growth. The *Tragedy* is a situation where a set of appropriators consume a common good—or common-pool resource (CPR). These appropriators have incentives towards an over development or excessive exploitation of the common good, thus leading to depleting it. The basis of these incentives lays on the fact that increasing their consumption capacity brings them a direct benefit, while the cost of that increment is divided among all appropriators, thus the option of augmenting consumption capacity always beneficial. Assuming all agents are rational, everybody will. Hardin noticed that this problem cannot be solved by means of technical solutions, since it requires a change in the values and morality of people. That is why Hardin coined this as a *Tragedy*, not as in its common meaning of drama work, but as how the own rationality of agents lead to an *inexorable* fatal destiny. However, this is not necessarily what occur in this kind of scenarios.

Ostrom et al. (1994) presents a list of cases were the tragedy is avoided and highlights the case of how a South California basin area was heading to an over-exploited scenario and how an institutional arrangement—by means of an equity court system and establishing special districts—to use basins allowed to not only prevent the tragedy, but ensured water availability even in significant drought periods. Hardin, then reviewed his position and clarified that the Tragedy occurs mainly in unmanaged commons (Hardin 2007). Ostrom (2000) also showed criticism towards solutions to manage CPR by means of central government institutions, that are far away from the local people who has to deal with the common good. According to her, the results are always suboptimal and temporary, since they are usually based on coercive measures and, if they are not accompanied of monitoring and sanction capabilities, instead of avoiding the tragedy, it is even fostered. Ostrom prefers self-organised institutions who devise its own rules, since it seems to be a common factor on long-live surviving CPR (Ostrom 1990, 1999).

Ostrom defines a CPR *facility* as an element which provides the conditions to sustain a stock of resource units. This stock produces a flow of resource units over time that can be appropriated (and diminished) as it is consumed (Ostrom et al. 1994). For instance, a fishing grounds and tons of fish, a windmill field and electricity. If the common good is renewable, it is possible to define a regeneration rate. While the amount of appropriated units does not exceed this regeneration rate, the CPR will be sustainable. If the common good is an exhaustible resource—no regeneration rate—or the appropriation exceeds the regeneration rate, the common goods will be eventually depleted.

With this representation of CPR, Ostrom also proposes to distinguish the problems of a CPR situation into two types (Ostrom et al. 1994): appropriation and provision problems. Each of them also poses additional sub-problems.

Appropriation problems refer to the development of *rules to manage common good consumption*: excluding potential beneficiaries and resource allocation from

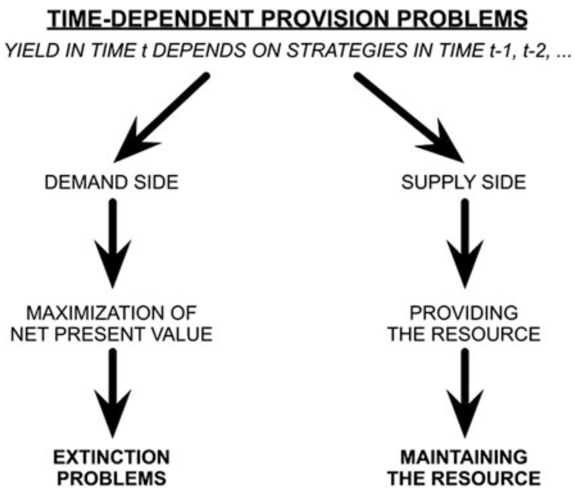

Fig. 4.1 A framework for provision problems. Adapted from Ostrom et al. (1994)

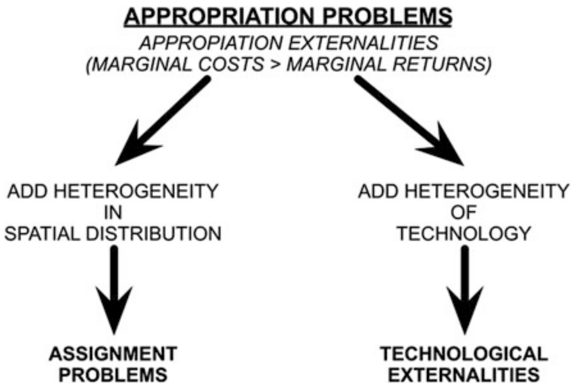

Fig. 4.2 A framework for appropriation problems. Adapted from Ostrom et al. (1994)

the resource flow produced by the CPR stocks—the main concern of this kind of problems is the flow of common good. In this kind of problems it is assumed that the relation between the yield provided by the CPR and the required inputs to obtain that yield, is given (see Fig. 4.1).

Provision problems refer to the development of *rules to manage contributions to*: creating a resource, maintaining or improving its production capabilities and/or avoiding its destruction—the main concern of provision problems is the CPR stocks (see Fig. 4.2).

4.3.1 Designing Institutions for CPR

Institutions, understood as a set of agreed conventions on a community of agents, is relevant in the way common goods are managed. The rules that agents create or are imposed by external agencies, drive *how* appropriators interact with the common good which is a key factor on ensuring its sustainability.

Humans relate and interact with other people according to conventions or rules that have emerged from communities and society. All human societies devise constraints to structure and regulate the relationship between its members (Vázquez-Salceda 2003). Institutions are distinguishable by the set of constraints that govern these relations.

North studied the effect of institutions (which he considers a set of constraints) on the behaviour of human organizations. He points out that these institutional constraints ease the interaction among humans, shaping choices and making outcomes predictable (North 1990). The devising of these constraints allows for a growth on the complexity of the organizations while keeping interaction costs reduced, and similarly, allows the participants of the institution to act, and expect other participant to act according to a list of rights, duties, and protocols of interaction.

For this reason, the creation of Institutions provides trust among parties even when they do not have much information about each other. In environments with incomplete information, cooperative interactions can perform ineffectively unless there are institutions which provide sufficient information for all the individuals to create trust and to control deviations.

Institutions can be classified according to how they are created and maintained, or on the formality of its rules. On the former case, Institutions can be created from scratch and remain static or be continuously evolving. On the latter, institutions can be informal, that is, defined by informal constraints such as social conventions and codes of behaviour, or formal, defined by formal rules. Those can be political and legal rules, economic laws, or contracts.

In formal institutions the purpose of formal rules is to promote certain kinds of exchange while raising the cost of undesired kinds of exchange. Ostrom (1999) classifies formal rules in 7 types:

1. boundary rules affect the characteristics of the participants,
2. position rules differentially affect the capabilities and responsibilities of those in positions,
3. authority rules affect the actions that participants in positions may, must or must not do,
4. scope rules affect the outcomes that are allowed, mandated or forbidden,
5. aggregation rules affect how individual actions are transformed into final outcomes,
6. information rules affect the kind of information present or absent in a situation,
7. pay-off rules affect assigned costs and benefits to actions and outcomes.

As norms are the elements that characterize institutions, they do not only serve as norms to be followed, but also serve as indication for people to recognize an organization as being an instance of a particular kind of institution, and then use this knowledge to predict other norms that could be applicable.

4.4 Wastewater Systems' Organizational Model

Agent based systems (Wooldridge and Jennings 1995) are an alternative for designing and implementing open and dynamic systems. As defined by Wooldridge and Jennings: *An agent is an encapsulated computer system that is situated in some environment and that is capable of flexible, autonomous action in that environment in order to meet its design objectives*. Agents are capable of social behaviour, they can communicate, compete and cooperate among them.

The main idea behind a society is to allow its members to coexist in a shared environment and pursue their respective goals in cooperation or competition with others. Therefore, artificial social systems (Moses and Tennenholtz 1995) define an abstract social level over computational systems. The social level models the MAS as an organization of entities, defining structured patterns of behaviour that facilitate and enhance the coordination of agent activities (Vázquez-Salceda 2003), effectively providing an *Organizational Model* agent's can understand and use. We will use a Institution as the ones described in Sect. 4.3 to model agent's interaction in the Besòs River Basin.

This section briefly introduces the Organizational Model of our scenario, including the *Social Structure* (with roles and their relationships) the *Interaction Structure* (with the *Landmarks*, patterns of interaction by which agents coordinate their behaviour) and the *Social model* (mapping abstract roles to particular agents). For a in-depth discussion see (Gómez-Sebastià 2016).

4.4.1 Social Structure

ALIVE Social Structure allows the description of the roles and their relationships, connecting them with both the individual goals and the societal aims. In our proposal the global aim of the wastewater systems' organizational structure is to achieve an effluent with characteristics adequate to the quality requirements of receiving waters. The roles model the distribution of *responsibilities* among stakeholders and their dependencies. Figure 4.3 shows the set of roles and their associated objectives and sub-objectives. For the sake of brevity we will not explain all of them but the most relevant. Role dependencies come in three wastewater, *hierarchically dependencies* (where the parent role has some form of authority over the child role, and therefore when the parent role requests the child role to perform a task, the child role is expected to abide), which are indicated with *H* in Fig. 4.3, *network dependencies* (where roles coordinate themselves as peers by mutual interest and support each other to fulfil a common goal) and *market dependencies* (where there is a set of producer roles offering information and/or services to consumer roles for a given price), which are indicated with a *M* in Fig. 4.3.

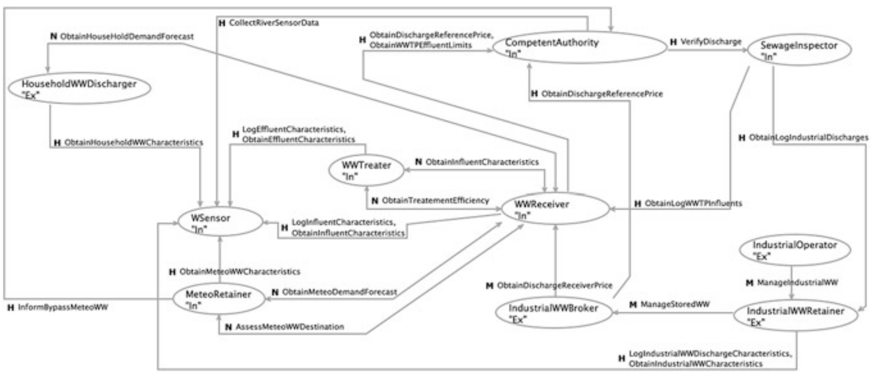

Fig. 4.3 Social structure

Also in Fig. 4.3 External *Ex* and Internal *In* roles are shown. Internal roles are controlled by the organization. Typically, if they are software components it means the organization has access to the software source code and is able to control and verify it. External roles are those participating in the organization, but not controlled by it. Following the same example, in the case of software components it means they have not been necessarily developed by the organization, and therefore there it might be no way to access the component's code and formally verify its behaviour.

The following list describes the most relevant roles in the system. The whole list of roles is introduced in Verdaguer et al. (2016). Roles are depicted in **bold** while their objectives are in *italics*. Dependencies with other roles are also presented and, when relevant, the dependency relation is also introduced.

- **IndustrialOperator**: This role is aimed on industrial processes that generate economic revenue and, therefore, allow fulfilling the objective of making profit (*MakeProfit*). These industrial processes produce polluted water masses as a trade-off of their activity (*Produce*). Dealing with this wastewater requires the collaboration of a **IndustrialWWRetainer** which stores the wastewater to be discharged into the sewer system later on (*StoreIndustrialWW*).
- **IndustrialWWRetainer**: Stores wastewater produced by an **Industrial-Operator** (*StoreIndustrialWW*) and takes care of it (*ManageStoredWW*) until it is possible to discharge it to the sewer system (*DischargeIndustrialWW*). To perform such discharge it is required the support of a **IndustrialWWBroker** to negotiate the discharge price and assess the feasibility of discharging some or all the wastewater, or keep storing it. Besides this, it keeps up a registry of all its industrial wastewater discharges performed (*LogIndustrialWWDischarge-Characteristics*), which requires the support of a **WSensor** to analyse the characteristics of discharged wastewater. This information can be used by a **SewageInspector** to verify I are properly managing discharges (*Verify-Discharge*).
- **IndustrialWWBroker**: Negotiates industrial wastewater discharges with a **WWReceiver** to assess how much wastewater is feasible to be discharged (*AssessAmountOfIndustrialWWDischarge*). From the **IndustrialWWBroker** perspective this assessment requires knowing its reserved cost (*ObtainDischargeReservedCost*) (i.e., how much I_i is willing to pay according to the discharge price given by the **WWReceiver**). **IndustrialWWBroker** is consuming treatment capacity to discharge wastewater and comply with the policies and norms that regulate wastewater discharges and ensure water quality. **WWReceiver** is offering such service thus the relation is a consumer-provider one thus the dependency between both roles in the *role dependency* diagram is a market dependency.
- **WWReceiver**: Takes care of negotiating the reception of wastewater masses (*NegotiateDischarge*). This includes providing discharge prices for I (*CalculateIndustrialWWDischargePrices*) and the treatment capacity available for industrial wastewater (*CalculateIndustrialWWAvailability*). To calculate discharge prices the **WWReceiver** uses discharge reference prices provided by

the **CompetentAuthority**, the current treatment efficiency in W_j (*ObtainTreatmentEfficiency*) as well as the characteristics of the industrial wastewater that I_i wants to discharge, which are provided by the **IndustrialWWRetainer** as part of the wastewater discharge negotiation process. Concerning treatment capacity availability, it depends on three main elements: Wastewater being received from households (*ObtainHousehold DemandForecast*), meteorological retainers status (*ObtainMeteoDemand Forecast*) and current W_j effluent limits imposed by the **CompetentAuthority**. Once influent is received, the **WWReceiver** determines its destination, either to be sent for treatment or bypass it directly to the river. This decision depends on (*EvaluateInfluentDestination*) wastewater characteristics (*ObtainInfluent Characteristics*), W_j current treatment efficiency (*ObtainTreatmentEfficiency*) and available capacity (*CalculateAvailableCapacity*). Finally, it also keeps a record of the influent characteristics received (*LogInfluentCharacteristics*) for the **SewageInspector** (as part of the *VerifyDischarge* task) and **WWTreater** (in order to calculate treatment efficiency).
- **WWTreater**: Processes the wastewater to reduce its pollutants concentration (*WWTreatment*). Once the treatments ends, treated water is discharged as an effluent to the river. This effluent is analyzed (*ObtainEffluentCharacteristics*) and information is logged so the **CompetentAuthority** can audit it (*VerifyWWTPEffluent*). Given the effluent and influent characteristics (*Obtain InfluentCharacteristics/ObtainEffluentCharacteristics*), **WWTreater** can calculate treatment efficiency (*CalculateTreatmentEfficiency*). This calculation is used to keep W as efficient as possible (*AchieveAdequatePerformance*). It is also used to support **WWReciever** during discharge price negotiation described before.

4.4.2 Interaction Structure

ALIVE Interaction Structure allows the description of abstract patterns of interaction which are the way the roles coordinate their behaviour, managing their dependencies while they pursue their individual and collective objectives. The interaction structure defines interaction patterns known as *scenes* (Dignum et al. 2009) that allow actors to coordinate. The structure defines a set of scenes and transitions among them. On every scene one or more role dependencies (identified in the previous phase) are managed.

The structure's entry point is represented by a circle (*init* label), while the exit points are represented by triangles (*end* label). Scenes are represented by rectangles and connected by lines (scene transition arcs) that allow the system to navigate from scene to scene. Inside every scene, the landmark patterns describe the protocol that must be used to achieve the scene result (Dignum et al. 2009). This diagram will focus on *scene transition*, allowing the following diagrams to focus on the different

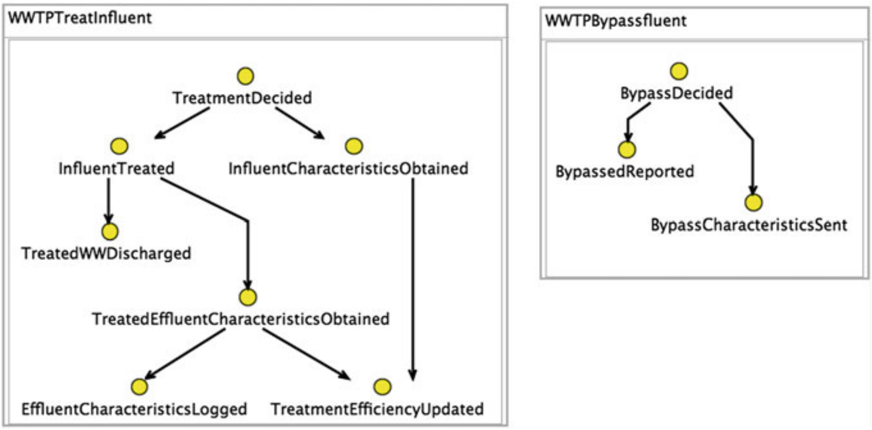

Fig. 4.4 Landmark patterns for WWTP influent treatment

particular scenes by showing the landmark patterns inside them. The entry point leads to the different wastewater generation scenes (*Household*, *MeteoWWGenerate* and *IndustryWWGenerate*) and the scenes related to water quality protection by the competent authority (*EnforceWaterQualityPolicies*, *ComputeWWTPEffluentLimits*, *ComputeIndustryPermissionLimits* and *ComputeDischargeReferencePrices*). *House holdWWGenerate* leads directly to wastewater treatment scenes. *MeteoWWGenerate Scene* contain particular scenes for discharging the water to W (*MeteoWWDischarge*) or bypassing it (*MeteoWWBypass*). Industrial production is divided in two parts: first wastewater is generated and stored *IndustryWWGenerate* and, later on, a negotiation to discharge wastewater in tank is done (*IndustryManageWWTank*) where a price to discharge is formed (*WWTPAssessDischargePrice*); depending on the negotiation result (*IndustryAssessWWDischarge*) wastewater is discharged (*IndustryWW Discharge*) or it is kept.

Some discharges will have a discharge verification performed asynchronously by the competent authority (*VerifyDischarge*). Wastewater treatment scenes include receiving influent (*WWTPReceiveInfluent*) and either treating (*WWTPTreatInfluent*) or bypassing it (*WWTPBypassfluent*)).

Figure 4.4 depicts the internal landmark patterns of the scenes *WWTP TreatInfluent* and *WWTPBypassfluent*. See Verdaguer et al. (2016) for a full description of all the scenes introduced in our scenario.

4.4.3 Social Model

Up to this point the overall system has been defined in terms of roles, their aims and dependencies, without taking into account who will actually enact those roles at run-time. The *Social Model* defines the way concrete agents enact the organization

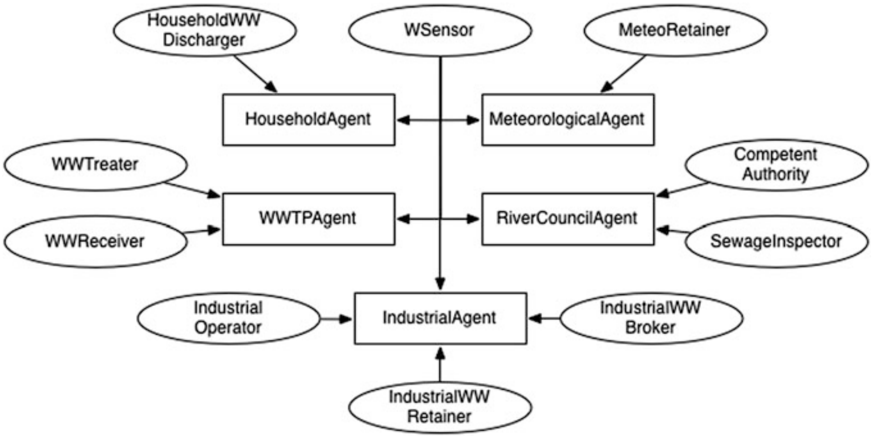

Fig. 4.5 The model of agents describes the roles that each kind of agent can enact during its lifetime

roles, guiding their behaviour and achieving coordinated action by following the organizational patterns established for the roles they enact. An agent can enact one or several roles, depending on their objectives, and one role can be enacted by more than one agent. In the case study, the objectives of UWS infrastructures act as the main driving force for allocating roles into agents.

Figure 4.5 shows the model of agents. The central axis is composed by the types of agents with a *Household, Meteorological, Industrial, WWTP* and *River Council agents* (square-shaped). The surrounding nodes represent the roles (round-shaped). The arrows connect each role with the agents type that performs it.

4.5 Agents: Behavior and Decision-Making

The most important roles in our system, from an integrated management perspective, are two. First, the *Competent Authority* is responsible for all matters relating to the collection, treatment and disposal of wastewater. Second the W_k which is responsible for treating wastewater in that sector or city. In this section we focus on the latter to describe the decisions it has to make to carry out the negotiation with industries that would like to discharge the wastewater resulting from their activities. The discharge of a wastewater mass requires an *agreement* between a particular and a particular that can accept it for treatment. This process requires *knowing* whether a W_j is capable to properly handle the proposed wastewater discharge.

We define the water characteristics of a water mass M_k as the pair (V, C), where: V is the volume of water mass given in cubic meters m^3 and, C is the pollutant concentration in the water mass. We also define $C = (C^1, \ldots, C^r)$ as the set of pollutants concentrations[1] where each C^i corresponds to a specific pollutant concentration $(1 \leq i \leq r)$. In our system, as already explained in Sect. 4.2.1, we consider five different pollutants: (TSS, BOD, COD, TN, TP). Thus $C = (C^1, C^2, C^3, C^4, C^5) = (TSS, BOD, COD, TN, TP)$ (Verdaguer et al. 2012).

Given these premises, the *negotiation* process between I_i and a W_j can be described as follows: The W_j checks if it can *manage* the wastewater that the industry wants to discharge (a W_j characterized as (V_i, C_i)). This means ensuring there is enough physical space to receive it (*volume availability*) and that the plant can effectively treat the pollutants contained in the wastewater mass (*pollutant concentration admissibility*); if wastewater contains a high pollutant concentration it can harm the treatment process since it depends on bacteria colonies that may perish.

Volume availability ($V_{available}$) depends on the design volume of the W_j ($V_{capacity}$), the amount of domestic wastewater sent by households (V_d) and meteorological phenomena (V_m) (e.g., rain), whose treatment is mandatory. Finally, previously agreed industrial discharges ($V_{scheduled}$) have to be taken into account to know what volume capacity remains available for new industrial discharges:

$$V_{available} = V_{capacity} - V_d - V_m - V_{scheduled} \tag{4.1}$$

Therefore, if $V_i \leq V_{available}$ then there is enough space in the W_j to accept the wastewater mass.

To verify pollutant concentration admissibility the process is similar although a W_j can admit a higher concentration than the one it can effectively manage; however, this will imply a significant higher cost for the industry. Pollutant concentration admissibility depends on how much pollutant concentration W_j can manage as a parameter design of the plant ($C^r_{admissible}$). Thus, if $C^r_{admissible} \geq C^r_i$ the wastewater mass will be accepted without extra cost. Otherwise, the pollutant overload will carry an extra cost to the price that industry has to pay. This price is calculated by W_j as follows:

$$P(WW_i, W_j) = P((V_i, C_i), wwtp_j) = VC(V_i, W_j) + PC(WW_i) \tag{4.2}$$

Equation 4.2 is divided into two parts: a volumetric cost and a pollutant cost. The first represents the cost of accepting a certain volume of wastewater generated by I_i according to the current state of the W_j as well as the taxes defined by the competent authority. The second computes the price of processing the wastewater discharged by industry I_i according to its pollutant concentration.

[1]Pollutant concentration is given in $(\frac{\text{kg}}{\text{m}^3})$.

4.6 Norms

Scenarios like the one introduced in this *Chapter* present several actors (e.g., *Industrial Operator*, *Industrial WWRetainer*, *WWTreater* etc.) with a variety of goals that sometimes are conflicting between them. For instance, the *Industrial Operator* aims at making profit which in turn will generate wastewater, effectively polluting the environment. The *WWTreater* aims at cleaning wastewater for protecting the environment at the lowest possible price. Therefore, from the individual point of view of an *Industrial Operator*, the more industrial activity the better, even if it results in more polluted water. However, from the individual point of view of a *WWTreater* the less industrial activity the better, as the water will be less polluted and therefore will be easier and cheaper to clean. Bringing this self-interest to the extreme, the ideal situation for *Industrial Operator* is a scenario with no environmental protection, where the river can be polluted without constraints. The ideal situation for *WWTreater* is a scenario where there are no polluting elements (no industries, no households) and therefore the river is never polluted. However, the ideal situation from the holistic point of view of the society (as a group of interconnected individuals) is to find a balance to protect the environment while promoting industrial activity.

Furthermore, the roles in the scenario depend on each other for achieving their goals, and therefore they interact in multiple ways. The combination of these two factors results in a society of interacting agents with heterogeneous goals. In order to tame the complexity of these interactions, and to align the overall system with a common high level goal (e.g., protecting the environment without compromising industrial activity) norm-aware electronic distributed systems can be used.

Electronic specifications of norms are one of the mechanisms being applied to define and enforce acceptable behaviour of electronic distributed systems which should comply with some (typically human) regulations. One of the options for providing norm-aware MAS are Electronic Institutions (*EI*) (Vázquez-Salceda 2003). They are models of human institutions with a norm specification provided in a machine-readable formalism. The main idea behind *EI* is capturing the essence of an institution (mainly norms and protocols) in a machine processable form.

Some functionalities in the system depend on the *Competent Authority* role detecting exceptional situations and applying the appropriate restrictions. For instance, if a meteorological overflow is notified WWPTs can exceed their treatment capacity if they take water from the influent. Therefore plants must limit their influent intake until the overflow is solved. It means water from the influent is not completely treated and to protect the environment industries can not discharge wastewater to the river until the overflow is solved. In order to tackle these restrictions we use *ALIVE*'s normative structure, grounded on regulative and constitutive norms. Such norms specify actor's obligations (WWTPS must limit influent intake until the overflow is solved), prohibitions (discharging water masses with high concentrations of mercury) and permissions (industries can not discharge wastewater to the river until the overflow is solved). In scenarios like the one presented here, MAS are applied to systems with an overall holistic goal and it is not desirable that an agent's autonomous and emergent behaviour diverges from the overall goal of the system. In order to limit this agent autonomy and ensure a certain coherence between the goals of the particular agents and the overall goals of the system, norms can be applied. Furthermore, norms make the behaviour more predictable, effectively reducing the complexity of the system. Taking this into account, the scenario presented in Sect. 4.2.1 provides an exciting new line of research: modelling and implementing the set of norms that will make the system's objectives (e.g., have an environmental sustainable system) stand on top of individuals' objectives (e.g., make profit in the case of the industries). Furthermore, the set of norms provided is not static, as norms will have to evolve through time just as individuals' behaviour changes to adapt to dynamic circumstances. Not only deciding how these norms will have to be adapted is an exciting challenge, but also designing mechanisms to support norm dynamics at run-time. Such mechanisms effectively support adding, removing or updating norms at run-time and while inferring the social state. On the one hand, we can not afford to miss the violation of a norm just because we are updating it. On the other hand, we have to infer a social state consistent with the changes performed in the norms (e.g., it makes no sense to punish an agent for violating a norm that has been removed).

This section provides examples of norms modelled used the framework introduced in Gómez-Sebastià (2016) and examples on how social and technological changes can affect these norms. For each norm a formal model is provided, as well as the time line depicting the implications of the norm change. Examples for all operations supported by our framework are provided. Norms are inspired on European, national and local wastewater treatment directives.

Our model supports two possible operations (adding and removing norms, accounting norm update as a combination of the two basic operations) in two forms (retroactively and prospectively). The model also supports regulative norms (with obligations, prohibitions and permissions), constitutive norms and institutional powers (including both constitutive powers and normative powers).

4.6.1 Obligation Prospective Add

The European council directive for Wastewater treatment (European Council 1991) in Article 4 and the Catalan plan for Wasterwater treatment inspired on this directive (Generalitat de Catalunya 2005) state:

Member States shall ensure that urban wastewater entering collecting systems shall before discharge be subject to secondary treatment or an equivalent treatment as follows:

- *at the latest by 31 December 2000 for all discharges from agglomerations of more than 15,000 p.e. (population equivalent)*
- *at the latest by 31 December 2005 for all discharges from agglomerations of between 10,000 and 15,000 p.e.*

Norm N_1: Let $W_i \in \mathcal{W}$ be a Wastewater Treatment Plant, $M_j \in \mathcal{M}$ a water mass and $T_k \in \mathcal{T}$ a secondary treatment. Once W_i receives a particular water mass M_j, the plant has the obligation to treat the water mass with secondary treatment T_k before discharging the water mass.
Sanction S_1: A generic sanction is applied to the Wastewater Treatment Plant if the norm is not complied with.

Activation Condition N_1	$received(W_i, M_j)$
Expiration Condition N_1	$discharged(W_i, M_j)$
Maintenance Condition N_1	$True$
Deadline N_1	$performed(T_k, W_i, M_j) \wedge counts\_as(T_k, SecondaryTreatment)$
Activation Condition S_1	$isViolated(N_1, W_i)$
Expiration Condition S_1	$GenericSanction(W_i)$
Maintenance Condition S_1	$True$
Deadline S_1	$True$

Fig. 4.6 Example of formal norm specification for obligation

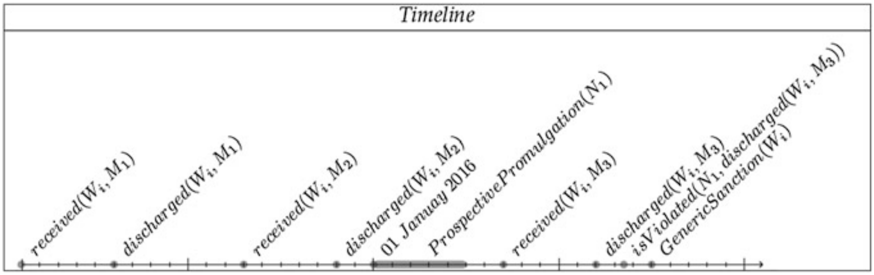

Fig. 4.7 Example of timeline for prospective add of a an obligation

It means that, by the date '01 January 2006' each $WWTP_i \in$ W with a *p.e.* of 10,000 or more have the obligation to perform a secondary treatment (or a treatment that *counts-as* secondary treatment, that is, an equivalent) before discharging water to the river. Failing to comply with the norm will result in the WTTP being sanctioned. Figure 4.6 shows the formal specification of the regulative norm in our model.

Following the example, the regulative norm is introduced in the system via a Prospective Promulgation operation on the date '01 January 2006'. Therefore, if a $W_i \in$ W with a *p.e.* of 10,000 or more violated the regulative norm (i.e. discharged water without treating it) before '01 January 2006', the act has no legal consequences. However, if the plant violates the norm after the promulgation date, it will be sanctioned for the act. In the example depicted in Fig. 4.7, W_i discharges untreated water masses M_1, M_2 before norm promulgation without legal consequences. However, discharging untreated water M_3 after promulgation results in a sanction being applied.

4.6.2 Obligation Prospective Remove

The European council directive for Wastewater treatment (European Council 1991) states in *Annex I* point *D.5*:

Extreme values for the water quality in question shall not be taken into consideration when they are the result of unusual situations such as those due to heavy rain.

In our example it stands for the obligation to perform a secondary treatment not having effect in unusual situations, such as *heavy rain*. The obligation has already been introduced in Sect. 4.6.1 and formally modelled in Fig. 4.6. However, the model does not take into account the fact that the norm is not in place in case of unusual situations. One option is to include the exception on the model of the norm (i.e. preventing the norm from activating if water is received by the plant, but an unusual situation is in place). Formally, it would imply substituting the activating condition of Norm N_1, which is currently $received(W_i, M_j)$ for $received(W_i, M_j) \wedge unusualSituation()$. However, this solution would result in more complex norm formalizations. Furthermore, if new exceptions to the norm are added, more conditions would be included in the activating condition, resulting in complex and hard to understand norms. A cleaner solution is to allow the competent authority (or any other actor with power to alter the norms that govern the system) to temporally remove the norm from the system when it is considered appropriate (in our example, while the unusual situation takes place). On the one hand, these norm could be used to keep norms simple and easy to understand. That is because we are leaving the decision of which norms should be active in every scenario to higher level (and more expressive) reasoning processes performed by the agents responsible of introducing and removing norms in the system. On the other hand, all the exceptions to the different norms do not have to be taken into consideration at norm design time. They can be introduced later when designing a process that decides which norms are active in the system at every point of time. That is, our approach allows supporting a normative system which is truly dynamic and adapts to changing (and sometimes even not foreseen) situations.

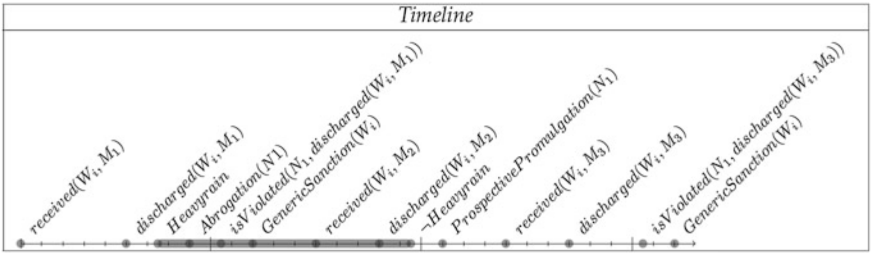

Fig. 4.8 Example of timeline for the prospective remove of an obligation

Following the example depicted in Fig. 4.8, the norm N_1 is removed from the system via an Abrogation operation. This allows to effectively implement a general exception to the norm while an unusual situation of heavy rain takes place. Therefore, if a particular Wastewater Treatment Plant $W_i \in \mathrm{W}$ violated the norm (i.e. discharged water without treating it) in a situation of heavy rain, the act has no legal consequences. However, if the plant violates the norm outside the unusual situation, it will be sanctioned for the act. In this example, a Wastewater Treatment Plant W_i discharges untreated water masses M_2 during heavy rain without legal consequences. However, discharging untreated water M_1, M_3 outside the unusual situation results in a sanction being applied. Please note that one of the sanctions (associated to the discharge of M_1) is applied during the unusual situation. This is because the action causing the norm violation occurred outside the unusual situation, and our framework is expressive enough to detect this particular fact.

4.7 Conclusions and Related Work

Once we have finished introducing our approach of a norm-aware multi-agent simulator, we proceed to put it in contrast with similar approaches, focusing on detecting confluence points where our work can be complemented by the different approaches in the state of the art. Then, we will outline conclusions.

The work in Verdaguer et al. (2012) aims at coordinating coordinating industrial wastewater discharges between different actors, based on ant colony optimization. The system aims at finding the best combination of industrial discharges *w.r.t.* WWTP efficiency, that is, as much capacity as possible is used from the plant without overloading it. For doing it, ants are randomly placed on a graph-like search space, where nodes are industrial activities and edges possible discharges. The work neglects some issues such as the efficiency of a centralized decision system in real-world scenarios, or the need to have complete information about industry production plans in order to entail expected industrial wastewater discharges. Furthermore, the work presented in Verdaguer et al. (2012) does not take into account agents not abiding to the expected patterns of behaviour, and lacks methods to deal with such issues.

The work in Verdaguer et al. (2012) focuses on the internal reasoning process of a coordinator agent (which can be fulfilled by the WWTP agent in our scenario) whereas our approach focuses on the structure of the agent society and the interactions among agents from an organizational point of view, without detailing the internal reasoning processes of the agents. Therefore, we could state both approaches are complementary and can benefit from each other. The work in Verdaguer et al. (2012) could benefit from the normative system we propose for enforcing acceptable patterns of behaviour (e.g., industries comply with the agreements they reach with WWTPs for wastewater treatment) as well as from our institutional model to facilitate coordination in complex scenarios where a particular agent can fulfil more than one role (e.g., industries with their own WWTP that can accept other industry wastewater as long as they are paid enough for treating it).

Market-based approaches are another alternative to coordinate the use of natural resources in heterogeneous societies of actors. In Garrido et al. (2013) *m* Water is introduced. *m* Water is a regulated virtual market simulation where autonomous agents trade rights for the use of water in a closed basin. The idea behind *m* Water is allowing policy makers to compare different market configurations using market performance indicators. Market configurations contain several parameters, including participant population (supporting different behavioural templates) and the set of regulations and protocols to be used during the negotiation process. Just like our approach, *m* Water aims at narrowing the gap between water management simulations (based on equational descriptions) and social simulations. The motivation behind social simulations is to mimic the behaviour of autonomous rational individuals and groups of individuals (Smajgl et al. 2009). The main idea is modelling not only hydraulic factors (which can be perfectly modelled using equational systems) but also social factors, including norm typology and actor's behavioural templates.

m Water and our proposal have several characteristics in common. Both are social simulations grounded on Electronic Institutions able to represent roles, coordination scenes, objectives and a normative system. However, when compared to our approach *m* Water presents a more specific and in-depth proposal. *m* Water focuses on negotiation for water use rights, whereas our proposal covers the whole river basin management scenario, therefore the negotiation process is not presented with such detail. Furthermore, while *m*Water correctly emphasises the need to flexible and dynamic normative systems (e.g., authors stress the need of '*organization schemes that are flexible and able to adapt to a changing environment with multiple situations*') no method for supporting them is presented. Our proposal clearly remarks that this method is available, and we provided an exhaustive set of examples based on river basin management. On the one hand, we consider our proposal could benefit from the work done in *m* Water for implementing more expressive and powerful auction mechanisms when negotiating for wastewater treatment resources. On the other hand, we consider *m* Water could benefit from our proposal to widen the application scenario (limited not only to interactions involved on the negotiation for water use rights, but covering the whole set of interactions present in river basin management) and support dynamic normative systems, able to change the set of norms during the simulations, effectively adapting them to new situations and requirements. This would allow to simulate not only new sets of policies but also sets of policies evolving through time, allowing to evaluate not only the impact of the new set of policies in the system, but also the performance of the evolution (e.g., measuring how long does it take for the new policies to be adopted and the performance of the system during the transition between different sets of policies). In general we consider evaluating the impact on the system of policy evolution, while the simulation keeps running and the different actors pursuing their objectives, opens new, more realistic and exciting lines of future work *w.r.t.* simulations for policy optimisation.

In Ernst et al. (2007) an agent-based Decision-Support-System (DSS) for water resource management is introduced. The work's main aim, integrated in the GLOWA-Danube project, is to represent both social and environmental processes in the DSS. This is achieved by integrating 16 fully coupled process models from 11 scientific disciplines (ranging from hydrology to tourism research) into the DSS core engine. The different components and their models are effectively integrated via a simulation framework, where agent-based modelling plays a central role in representing the behaviour of the different actors. Agent reasoning is based on agent's mental states and by the state of the environment, which is affected by the actions performed by other actors in the society. The environment includes social and legal perceptions, such as 'specific appeals from a community official to save water'. Agent preferences are modelled via profiles, effectively supporting agents with heterogenous goals and personalities.

The work presented in Ernst et al. (2007) presents a social simulator integrated with a DSS where a set of heterogeneous agents interacts. We like the idea of merging different agent behaviours and perceptions (including environmental, social and legal perceptions) via a 5 step reasoning process. However, we consider the approach could benefit from a clearly defined social model integrated in the reasoning process via socially-aware reasoning methods. Furthermore, it might be interesting to integrate protocols and regulations in the reasoning process (e.g., in the form of sanctions for agents consuming too much water in drought situations).

The work presented in Gailliard et al. (2014) proposes a model for river basin governance that includes what is known as a '*boundary worker*'. Boundary workers, such as river basin managers, are interfaces aimed at facilitating an evolution towards more sustainable practices in river-basin governance. The main aim of Gailliard et al. (2014) is to analyze the impact of boundary workers on the behaviour of heterogeneous actors interacting on a common social-hydrosystem. This is achieved by creating an agent-based model including qualititative data (research questions, expected rules of behaviour, interactions between agents and some scenarios to simulate) which can be reviewed via a return field in order to calibrate the model as finely as possible. In contrast to Gailliard et al. (2014) our approach supports governance either via a pre-defined set of rules (e.g., provided by a river basin manager) or via a consensual agreement between the different actors involved in the scenario. In any case, this set of rules will not be static, but will evolve through time as new regulations and behaviours emerge in the society of actors involved in river basin management.

To conclude, this chapter has presented a norm-aware agent-based model for integrated wastewater management systems. The chapter provides an example on how normative systems can be integrated in multi-agent systems where actors' objectives are heterogeneous and sometimes conflicting. The normative system allows to align agent's objectives with common organisational objectives. At the same time, it allows to detect undesirable patterns of behaviour in the agents, such as free raiders. Thanks to our proposal, misbehaving actors can be sanctioned, effectively enforcing good practices among the actors.

In this aspect, our proposal shows many features in common with several works in the state of the art. However, our proposal goes beyond, as it allows the set of norms governing the multi-agent system to evolve through time. We provide a wide range of examples, where regulative norms in the form of obligations, prohibitions and permissions are inserted, removed and updated. Furthermore, we also show examples of dynamic operations on constitutive norms and constitutive powers.

While most of the systems analysed show a less expressive normative language (they typically do not account for constitutive norms and constitutive powers) we provide a rich set of normative elements (Alvarez-Napagao 2016), supporting deontic elements (obligations, prohibitions and permissions), constitutive norms, constitutive powers and violation handling norms (i.e. sanctions). Furthermore, our normative elements contain a rich structure with activation, maintenance and deactivation conditions, as well as deadlines.

Finally, we support norm dynamics (Gómez-Sebastià, 2016), which is not supported by the proposals analysed in the state of the art. We propose four operations to update the normative system accounting for norm promulgation and derogation both in prospective and retroactive forms. On the one hand, we combine norm operations with a rich set of normative elements providing a dynamic normative language that can be adapted to a numerous set of contexts and situations. This is specially important in wastewater management scenarios, where the set of norms will evolve adapting to situations which are typically out of control of managers and legislators (e.g., heavy rains, droughts, pollution of the environment). On the other hand we can adapt norms while our system is on-line, inferring a normative state consistent with the update. In scenarios like wastewater management we can not afford to stop observing the social reality, as *free* raiders and other misbehaving actors could take advantage of this situation.

In contrast, our proposal does not present complex reasoning processes and decision taking mechanisms for the agents involved in the system. We focus on the normative system, so we can effectively benefit from more expressive and complex agents the other proposals include. As a future research direction we plan to integrate a norm reasoning process into our simulator. This will allow the agents to decide which norms should be changed and how. Our hypothesis is agents can adapt norms to the scenario in order to regulate the usage of natural resources. The objective is to avoid or delay the tragedy of the commons from occurring.

As a summary, in this chapter we have seen a wide range of norms and norm operations, based in real world regulations and protocols, such as (European Council 1991). This chapter focuses on how the normative system can evolve. On the one hand adapting itself to new regulations and protocols caused by technological advances or social changes. On the other hand, adapting itself to unexpected situations which are typically out of control of managers and legislators, such as *heavy rains*. Furthermore the work presented in this chapter is being integrated into a social simulation system that models the Besòs river basin. In such simulation agents participate in a Tragedy of the Commons scenario where water quality represents the common good. Agents face the dilemma of breaking the rules to increase their utility functions or act legally according to current state of norms. Including normative dynamics allows us to adapt norms to environmental changes and see if those changes allow the common good to be preserved despite agents' behaviours and selfish interests that drives them to, under certain circumstances, act as free riders.

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References

Aldewereld, H., & Dignum, V. (2010). OperettA: Organization-oriented development environment. In *Languages, methodologies, and development tools for multi-agent systems* (pp. 1–18). Berlin, Heidelberg: Springer.

Aldewereld, H., Padget, J., Vasconcelos, W., Vázquez-Salceda, J., Sergeant, P., & Staikopoulos, A. (2010). Adaptable, organization-aware, service-oriented computing. *IEEE Intelligent Systems, 25*(4), 26–35.

Alvarez-Napagao, S. (2016). *Bringing social reality to multiagent and service architectures. Practical reductions for monitoring of deontic-logic and constitutive norms*. PhD Dissertation. Universitat Politècnica de Catalunya-BarcelonaTech.

Dignum, F., Dignum, V., Padget, J., & Vázquez-Salceda, J. (2009, December). Organizing web services to develop dynamic, flexible, distributed systems. In *Proceedings of the 11th International Conference on Information Integration and Web-based Applications & Services* (pp. 225–234). ACM.

Ernst, A., Schulz, C., Schwarz, N., & Janisch, S. (2007). Modelling of water use decisions in a large, spatially explicit, coupled simulation system. In *Social simulation: Technologies, advances and new discoveries* (pp. 138–149). Oxford: Elsevier.

European Council. (1991). *Directive concerning urban waste water treatment (91/271/EEC)*, Vol. 30.

Gailliard, N., Barreteau, O., & Richard-Ferroudji, A. (2014). Participatory policy making in practice: simulating boundary work in water governance. In *Advances in social simulation* (pp. 333–342). Berlin, Heidelberg: Springer.

Garrido, A., Giret, A., Botti, V., & Noriega, P. (2013). mWater, a case study for modeling virtual markets. In *Agreement technologies* (pp. 565–582). Netherlands: Springer.

Generalitat de Catalunya. Psaru. (2005). http://aca-web.gencat.cat/aca/appmanager/aca/aca?_nfpb=true_pageLabel=P1204654461208200526170profileLocale=es. Accessed March 30, 2015.

Gómez-Sebastià, I. (2016). *NoMoDEI a framework for norm monitoring on dynamic electronic institutions*. PhD Dissertation. Universitat Politècnica de Catalunya-BarcelonaTech. http://futur.upc.edu/17497419. Accessed May 03, 2016.

Hamilton, H. R. (1969). *Systems simulation for regional analysis: An application to River-Basin planning*. Cambridge, Massachusetts/London: Massachusetts Institute of Technology.

Hardin, G. (1968). The tragedy of the commons. *Science, 162*(3859), 1243–1248.

Hardin, G. (2007). The tragedy of the unmanaged commons. In *Evolutionary perspectives on environmental problems* (pp. 105–107). New Brunswick, NJ: Transaction Publishers.

Lloyd, W. F. (1833). Two lectures on the checks to population: Delivered before the University of Oxford. In *Michaelmas TERM 1832*. Oxford: JH Parker.

Moses, Y., & Tennenholtz, M. (1995). Artificial social systems. *Computers and Artificial Intelligence, 14*, 533–562.

North, D. C. (1990). *Institutions, institutional change and economic performance*. Cambridge: Cambridge University Press.

Ostrom, E., Gardner, R., & Walker, J. (1994). *Rules, games, and common-pool resources*. Ann Arbor: University of Michigan Press.

Ostrom, E. (1990). Governing the commons: The evolution of institutions for collective action. In *Political economy of institutions and decisions*. Cambridge: Cambridge University Press.

Ostrom, E. (1999). Coping with tragedies of the commons. *Annual Review of Political Science, 2* (1), 493–535.

Ostrom, E. (2000). Collective action and the evolution of social norms. *Journal of Economic Perspectives, 14*(3), 137–158.

Poch, M., Comas, J., Rodriguez-Roda, I., Sanchez-Marre, M., & Cortés, U. (2004). Designing and building real environmental decision support systems. *Environmental Modelling and Software, 19*(9), 857–873.

Smajgl, A., Heckbert, S., Ward, J., & Straton, A. (2009). Simulating impacts of water trading in an institutional perspective. *Environmental Modelling and Software, 24*(2), 191–201.

Vázquez-Salceda, J., Vasconcelos, W. W., Padget, J., Dignum, F., Clarke, S., & Roig, M. (2010). ALIVE: An agent-based framework for dynamic and robust service-oriented applications. In *Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems* (Vol. 1, pp. 1637–1638). International Foundation for Autonomous Agents and Multiagent Systems.

Vázquez-Salceda, J. (2003). The role of norms and electronic institutions in multi-agent systems applied to complex domains. The HARMONIA framework. *Ai Communications, 16*(3), 209–212.

Verdaguer, M., Clara, N., & Poch, M. (2012). Ant colony optimization-based method for managing industrial influents in wastewater systems. *AIChE Journal, 58*(10), 3070–3079.

Verdaguer, M., Poch, M., Gómez-Sebastià, I., Oliva, L., Vázquez-Salceda, J., & Cortés, U. (2016). *Organizational structure of an agent-based model for integrated wastewater management systems*. Elsevier.

Wooldridge, M., & Jennings, N. R. (1995). Intelligent agents: Theory and practice. *Knowledge Engineering Review, 10*(2), 115–152.

Chapter 5
Decision Making in Solid Waste Management Under Fuzzy Environment

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Abstract Solid waste management is regarded as one of the most stimulating matter by managers due to the incremental tendency of waste generation. Procuring consistent data on waste generation makes solid waste management a complex procedure. Therefore, the influencing characteristics that affect the outcomes of the waste system should be analyzed carefully. These characteristics can be mainly classified as determination, collection, transportation, treatment, recycling and disposal. This chapter proposes a mathematical model that, along with the cost (facility establishing, transportation, and processing) minimizing, considers a second objective which minimizes the pollution affecting populated districts. While the model minimizes the total cost and pollution, it also determines the optimal locations of transfer centers and land filling areas. The objective functions were optimized in a fuzzy environment and the study was conducted in Istanbul, the most populated city of Turkey. The results indicate that a tremendous amount of reduction in pollution is possible at a very reasonable cost. The proposed model is generated such that it can be generalized and applied to any municipal solid waste systems where similar objectives exist.

5.1 Introduction

Solid waste management is regarded as one of the most challenging issue by municipality managers of flourishing countries due to the incremental trend in waste generation (Grazhdani 2015). Obtaining consistent data on waste generation and related factors is often troublesome; however, forecasting accurate waste quantities necessitates collecting information from numerous sources. Hence, solid waste management is a complex procedure (Lebersorger and Beigl 2011; Grazhdani

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2015) and the influencing attributes that affect the outcomes of the waste system should be analyzed carefully (Lu et al. 2012). These attributes can be classified as determination, collection, transportation, treatment, recycling and disposal. All these attributes are also affected by technological changes. Accordingly, Lu et al. (2012) proposed an approach which is able to identify the “key factors and/or input conditions” that may affect the performance of the system for future administration processes. On the other hand, the type of generated waste, also, differs from region to region, (Purcell and Magette 2009) with regard to socio-economic, demographic and environmental conditions. Thus, waste management practices and procedures may be unique to each municipality (or country) based on their technological capabilities or type of the waste generated. Even though technological capabilities differentiate, all municipalities or the managers who are in charge of managing the waste system in their region need to determine proper locations for their processes (i.e., treatment, recycling, and disposal) in such a way that city-dwellers are not bothered.

As Eiselt and Marianov (2014) mentioned, determination of facility locations has been studied by various researchers and after a relatively long thread of discussion on the topic, it is realized that not all such locations are favored by residents to be in their neighborhood due to probability of bothering noise, smell and different sorts of pollution. Even though the pollution level or type changes according to the industry the facilities that release pollution are in, these facilities are undesirable by the residents who live in the neighboring districts. These types of facilities were named as “undesirable facilities” in Erkut and Neuman (1989). For instance, although both airports and sewage plants (Melachrinoudis 2011) are undesirable facilities, the type of pollution they release differentiate in terms of risk level and risk type. Thus, while locating facilities, the types of risk and pollution need to be considered in the model. Other types of “undesirable facilities” such as waste transfer centers and landfilling locations, which process solid waste, are not favored by the residents that live in their vicinity.

This chapter aims to determine the locations for both transfer centers and landfilling areas that is inspired by Eiselt and Marianov (2014) in which landfilling locations were investigated. In our determination process, while minimizing the total process cost, we also considered the environmental risk and pollution that may be released from transfer centers and landfilling areas as studied in Eiselt and Marianov (2014). Locating these types of facilities can be handled via proper constraints in the model, i.e., prohibiting locating the land filling areas in the districts that do not have appropriate soil type or districts that are close to populated districts or forcing a certain degree of distance between land filling areas and populated districts. In today’s world, even if those types of facilities are not in their districts, residents do not want them at any place that may bother them by noise, traffic, and air pollution (Eiselt and Marianov 2014). In this chapter, we apply these restrictions (forcing a certain degree of distance between undesirable facilities and populated areas in terms of amount of pollution) both by adding them to the objective function and to the constraints as applied in Eiselt and Marianov (2014). The constraints prohibit locating facilities if they release over a certain level of pollution in which pollution level is calculated based on waste amount and distance between populated areas. Aside from the constraints, a term in the objective function aims to minimize total pollution that affects people who live in a vicinity of the facilities.

On the other hand, residents of a city may not be willing to have transfer centers or landfilling areas close to them; however, they recognize the fact that these facilities have to be located at somewhere within the city. Locating these facilities is not the only issue that people or municipal managements have to deal with. The location of these facilities should be cost-effective in terms of transportation costs since thousands of tons of waste may be generated every day, i.e., in Istanbul more than 15,000 tons of waste is generated a day, on average. In parallel with the statements above, Fernández et al. (2000) proposed a non-convex model which locates a single undesirable facility that do not affect the residential life directly. They also considered environmental risks to avoid locating this facility if it might affect the inhabitants of the region. Models presented in the related field concern with different types of parameters: known locations of candidate sites, known number of residents who lives in the populated districts, known distance between candidate locations and populated districts. However, number of residents may change over time. Therefore, in this chapter, we use a forecast for the number of people that may be living in the districts, which are gathered from TUIK (2015). Note that Istanbul's population expected to increase approximately by 16.38 % in 2015. On the other hand, we consider different distances when transportation costs and pollution-wise effects of waste on residents are calculated. Regarding transportation cost, we use appropriate routes obtained from Google Maps; in pollution calculations, we use Euclidean distances demonstrating how pollution probably moves toward populated districts as applied in Eiselt and Marianov (2014). One other approach to determine the location of facilities (or undesirable facilities) is to use multi attribute decision making techniques as employed in Sumathi et al. (2008), Moeinaddini et al. (2010), Ekmekçioğlu et al. (2010), Tavares et al. (2011), Nazari et al. (2012), Ferretti (2011), Kara and Doratli (2012) or stochastic optimization or heuristic methods as in Aydin and Murat (2013) and Ayvaz et al. (2015). Transfer centers are developed to mitigate latter effects of the waste (Eiselt and Marianov 2014). At such centers, municipal waste is compressed and reloaded onto bigger trucks to transfer wastes to treatment centers or landfilling areas. Thus, the location of transfer centers and land filling areas must be considered in the same model to obtain optimal locations (with the aim of minimizing transportation costs and the effect of pollution) for both transfer centers and land filling areas.

Minimizing cost and the effects of pollution makes models complex and multi objective. In such problems, one of the most difficult decisions is the tradeoff between weights of different objectives. Two ways can be followed to handle this problem: goal programming (Simon 1957) or weighting approaches. By weighting approach, we mean Cohon's weighting method (1978). However, in real world, tradeoffs between items cause fuzziness and ambiguity. Zimmermann (1975) is the first to introduce fuzzy set theory to linear programming (LP) problems. The proposed model considered LP problems with fuzzy constraints and a fuzzy objective function. Later, Zimmermann (1978) extended his LP approach (Zimmermann 1975) to a straight multi-objective LP problem. Afterwards, fuzzy linear programming (FLP) was proposed on which Hintz and Zimmermann (1989) mainly based their methodology. Assume that the decision maker (DM) encounters fuzziness for each of the objective functions in the problem. The fuzziness occurs in such a way that the values of the objective functions should be less than or equal to a specific value. Then, the decision making process proposed by Bellman and Zadeh (1970) is applied to associate the objective functions. After this application, the problem can be transformed into the equivalent LP and solved with any optimization method. Subsequent studies on fuzzy optimization in municipal solid waste can be found in Huang et al. (1993, 2001), Chang and Wang (1997), Chang et al. (1997), Aydin (2007), Srivastava and Nema (2012), Wang et al. (2012). Further, fuzziness can be handled via several types of fuzzy numbers: triangular fuzzy numbers (Li and Chen 2011), trapezoidal fuzzy numbers (Liu et al. 2014), and interval valued fuzzy numbers (Wang et al. 2012). Wang et al. (2012) applied "interval-valued fuzzy sets" to describe managerial decisions in a healthy manner and increase the robustness of the system. Li and Chen (2011) developed a method that provides a better solution than the conventional interval fuzzy programming and two-stage stochastic programming, and effectively handles fuzziness. The authors stated that the findings support managers by providing tradeoffs between cost and the system risk.

Furthermore, important gaps exist in the related literature of municipal solid waste management besides several recent studies such as an integrated application of TOPSIS and VIKOR for optimization of solid waste management (Mir et al. 2016); a fuzzy robust optimization for the optimization of "regional solid waste management" under fuzzy environment (Xu et al. 2016); a fuzzy multi criteria decision making to rank land filling areas to find the most accurate one for a region in India (Christian and Macwan 2016); another for land filling area selection for a region in Iran (Torabi-Kaveh et al. 2016). Beskese et al. (2015) determined land filling areas for Istanbul via fuzzy AHP and fuzzy TOPSIS using expert opinions. Further studies on land filling selection for solid waste management for the last forty years can be found in Eiselt and Marianov (2015). Also, research gaps in the logistics of solid waste management can be found in Bing et al. (2016).

This chapter contributes to the related literature by proposing a mixed integer linear problem to locate waste transfer centers and determine the location for land filling areas, simultaneously. While optimizing the locations of these facilities, we minimize the total fixed cost of locating them and the cost of transporting wastes from the points of origin (populated districts) to the facilities. Five types of centers are considered: *city centers* where solid wastes occur; *transfer centers* where wastes are compressed and reloaded into bigger trucks; *recycling centers* where wastes are recycled for possible reuse as they are or as raw material; *disposal centers* where hazardous wastes are disposed; and *disposal areas* where wastes and ash that occurred at recycling centers are land filled. Pollution released from centers towards populated districts is minimized through the objective function via forcing some constraints to keep the amount of pollution less than a certain value (as an upper bound). In this model, we determine the locations and the number of transfer centers and land filling areas while the location and numbers of recycling and disposal centers are known in advance. The remainder of this chapter is organized as follows: Sect. 5.2 explains the methodology in detail; Sect. 5.3 presents the results of the experimental study which has three subsections—mathematical model, fuzzy mathematical model, and results and sensitivity analysis; Sect. 5.4 concludes with an emphasis on possible avenues for future research.

5.2 Methodology-Fuzzy Multi-objective LP

Classical LP models are used to find the optimal values of the decision variables of an objective function under specific constraints. Nevertheless, the coefficients in the problem are not always known by the DM and there may be more than one objective function as in the case of most real-world problems. Under these circumstances, fuzzy multi-objective linear programming (FMOLP) is employed by the DM. The mathematical model of FMOLP based on Paksoy et al. (2013) can be written as follows:

$$\max \; Z_1(x) = c_1 x \tag{5.2.1}$$

$$\max Z_2(x) = c_2 x \tag{5.2.2}$$

$$\vdots$$

$$\max Z_k(x) = c_k x \tag{5.2.3}$$

Subject to:

$$\tilde{A}x \le \tilde{b} \tag{5.2.4}$$

$$x \ge 0 \tag{5.2.5}$$

where x is an n-dimensional vector of decision variables, $Z_k(x)$ denotes the kth objective function, c_k is the kth n-dimensional cost factor vector, $\tilde{A}$ is an $m \times n$ constraint matrix, $\tilde{b}$ is an m-dimensional constant fuzzy vector.

The membership functions of the fuzzy matrix $\tilde{A}$ and the vector $\tilde{b}$ are given below:

$$\mu_{\tilde{A}}(x) = \begin{cases} 1, & x \le a_{ij} \\ \frac{a_{ij} + d_{ij} - x}{d_{ij}}, & a_{ij} \le x \le a_{ij} + d_{ij} \\ 0 & x \ge a_{ij} + d_{ij} \end{cases} \tag{5.2.6}$$

$$\mu_{\tilde{b}}(x) = \begin{cases} 1, & x \le b_i \\ \frac{b_i + p_i - x}{p_i}, & b_i \le x \le b_i + p_i \\ 0 & x \ge b_i + p_i \end{cases} \tag{5.2.7}$$

where $x \in R$ and $d_{ij} > 0$, $p_i > 0$ (tolerance levels) for $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$.

Fuzzy multi-objective programming approaches can be classified as follows:

- The Max-Min Approach by Zimmermann (1978)
- The Interactive Fuzzy Multi-Objective Approach by Sakawa and Nishizaki (2002)
- The Fuzzy Multi-Objective Approach by Ling and Cheng (2009).

In this chapter, due to its simplicity, we adopt the approach proposed by Sakawa and Nishizaki (2002) to overcome the fuzziness of objective functions.

5.2.1 The Interactive Fuzzy Multi-objective Approach

The approach by Zimmermann (1978) assumes that each fuzzy objective is optimized by only one DM. However, in real life, there may be multiple DMs and the relative hierarchy between each pair of DMs may differ. Herewith a "Top Level" DM is specified as a DM that has the priority on the decisions taken, whereas "Lower Level" DMs are those that influence the decisions with a limited importance. For instance, the CEO (or the manager) in a company who receives a service is a "Top Level" DM, whereas the managers (or the supervisors) of the serving company are considered as the "lower level" DMs. Furthermore, each objective function has its own satisfaction level and the top-level DM can have an effect on the objectives of the lower-level DMs to satisfy the top-level objective.

If it is assumed that the top-level DM (Z_0) and the lower-level DMs $(Z_1, Z_2, \ldots, Z_k)$ aim at minimizing their objectives simultaneously, then the multi-objective linear programming model can be written as follows:

$$\min Z_0(x) = \sum_{i=1}^{k} c_i x_i \quad \text{(Top level DM's objective function)} \tag{5.2.8}$$

$$\min Z_1(x) = c_1 x_1 \quad \text{(Lower level DM 1's objective function)} \tag{5.2.9}$$

$$\min Z_2(x) = c_2 x_2 \quad \text{(Lower level DM 2's objective function)} \tag{5.2.10}$$

$$\vdots$$

$$\min Z_k(x) = c_k x_k \quad \text{(Lower level DM k's objective function)} \tag{5.2.11}$$

Subject to:

$$A_i x_i \le b_i, \quad i = 1, 2, \ldots, k \tag{5.2.12}$$

$$x_i \ge 0, \quad i = 1, 2, \ldots, k \tag{5.2.13}$$

The mathematical model given above may have either only maximization objectives or only minimization objectives. Nevertheless, maximization objectives and minimization objectives can be written together in the same mathematical model. Sakawa and Nishizaki (2002) assumed that each objective function must be fuzzy due to the uncertainties caused by environmental effects. Primarily, independent solutions of each objective function are calculated to find the lower-bound $\left(Z_k^L\right)$ and the upper-bound $\left(Z_k^u\right)$. Afterwards, the membership functions $\mu_0(Z_0(x))$, $\mu_1(Z_1(x))$, …, $\mu_k(Z_k(x))$ of each objective function (maximization or minimization) are determined as follows:

$$\mu_i(x) = \begin{cases} 1, & Z_i(x) \le Z_i^L \\ \frac{Z_i^U - Z_i(x)}{Z_i^U - Z_i^L}, & Z_i^L \le Z_i(x) \le Z_i^U \\ 0, & Z_i(x) \ge Z_i^U \end{cases} \quad \text{for all } i, \text{ for min} \tag{5.2.14}$$

$$\mu_i(x) = \begin{cases} 1, & Z_i(x) \ge Z_i^U \\ \frac{Z_i(x) - Z_i^L}{Z_i^U - Z_i^L}, & Z_i^L \le Z_i(x) \le Z_i^U \\ 0, & Z_i(x) \le Z_i^L \end{cases} \quad \text{for all } i, \quad \text{for max} \tag{5.2.15}$$

$$\max \mu_0(Z_0(x)) \quad \text{(Top level DM)} \tag{5.2.16}$$

$$\max \mu_1(Z_1(x)) \quad \text{(Lower level DM 1)} \tag{5.2.17}$$

$$\max \mu_2(Z_2(x)) \quad \text{(Lower level DM 2)} \tag{5.2.18}$$

$$\vdots$$

$$\max \mu_k(Z_k(x)) \quad \text{(Lower level DM k)} \tag{5.2.19}$$

Subject to:

$$A_i x_i \le b_i, \quad i = 1, 2, \ldots, k \tag{5.2.20}$$

$$x_i \ge 0, \quad i = 1, 2, \ldots, k \tag{5.2.21}$$

Since the basic aim is to maximize the minimum satisfaction levels of each DM, the mathematical model is rewritten as a single objective model as follows:

$$\alpha = \min\left\{\mu_0(Z_0(x)), \min_{i=1,2,\ldots,k}\mu_i(Z_i(x))\right\} \tag{5.2.22}$$

$$\max \alpha \tag{5.2.23}$$

Subject to:

$$Z_0(x) + \left(Z_0^U - Z_0^L\right)\alpha \le Z_0^U \quad (\text{Top level DM}) \tag{5.2.24}$$

$$Z_1(x) + \left(Z_1^U - Z_1^L\right)\alpha \le Z_1^U \quad (\text{Lower level DM } 1) \tag{5.2.25}$$

$$Z_2(x) + \left(Z_2^U - Z_2^L\right)\alpha \le Z_2^U \quad (\text{Lower level DM } 2) \tag{5.2.26}$$

$$\vdots$$

$$Z_k(x) + \left(Z_k^U - Z_k^L\right)\alpha \le Z_k^U \quad (\text{Lower level DM } k) \tag{5.2.27}$$

$$A_i x_i \le b_i, \quad i = 1, 2, \ldots, k \tag{5.2.28}$$

$$x_i \ge 0, \quad i = 1, 2, \ldots, k \tag{5.2.29}$$

$$0 \le \alpha \le 1 \tag{5.2.30}$$

The procedure completes if α, which maximizes the minimum satisfaction levels of each DM, reaches the top-level DM satisfaction level. Otherwise, the minimum satisfaction level for the top-level objective, $\widetilde{\delta}$, is determined.

$$\max \alpha \tag{5.2.31}$$

Subject to:

$$Z_0(x) \le Z_0^U - \widetilde{\delta}\left(Z_0^U - Z_0^L\right) \quad (\text{Top level DM}) \tag{5.2.32}$$

$$Z_1(x) + \left(Z_1^U - Z_1^L\right)\alpha \le Z_1^U \quad (\text{Lower level DM } 1) \tag{5.2.33}$$

$$Z_2(x) + \left(Z_2^U - Z_2^L\right)\alpha \le Z_2^U \quad (\text{Lower level DM } 2) \tag{5.2.34}$$

$$\vdots$$

$$Z_k(x) + \left(Z_k^U - Z_k^L\right)\alpha \le Z_k^U \quad (\text{Lower level DM } k) \tag{5.2.35}$$

$$A_i x_i \le b_i, \quad i = 1, 2, \ldots, k \tag{5.2.36}$$

$$x_i \geq 0, \quad i = 1, 2, \ldots, k \tag{5.2.37}$$

$$0 \leq \alpha, \tilde{\delta} \leq 1 \tag{5.2.38}$$

The latest version of the mathematical model is expected to report a value that is greater than or equal to the satisfaction level of the top-level DM $(\tilde{\delta})$. On the other hand, it is possible to recognize the differences between the satisfaction levels of lower-level DMs (α) and the satisfaction level of the top-level DM $(\tilde{\delta})$. This is not conforming to the approach by Sakawa and Nishizaki (2002), and therefore the equation below should be used to overcome this problem.

$$\Delta = \frac{\min_{i=1,2,\ldots,k} \mu_i(Z_i(x))}{\mu_0(Z_0(x))} \tag{5.2.39}$$

The value of Δ is expected to be between Δ_L (the lower bound) and Δ_U (the upper bound). If $\Delta > \Delta_U$, $\tilde{\delta}$ is increased and Δ is revised by the top-level DM. Otherwise, if $\Delta < \Delta_L$, $\tilde{\delta}$ is decreased and Δ is revised. Then, we expect the following conditions are met:

1. The satisfaction level of the top-level DM is greater than or equal to the revised satisfaction level $\tilde{\delta}$, $\mu_0(Z_0(x)) \geq \tilde{\delta}$.
2. The proportion of the minimum satisfaction level of a lower-level DM to that of the top level DM (Δ) is between $[\Delta_L, \Delta_U]$.

The first condition is a necessity according to Sakawa and Nishizaki (2002). However, the second one is necessary only if the aim is to balance the satisfaction levels between hierarchical levels. At the first step of the approach by Sakawa and Nishizaki (2002), one expects to maximize the minimum satisfaction levels of lower-level DMs (α) simultaneously. Next, the proportion of the satisfaction level of the top-level DM to that of each lower level DM is calculated and analyzed as follows:

$$\Delta_j = \frac{\mu_j(Z_j(x))}{\mu_0(Z_0(x))}, \quad j = 1, 2, \ldots, k \tag{5.2.40}$$

If Δ_j, the proportion of the satisfaction level of the jth lower-level DM, is greater than Δ_U, which is originally decided by the top-level DM, the satisfaction level of the lower-level DM is revised using the new satisfaction level $\tilde{\delta}$ and the mathematical model is modified as follows:

$$\max \alpha \tag{5.2.41}$$

Subject to:

$$Z_0(x) \le Z_0^U - \widetilde{\delta}\left(Z_0^U - Z_0^L\right) \quad \text{(Top level DM)} \tag{5.2.42}$$

$$Z_j(x) \ge Z_j^U - \widetilde{\delta}\left(Z_j^U - Z_j^L\right), \quad (j \in J) \tag{5.2.43}$$

$$Z_1(x) + \left(Z_1^U - Z_1^L\right)\alpha \le Z_1^U \quad \text{(Lower level DM 1)} \tag{5.2.44}$$

$$\vdots$$

$$Z_k(x) + \left(Z_k^U - Z_k^L\right)\alpha \le Z_k^U \quad \text{(Lower level DM } k\text{)} \tag{5.2.45}$$

$$A_i x_i \le b_i, \quad i = 1, 2, \ldots, k \tag{5.2.46}$$

$$x_i \ge 0, \quad i = 1, 2, \ldots, k \tag{5.2.47}$$

$$0 \le \alpha, \widetilde{\delta}, \quad \overline{\delta} \le 1 \tag{5.2.48}$$

The revised satisfaction level of the lower-level DM $(\widetilde{\delta})$ is determined by the equation below, where $\widetilde{\delta}$ is the satisfaction level of the top-level DM and Δ_U is the upper bound of the proportion of the minimum satisfaction level of the lower-level DM.

$$\overline{\delta} = \widetilde{\delta} \times \Delta_U \tag{5.2.49}$$

If the revised satisfaction level of the lower-level DM $\widetilde{\delta}$ is between Δ_L and Δ_U, the iteration ends. Otherwise, is revised until its value falls within Δ_L and Δ_U.

5.3 The Experimental Study

We investigate the problem of locating the transfer centers and landfilling areas in the European side of Istanbul, which contains around 65 % of the city's total population. First, we provide a mathematical model and its fuzzy version; then, we present the experimental results along with a sensitivity analysis.

5.3.1 Mathematical Model

In the formulation, we purposely represent different types of wastes with different notations (for the sake of simplicity) and do not use extra subscripts since each type of waste is exposed to a different type of process.

Indices and Parameters

i	indice of city centers,
j	indice of transfer centers,
r	indice of recycling centers,
s	indice of disposal centers,
l	indice of land filling centers,
t	indice of products,
I	set of city centers, $i = 1, 2, \ldots, I$
J	set of transfer centers, $j = 1, 2, \ldots, J$
R	set of recycling centers, $r = 1, 2, \ldots, R$
S	set of disposal centers, $s = 1, 2, \ldots, S$
L	set of land filling centers, $l = 1, 2, \ldots, L$
T	set of products, $t = 1, 2, \ldots, T$
PL	maximum allowable population at the populated (city) center,
Rv	revenue from selling recycled waste (type 1 only) in \$/ton,
CT	transportation cost from city centers to transfer centers in \$/km,
TR	transportation cost from transfer centers to recycling centers in \$/km,
TS	transportation cost from transfer centers to disposal centers in \$/km,
TL	transportation cost from transfer centers to land filling areas in \$/km,
RS	transportation cost from recycling centers to disposal centers in \$/km,
RL	transportation cost from recycling centers to land filling areas in \$/km,
SL	transportation cost from disposal centers to land filling areas in \$/km,
tf_j	fixed cost of locating a transfer center at location j in \$,
lf_l	fixed cost of locating a land filling area at location l in \$,
tpr	annual processing cost at transfer centers in \$/ton,
rpr	annual processing cost at recycling centers in \$/ton,
spr	annual processing cost at disposal centers in \$/ton,
lpr	annual processing cost at land filling areas in \$/ton,
d_{ij}	distance from city center i to transfer center j in km,
d_{jr}	distance from transfer center j to recycling center r in km,
d_{js}	distance from transfer center j to disposal center s in km,
d_{jl}	distance from transfer center j to land filling area l in km,
d_{rs}	distance from recycling center r to disposal center s in km,
d_{rl}	distance from recycling center r to land filling area l in km,
d_{sl}	distance from disposal center s to land filling area l in km,
ect_{ij}	Euclidean distance from collecting center i to transfer center j in km,
ecr_{ir}	Euclidean distance from collecting center i to recycling center r in km,
ecs_{is}	Euclidean distance from collecting center i to disposal center s in km,
ecl_{il}	Euclidean distance from collecting center i to land filling area l in km,
p_i	population in city center i,
π_j	pollution factor for transfer center j in km^2/ton,
π_r	pollution factor for recycling center r in km^2/ton,
π_s	pollution factor for disposal center s in km^2/ton,
π_l	pollution factor for land filling area l in km^2/ton,

$Tcap_j$ capacity of transfer center j in ton,
$Rcap_r$ capacity of recycling center r in ton,
$Scap_s$ capacity of disposal center s in ton,
$Lcap_l$ capacity of land filling area l in ton,
a_1 recyclable percentage of waste type 1,
a_2 recyclable percentage of waste type 1 sent to disposal centers from recycling centers,
b percentage of ash remained after the disposal process,
$wt1_i$ amount of waste type 1 occurred in city center i in ton,
$wt2_i$ amount of waste type 2 occurred in city center i in ton,
$wt3_i$ amount of waste type 3 occurred in city center i in ton,
β weights on pollution and cost,

Decision variables

xct_{ij} amount of waste type 1 collected in transfer center j from city center i,
xtr_{jr} amount of waste type 1 sent from transfer center j to recycling center r,
xrs_{rs} amount of waste type 1 sent from recycling center r to disposal center s,
xrl_{rl} amount of waste type 1 sent from recycling center r to land filling area l,
xsl_{sl} amount of waste type 1 sent from disposal center s to land filling area l,
xre_r amount of waste type 1 sold after recycling process in ton,
wct_{ij} amount of waste type 2 collected in transfer center j from city center i,
wts_{js} amount of waste type 2 sent from transfer center j to disposal center s,
wsl_{sl} amount of waste type 2 sent from disposal center s to land filling area l,
θct_{ij} amount of waste type 3 collected in transfer center j from city center i,
θtl_{jl} amount of waste type 3 sent from transfer center j to land filling area l,
y_j equals 1 if the transfer center is established at location j; 0, otherwise,
z_l equals 1 if the land filling area is established at location l; 0, otherwise,
o_c objective function for cost minimization,
o_p objective function for pollution minimization.

$$\min \beta o_c + (1-\beta) o_p \tag{5.3.1}$$

$$\begin{aligned}
o_c = {} & \sum_{j=1}^{J} tf_j y_j + \sum_{l=1}^{L} lf_l z_l + \sum_{i=1}^{I}\sum_{j=1}^{J}\left[\left(CT \cdot d_{ij} + tpr\right)\left(xct_{ij} + wct_{ij} + \theta ct_{ij}\right)\right] \\
& + \sum_{j=1}^{J}\sum_{r=1}^{R}\left[\left(TR \cdot d_{jr} + rpr\right) xtr_{jr}\right] + \sum_{r=1}^{R}\sum_{s=1}^{S}\left[\left(RS \cdot d_{rs} + spr\right) xrs_{rs}\right] \\
& + \sum_{r=1}^{R}\sum_{l=1}^{L}\left[\left(RL \cdot d_{rl} + lpr\right) xrl_{rl}\right] + \sum_{s=1}^{S}\sum_{l=1}^{L}\left[\left(SL \cdot d_{sl} + lpr\right) xsl_{sl}\right] \\
& + \sum_{j=1}^{J}\sum_{s=1}^{S}\left[\left(TS \cdot d_{js} + spr\right) wts_{js}\right] + \sum_{s=1}^{S}\sum_{l=1}^{L}\left[\left(SL \cdot d_{sl} + lpr\right) wsl_{sl}\right] \\
& + \sum_{j=1}^{J}\sum_{l=1}^{L}\left[\left(TL \cdot d_{jl}\right) \theta tl_{jl}\right] - \sum_{r=1}^{R} Rv \cdot xre_r
\end{aligned} \tag{5.3.2}$$

$$o_p = \sum_{i=1}^{I} p_i \left[\sum_{j=1}^{J} \left(\frac{\pi_j \left(\sum_i xct_{ij} + wct_{ij} + \theta ct_{ij} \right)}{e_{ij}^2} \right) + \sum_{r=1}^{R} \left(\frac{\pi_r \left(\sum_j xtr_{jr} \right)}{e_{ir}^2} \right) \right.$$
$$+ \sum_{s=1}^{S} \left(\frac{\pi_s \left(\sum_r xrs_{rs} + \sum_j wts_{js} \right)}{e_{is}^2} \right) \tag{5.3.3}$$
$$\left. + \sum_{l=1}^{L} \left(\frac{\pi_l \left(\sum_r xrl_{rl} + \sum_s (xsl_{sl} + wsl_{sl}) + \sum_j \theta tl_{jl} \right)}{e_{il}^2} \right) \right]$$

Subject to:

$$\sum_{j=1}^{J} \left(\frac{\pi_j \left(\sum_i xct_{ij} + wct_{ij} + \theta ct_{ij} \right)}{e_{ij}^2} \right) + \sum_{r=1}^{R} \left(\frac{\pi_r \left(\sum_j xtr_{jr} \right)}{e_{ir}^2} \right)$$
$$+ \sum_{s=1}^{S} \left(\frac{\pi_s \left(\sum_r xrs_{rs} + \sum_j wts_{js} \right)}{e_{is}^2} \right) \tag{5.3.4}$$
$$+ \sum_{l=1}^{L} \left(\frac{\pi_l \left(\sum_r xrl_{rl} + \sum_s (xsl_{sl} + wsl_{sl}) + \sum_j \theta tl_{jl} \right)}{e_{il}^2} \right) \le PL, \quad \forall i \in I,$$

$$\sum_i \sum_j \left(xct_{ij} + wct_{ij} + \theta ct_{ij} \right) \le Tcap_j \cdot y_j, \quad \forall j \in J, \tag{5.3.5}$$

$$\sum_j xtr_{jr} \le Rcap_r, \quad \forall r \in R, \tag{5.3.6}$$

$$\sum_r xrl_{rl} + \sum_s (xsl_{sl} + wsl_{sl}) + \sum_j \theta tl_{jl} \le Lcap_l \cdot z_l, \quad \forall l \in L, \tag{5.3.7}$$

$$\sum_r xrs_{rs} + \sum_j wts_{js} \le Scap_s, \quad \forall s \in S, \tag{5.3.8}$$

$$\sum_i xct_{ij} - \sum_r xtr_{jr} = 0, \quad \forall j \in J, \tag{5.3.9}$$

$$a_1 \sum_j xtr_{jr} - xre_r = 0, \quad \forall r \in R, \tag{5.3.10}$$

$$a_2 \sum_j xtr_{jr} - \sum_s xrs_{rs} = 0, \quad \forall r \in R, \tag{5.3.11}$$

$$(1 - a_1 - a_2)\sum_j xtr_{jr} - \sum_l xrl_{rl} = 0, \quad \forall r \in R, \tag{5.3.12}$$

$$b\sum_r xrs_{rs} - \sum_l xsl_{sl} = 0, \quad \forall s \in S, \tag{5.3.13}$$

$$\sum_i wct_{ij} - \sum_s wts_{js} = 0, \quad \forall j \in J, \tag{5.3.14}$$

$$b\sum_j wts_{js} - \sum_l wsl_{sl} = 0, \quad \forall s \in S, \tag{5.3.15}$$

$$\sum_i \theta ct_{ij} - \sum_l \theta tl_{jl} = 0, \quad \forall j \in J, \tag{5.3.16}$$

$$\sum_j xct_{ij} \geq wt1_i, \quad \forall i \in I, \tag{5.3.17}$$

$$\sum_j wct_{ij} \geq wt2_i, \quad \forall i \in I, \tag{5.3.18}$$

$$\sum_j \theta ct_{ij} \geq wt3_i, \quad \forall i \in I, \tag{5.3.19}$$

$$\begin{gathered} o_c, o_p, xct_{ij}, xtr_{jr}, xrs_{rs}, xrl_{rl}, xsl_{sl}, xre_r, wct_{ij}, wts_{js}, wsl_{sl}, \theta ct_{ij}, \theta tl_{jl} \geq 0, \\ \forall i \in I, j \in J, r \in R, s \in S, \\ l \in L, \end{gathered} \tag{5.3.20}$$

$$y_j, z_l \in \{0, 1\}, \quad \forall i \in I, \;\; j \in J, \tag{5.3.21}$$

Equation (5.3.1) presents the total cost and total pollution. The costs in Eq. (5.3.2) encompass:

- fixed cost of locating new transfer centers and land filling areas (note that for already existing facilities, these values are taken as 0),
- transportation costs of waste types 1, 2 and 3 from city centers to transfer centers and processing costs at transfer centers,
- transportation costs of waste type 1 from transfer centers to recycling centers and processing costs at recycling centers,
- transportation costs of waste type 1 from recycling centers to disposal centers and processing costs at disposal centers,
- transportation costs of waste type 1 from recycling centers to land filling areas and processing costs at land filling areas,
- transportation costs of waste type 1 from disposal centers to land filling areas and processing costs at land filling areas,

- transportation costs of waste type 2 from transfer centers to disposal centers and processing costs at disposal centers,
- transportation costs of waste type 2 from disposal centers to land filling areas and processing costs at land filling areas,
- transportation costs of waste type 3 from transfer centers to land filling areas and processing costs at land filling areas,
- income gathered from recycled waste type 1.

Equation (5.3.3) involves the calculation of

- pollution released from transfer centers to the populated areas (for waste types 1, 2, and 3),
- pollution released from recycling centers to the populated areas (for waste type 1),
- pollution released from disposal centers to the populated areas (for waste types 1 and 2),
- pollution released from land filling areas to the populated areas (for waste types 1, 2, and 3).

Constraints in (5.3.4) force an upper bound by which a populated area can be affected. Constraints in (5.3.5) through (5.3.8) are capacity constraints for transfer centers, recycling centers, land filling areas, and disposal centers, respectively. Note that variables that are related to opening decisions are taken as "1" for already existing centers. Constraints in (5.3.9)–(5.3.13) provide the flow conservation of waste type 1 for transfer, recycling and disposal centers. Constraints (5.3.14) and (5.3.14) provide the flow conservation waste type 2 for transfer and disposal centers.

Constraints in (5.3.6) provide the flow conservation of waste type 3 for transfer centers. Constraints in (5.3.17)–(5.3.19) ensure that waste occurred in city centers are completely collected for waste types 1, 2, and 3, respectively. Constraints in (5.3.20) and (5.3.21) are integrality constraints.

5.3.2 Data Acquisition

The related data are provided in Tables 5.1, 5.2, 5.3, 5.4, 5.5, 5.6 and 5.7. Note that some values are gathered from Eiselt and Marianov (2014) if applicable; otherwise, they are gathered from ISTAC (2015) or experimentally developed.

tf_j takes the values of 100,000 for $j = 5, 6, 7, 8$ and 0 for j = 1, 2, 3, 4 since transfer centers 1, 2, 3, and 4 are already established. Similarly, lf_l is taken as 0 for the existing land filling area 1 and 300,000 for $l = 2, 3, 4$. Two types of distances are used in the model. Manhattan distances, gathered from Google maps, are used

Table 5.1 Values of sets and parameters

I = 24	Rv = 6.57	RL = 0.4287	rpr = 30	π_s = 0.025, s = 1,…, S
J = 8	CT = 1.258	SL = 0.4287	spr = 21	π_l = 0.025, l = 1,…, L
R = 1	TR = 0.4287	PL = 10,000	lpr = 6	
S = 1	TS = 0.4287	a_1 = 0.2	tpr = 20	
L = 4	TL = 0.4287	a_2 = 0.4	π_j = 0.025, j = 1,…, J	
T = 3	RS = 0.4287	b = 0.4	π_r = 0.025, r = 1,…, R	

Table 5.2 Real (road) distances between city centers and transfer centers

d_{ij}	1	2	3	4	5	6	7	8
1	33.8	17.8	14.5	44.2	54.1	31.9	45.9	18.0
2	19.8	7.1	8.6	58.1	38.2	14.8	59.5	28.8
3	18.4	2.6	10.1	55.0	42.9	18.7	58.7	36.1
4	21.3	5.1	13.3	55.3	43.6	25.2	59.0	37.1
5	22.7	11.7	10.5	56.5	42.9	16.6	55.1	27.2
6	12.1	17.6	19.6	65.5	34.5	16.8	63.8	35.9
7	9.3	22.4	29.9	75.5	31.3	26.7	74.1	46.2
8	38.5	22.6	22.1	37.7	57.8	41.0	41.4	17.9
9	2.5	18.4	25.7	70.3	29.5	27.5	70.8	42.9
10	48.0	31.0	31.6	22.3	61.8	55.4	36.7	24.3
11	57.4	46.6	38.3	22.5	47.7	42.3	13.3	19.1
12	15.6	15.0	15.2	59.8	32.5	12.5	60.4	32.5
13	33.3	22.5	14.2	36.9	50.5	30.9	45.0	13.2
14	6.6	14.8	21.2	66.5	9.7	20.1	66.5	37.1
15	7.7	12.0	20.2	63.8	31.8	20.7	64.0	40.0
16	9.3	19.5	19.9	66.8	28.3	13.6	64.1	37.9
17	13.6	7.3	16.8	59.3	39.1	20.9	63.0	39.7
18	5.7	19.8	26.9	73.8	24.5	23.3	71.1	43.6
19	24.1	6.2	4.8	57.1	45.8	20.2	57.1	29.2
20	27.1	44.7	44.1	89.4	35.6	32.9	79.2	60.2
21	71.3	55.4	54.8	5.9	90.5	70.9	22.4	36.5
22	18.0	19.6	19.7	64.4	36.9	9.0	60.7	35.1
23	5.0	18.8	26.3	70.0	28.7	27.1	70.4	42.6
24	10.7	9.2	18.8	60.4	36.6	22.7	64.1	40.7

for waste transportation from one point to another. Euclidean distances are used for the calculation of pollution as stated in Eiselt and Marianov (2014). The data on distances are provided in Tables 5.2, 5.3, 5.4, 5.5 and 5.6.

We should also note that the distance between the recycling center and the disposal center, d_{rs}, is 7.5 km.

Capacities of the existing centers (in tons/year) are also obtained from ISTAC (2015) (transfer center 1:900,000, transfer center 2:1,000,000, transfer center

Table 5.3 Euclidean distances between city centers and transfer centers

e_{ij}	1	2	3	4	5	6	7	8
1	21.2	9.6	4.0	34.8	24.1	14.6	36.3	14.1
2	11.1	5.3	6.3	44.6	20.5	11.7	43.9	21.9
3	11.6	1.9	7.8	45.4	24.5	15.7	46.2	24.0
4	13.6	2.4	9.7	45.6	27.8	18.9	47.8	25.5
5	13.3	9.7	6.5	43.0	16.0	7.0	40.6	19.1
6	5.8	8.6	11.7	50.0	20.9	13.8	48.5	26.8
7	5.7	19.2	22.7	60.8	24.2	21.1	57.7	36.9
8	28.1	15.2	11.5	29.4	30.6	21.5	34.6	14.3
9	1.5	13.7	18.2	56.5	24.7	19.4	55.0	33.4
10	38.4	26.1	21.1	18.4	35.6	28.0	26.6	13.1
11	44.0	34.7	27.6	16.0	32.1	28.2	11.6	11.6
12	9.7	9.5	9.1	46.6	16.9	9.2	44.1	22.8
13	25.9	14.5	8.5	29.9	25.2	16.4	31.8	10.0
14	2.9	11.4	14.7	52.9	21.2	15.3	50.9	29.5
15	4.3	9.6	14.7	53.0	24.7	18.0	52.4	30.5
16	6.1	10.7	12.4	50.2	18.4	12.1	47.8	26.5
17	8.1	5.4	10.3	48.5	23.5	15.6	48.4	26.3
18	4.0	16.3	19.0	56.8	20.6	17.0	53.5	32.8
19	15.4	4.5	2.9	40.7	22.6	13.1	41.3	19.0
20	16.6	27.2	27.2	61.6	16.5	19.4	54.4	36.8
21	60.5	49.0	43.1	4.9	51.4	46.6	19.6	29.2
22	11.4	14.7	13.1	48.4	12.4	7.1	43.8	23.8
23	2.5	15.9	19.5	57.6	23.0	18.8	55.1	34.0
24	6.9	7.2	13.0	51.0	25.5	18.0	51.1	29.0

3:1,200,000) and capacities of the candidate locations for transfer centers are considered to be 1,500,000 tons/year; 3,832,500 tons/year for both the existing landfilling areas and the candidate landfilling areas. Capacities of the recycling and disposal centers are considered to be 1,000,000 and 1,450,000 tons/year, respectively.

Annual amount of waste for each populated district is calculated based on the data gathered from TUIK (2015). For instance, in Table 5.7, total waste for District 1 (Avcılar) is obtained as: (population of the district for year 2014) × (1 + annual population growth for Istanbul) × (daily average waste production per person) × (365 days/year) = 417,852 × 1.1638 × 365 ≅ 200,571.

Approximately, 23 % of the waste is considered as type 1, 12 % as type 2 and 65 % as type 3. Annual amount of waste for each district in Istanbul are provided in Table 5.7.

Table 5.4 Euclidean distances between city centers and recycling and disposal centers and land filling areas

	e_{ir}	e_{is}	e_{il}			
	1	1	1	2	3	4
1	23.1	25.4	23.4	14.6	36.3	14.1
2	19.8	20.8	18.5	11.7	43.9	21.9
3	23.8	24.9	22.5	15.7	46.2	24.0
4	27.1	28.2	25.9	18.9	47.8	25.5
5	15.3	16.7	14.4	7.0	40.6	19.1
6	20.4	20.6	18.3	13.8	48.5	26.8
7	24.1	22.8	21.0	21.1	57.7	36.9
8	29.6	32.1	30.3	21.5	34.6	14.3
9	24.4	23.8	21.7	19.4	55.0	33.4
10	34.7	37.7	36.3	28.0	26.6	13.1
11	31.3	34.5	34.0	28.2	11.6	11.6
12	16.3	17.0	14.7	9.2	44.1	22.8
13	24.3	26.9	25.2	16.4	31.8	10.0
14	20.8	20.6	18.4	15.3	50.9	29.5
15	24.3	24.3	22.0	18.0	52.4	30.5
16	18.0	18.0	15.8	12.1	47.8	26.5
17	22.9	23.5	21.2	15.6	48.4	26.3
18	20.5	19.5	17.5	17.0	53.5	32.8
19	21.8	23.4	21.2	13.1	41.3	19.0
20	17.0	14.3	13.7	19.4	54.4	36.8
21	50.6	53.8	53.2	46.6	19.6	29.2
22	11.9	12.1	9.8	7.1	43.8	23.8
23	22.8	21.9	19.9	18.8	55.1	34.0
24	25.0	25.3	23.0	18.0	51.1	29.0

Table 5.5 Real (road) distances between transfer centers and recycling and disposal centers and land filling areas

	d_{jr}	d_{js}	d_{jl}			
	1	1	1	2	3	4
1	29.2	28	24	25	68.3	40.4
2	41.4	41.7	37.7	21.6	56.4	31.8
3	43.7	44.5	40.5	21.6	54.7	26.9
4	79	86.9	83	67	24	31.8
5	3.4	5.5	6.8	24.1	51.1	40.9
6	27.4	28.1	24.1	0	51	27.6
7	55.1	55.9	57	56.2	0	31.6
8	45.3	46.2	50.9	33.4	29.9	0

Table 5.6 Real (road) distances between recycling and disposal centers

	l			
	1	2	3	4
r	7.1	24.4	55.1	45.3
s	7.7	25.2	55.8	46

Table 5.7 Annual amount of waste for districts

District	p	District	p
1	200,571.1	13	329,748.4
2	362,223.1	14	176,557.5
3	287,536.2	15	201,250
4	106,366.3	16	2,391,00.2
5	164,364.2	17	145,619.6
6	129,509.7	18	207,472.7
7	90,621.4	19	359,234.9
8	125,988.6	20	162,088.7
9	115,931	21	77,359.9
10	1,071,96.6	22	246,253.3
11	32,564.9	23	130,743.8
12	220,253.7	24	137,868.4

5.3.3 An Interactive Fuzzy Application in Multi-objective Programming

In this chapter, we have two objective functions to be minimized as shown in Eq. (5.3.1). Costs incurred in locating, processing and transporting are represented by o_c, and total pollution is represented by o_p. First, as shown in steps 2.8 through 2.13, each objective function is minimized independently to determine the lower-bounds $\left(o_c^L, o_p^L\right)$ and upper-bounds $\left(o_c^U, o_p^U\right)$. By independence, we mean the removal of one of the objective functions and then the optimization of the one left. In other words, setting $\beta = 1$ and $\beta = 0$, respectively, as shown in Eiselt and Marianov (2014). Note that o_p is considered as the objective of the top-level.

Optimizing independently, the following values in Table 5.8 are obtained.

At the next step, we determine the membership functions for each objective.

$$\mu_p(o_p) = \begin{cases} 1, & o_p \le 5,258,451,000 \\ \frac{45,024,600,000 - o_p}{45,024,600,000 - 5,258,451,000} & 5,258,451,000 \le o_p \le 45,024,600,000 \\ 0, & o_p \ge 45,024,600,000 \end{cases} \tag{5.3.22}$$

Table 5.8 Trade-off table

Time	o_c	o_p
min $o_c(\beta = 1)$	265,196,100	45,024,600,000
min $o_p(\beta = 0)$	554,561,100	5,258,451,000
Lower bounds	265,196,100	5,258,451,000
Upper Bounds	554,561,100	45,024,600,000

The mathematical model is coded in GAMS 23.5.1. BONMIN is selected as the solver and all problems are solved to the optimally.

$$\mu_c(o_c) = \begin{cases} 1, & o_c \leq 265,196,100 \\ \frac{554,561,100 - o_c}{554,561,100 - 265,196,100}, & 265,196,100 \leq o_c \leq 554,561,100 \\ 0, & o_c \geq 554,561,100 \end{cases} \quad (5.3.23)$$

After determining the membership functions, the satisfaction level (α) is included into the model and then the fuzzy multi-objective model is converted to the single objective mixed-integer problem. The formulation is provided below:

$$\max \alpha$$

Subject to:

$$\alpha \leq \mu_p(o_p) = \frac{45,024,600,000 - o_p}{45,024,600,000 - 5,258,451,000} \quad (5.3.24)$$

$$\alpha \leq \mu_c(o_c) = \frac{554,561,100 - o_c}{554,561,100 - 265,196,100}$$

and Eqs. (5.3.2) through (5.3.21)

$$0 \leq \alpha \leq 1$$

Solving (5.3.24) returns a value of 0.89 for the common satisfaction level (α) for all DMs; the satisfaction level for the top-level DM $(\mu_p(o_p))$ and the one for the lower-level DM $(\mu_c(o_c))$ are both obtained as 0.89. Thus, the top-level DM and the lower-level DM is satisfied by the same percentage: 89 %.

If the top-level DM (the satisfaction level of pollution) is not pleased with the results and would like to reduce the total pollution in cities or set up centers farther from the populated districts, then a minimum satisfaction level $(\widetilde{\delta})$ for the top-level DM should be determined. Assuming that the DM wants the satisfaction level of pollution to be at least 95 %, the model is revised as follows:

$$\max \alpha$$

Subject to:

$$\widetilde{\delta} = 0.95 \leq \mu_p(o_p) = \frac{45,024,600,000 - o_p}{45,024,600,000 - 5,258,451,000} \quad (5.3.25)$$

$$\alpha \leq \mu_c(o_c) = \frac{554,561,100 - o_c}{554,561,100 - 265,196,100}$$

and Eqs. (5.3.2) through (5.3.21)

Table 5.9 Experimental results for the revised model

	$0 \le \alpha \le 1$	$0 \le \alpha \le 1$ and $0.95 \le \tilde{\delta} \le 1$
α	0.89	0.801
$\tilde{\delta}$	–	0.95
$\mu_p(o_p)$	0.89	0.95
$\mu_c(o_c)$	0.89	0.801
o_p	9,645,223,000	7,246,758,000
o_c	297,117,200	322,802,600
y_j	1, 2, 3, 4, 6, 8	1, 2, 3, 4, 5, 6
z_l	1, 3	1, 3

$$0 \le \alpha, \quad \tilde{\delta} \le 1$$

Based on the results attained from (5.3.25), the new satisfaction levels are determined as $\mu_p(o_p) = 0.95$, $\mu_c(o_c) = 0.801$, and $\alpha = 0.801$. The satisfaction level for pollution is increased to the desired level. However, the satisfaction level for cost is decreased about 9 %. Details on the satisfaction levels and the objective functions are presented in Table 5.9.

Even though the number of new centers to open does not change in either cases, the objective function values differ and the satisfaction level of pollution increases.

Further, we conduct a sensitivity analysis in terms of objective functions (o_p, o_c). Corresponding results are presented in Fig. 5.1 and Table 5.10.

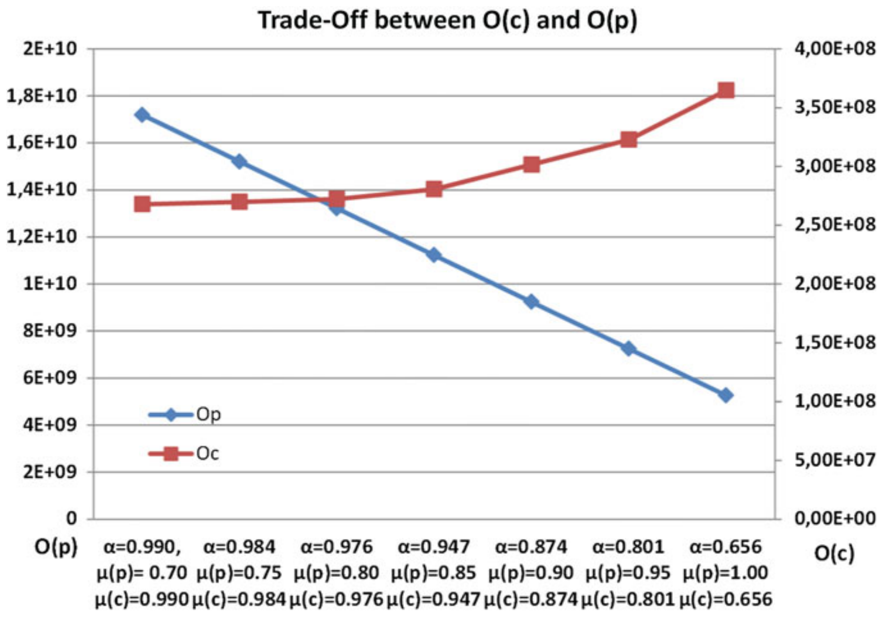

Fig. 5.1 Tradeoff between pollution and cost

Table 5.10 Decisions for different satisfaction levels

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
	α = 0.990, μ(p) = 0.70 μ(c) = 0.990	α = 0.984 μ(p) = 0.75 μ(c) = 0.984	α = 0.976 μ(p) = 0.80 μ(c) = 0.976	α = 0.947 μ(p) = 0.85 μ(c) = 0.947	α = 0.874 μ(p) = 0.90 μ(c) = 0.874	α = 0.801 μ(p) = 0.95 μ(c) = 0.801	α = 0.656 μ(p) = 1.00 μ(c) = 0.656
y	1, 2, 3, 4, 5, 6	1, 2, 3, 4, 6, 8	1, 2, 3, 4, 6, 8	1, 2, 3, 4, 6, 8	1, 2, 3, 4, 6, 8	1, 2, 3, 4, 5, 6	1, 2, 3, 4, 5, 6
z	1, 2	1, 4	1, 4	1, 4	1, 3	1, 3	1, 3

In Table 5.10, decisions on opening transfer centers and land filling areas for different satisfaction levels of pollution and costs are presented. For instance, in case 1, where $\alpha = 0.990$, $\mu(p) = 0.70$ and $\mu(c) = 0.990$, transfer centers 1, 2, 3, and 4 are already existing and candidates 5 and 6 are both decided to be opened. Furthermore, besides existing land filling area 1, land filling area 2 is also decided to be established.

5.4 Conclusion

This chapter proposes a mathematical model that, along with the minimization of cost regarding facility establishing, transportation, and processing, considers a second objective which minimizes the pollution that affects populated districts. While the model minimizes the total cost and pollution, it also determines the optimal locations for transfer centers and land filling areas.

Establishing transfer centers at different locations includes a tradeoff between the total cost and pollution (see Fig. 5.1 and Table 5.10). For instance, decreasing the pollution (in terms of satisfaction level for pollution) that affects the populated areas increases the costs. However, results indicate that this cost is reasonable.

Locating two or more transfer centers in addition to the existing centers (1, 2, 3, and 4) and one more land filling area seems satisfactory to manage solid waste in Istanbul. Locations of possible transfer centers or land filling areas play an important role on minimizing pollution. Establishing a land filling area at location 3 instead of location 2 (Case 1 vs. Case 3 as shown in Table 5.10), decreases the amount of pollution by 69 % while the cost increases only by 27 %.

Fuzzy approach helps managers in taking decisions more easily under uncertain environments. As applied in this chapter, the satisfaction level of different types of objective functions is held with fuzzy approach. The most important contribution of the proposed model lies within the combination of pollution alongside the transportation routes. Treating pollution level as a fuzzy variable also provides a contribution to the related literature.

Adapting different types of fuzzy-multi objective approaches (e.g., Zimmermann's or Cheng's multi-objective approaches) to similar cases might form one of many possible avenues for future research. Sensitivity analysis may also be enhanced; satisfaction levels may be revised for different sensitivity analyses or sensitivity analyses may be adapted to different subjects (capacities, costs, etc.). Furthermore, top-level decision relies on expert opinion and it may change in different cases subjectively (cost minimization may also be a top-level decision). On the other hand, besides location decisions, the process of municipal waste can also be analyzed as stated in Srivastava and Nema (2012). They considered the amount of waste to be fuzzy and then employed a fuzzy parametric programming model within a multi-objective problem. Merging both techniques (the one proposed and fuzzy parametric programming) may widen the range of current application areas in the related literature.

References

Aydin, N. (2007). *A fuzzy linear programming approach for optimal planning in solid waste management* (M.Sc. Thesis). Yildiz Technical University.

Aydin, N., & Murat, A. (2013). A swarm intelligence based sample average approximation algorithm for the capacitated reliable facility location problem. *International Journal of Production Economics, 145*(1), 173–183.

Ayvaz, B., Bolat, B., & Aydın, N. (2015). Stochastic reverse logistics network design for waste of electrical and electronic equipment. *Resources, Conservation and Recycling, 104*, 391–404.

Bellman, R. E., & Zadeh, L. A. (1970). Decision-making in a fuzzy environment. *Management science, 17*(4), B-141.

Beskese, A., Demir, H. H., Ozcan, H. K., & Okten, H. E. (2015). Landfill site selection using fuzzy AHP and fuzzy TOPSIS: A case study for Istanbul. *Environmental Earth Sciences, 73*(7), 3513–3521.

Bing, X., Bloemhof, J. M., Ramos, T. R. P., Barbosa-Povoa, A. P., Wong, C. Y., & van der Vorst, J. G. (2016). Research challenges in municipal solid waste logistics management. *Waste Management, 48*, 584–592.

Chang, N. B., Chen, Y. L., & Wang, S. F. (1997). A fuzzy interval multiobjective mixed integer programming approach for the optimal planning of solid waste management systems. *Fuzzy Sets and Systems, 89*(1), 35–60.

Chang, N. B., & Wang, S. F. (1997). A fuzzy goal programming approach for the optimal planning of metropolitan solid waste management systems. *European Journal of Operational Research, 99*(2), 303–321.

Christian, H., & Macwan, J. E. M. (2016). Fuzzy ranking for landfill site selection in Indian context. *International Journal, 11*(26), 2576–2580.

Cohon, J. L. (1978). *Multiobjective programming and planning*. New York: Academic Press.

Eiselt, H. A., & Marianov, V. (2014). A bi-objective model for the location of landfills for municipal solid waste. *European Journal of Operational Research, 235*(1), 187–194.

Eiselt, H. A., & Marianov, V. (2015). Location modeling for municipal solid waste facilities. *Computers & Operations Research, 62*, 305–315.

Ekmekçioğlu, M., Kaya, T., & Kahraman, C. (2010). Fuzzy multicriteria disposal method and site selection for municipal solid waste. *Waste Management, 30*(8), 1729–1736.

Erkut, E., & Neuman, S. (1989). Analytical models for locating undesirable facilities. *European Journal of Operational Research, 40*(3), 275–291.

Fernández, J., Fernández, P., & Pelegrın, B. (2000). A continuous location model for siting a non-noxious undesirable facility within a geographical region. *European Journal of Operational Research, 121*(2), 259–274.

Ferretti, V. (2011). A multicriteria spatial decision support system development for siting a landfill in the province of Torino (Italy). *Journal of Multi-Criteria Decision Analysis, 18*(5–6), 231–252.

Grazhdani, D. (2015). Assessing the variables affecting on the rate of solid waste generation and recycling: An empirical analysis in Prespa Park. *Waste Management, 48*, 3–13.

Hintz, G. W., & Zimmermann, H. J. (1989). A method to control flexible manufacturing systems. *European Journal of Operational Research, 41*(3), 321–334.

Huang, G. H., Baetz, B. W., & Patry, G. G. (1993). A grey fuzzy linear programming approach for municipal solid waste management planning under uncertainty. *Civil Engineering Systems, 10* (2), 123–146.

Huang, G. H., Sae-Lim, N., Liu, L., & Chen, Z. (2001). An interval-parameter fuzzy-stochastic programming approach for municipal solid waste management and planning. *Environmental Modeling and Assessment, 6*(4), 271–283.

ISTAC. (2015). www.istac.com.tr/. Last Accessed December 1, 2015.

Kara, C., & Doratli, N. (2012). Application of GIS/AHP in siting sanitary landfill: A case study in Northern Cyprus. *Waste Management and Research, 30*(9), 966–980.

Lebersorger, S., & Beigl, P. (2011). Municipal solid waste generation in municipalities: Quantifying impacts of household structure, commercial waste and domestic fuel. *Waste Management, 31*(9), 1907–1915.

Li, P., & Chen, B. (2011). FSILP: Fuzzy-stochastic-interval linear programming for supporting municipal solid waste management. *Journal of Environmental Management, 92*(4), 1198–1209.

Liu, H. C., You, J. X., Chen, Y. Z., & Fan, X. J. (2014). Site selection in municipal solid waste management with extended VIKOR method under fuzzy environment. *Environmental Earth Sciences, 72*(10), 4179–4189.

Lu, H. W., Huang, G. H., Xu, Y., & He, L. (2012). Inexact two-phase fuzzy programming and its application to municipal solid waste management. *Engineering Applications of Artificial Intelligence, 25*(8), 1529–1536.

Melachrinoudis, E. (2011). The location of undesirable facilities. *Foundations of location analysis* (pp. 207–239). Berlin: Springer.

Melikoglu, M. (2013). Vision 2023: Assessing the feasibility of electricity and biogas production from municipal solid waste in Turkey. *Renewable and Sustainable Energy Reviews, 19*, 52–63.

Mir, M. A., Ghazvinei, P. T., Sulaiman, N. M. N., Basri, N. E. A., Saheri, S., Mahmood, N. Z., et al. (2016). Application of TOPSIS and VIKOR improved versions in a multi criteria decision analysis to develop an optimized municipal solid waste management model. *Journal of environmental management, 166*, 109–115.

Moeinaddini, M., Khorasani, N., Danehkar, A., & Darvishsefat, A. A. (2010). Siting MSW landfill using weighted linear combination and analytical hierarchy process (AHP) methodology in GIS environment (case study: Karaj). *Waste Management, 30*(5), 912–920.

Nazari, A., Salarirad, M. M., & Bazzazi, A. A. (2012). Landfill site selection by decision-making tools based on fuzzy multi-attribute decision-making method. *Environmental Earth Sciences, 65*(6), 1631–1642.

Paksoy, T., Pehlivan, N. Y., & Ozceylan, E. (2013). Bulanık Küme Teorisi. *Nobel*, 180–194.

Purcell, M., & Magette, W. L. (2009). Prediction of household and commercial BMW generation according to socio-economic and other factors for the Dublin region. *Waste Management, 29* (4), 1237–1250.

Sakawa, M., & Nishizaki, I. (2002). Interactive fuzzy programming for decentralized two-level linear programming problems. *Fuzzy Sets and Systems, 125*(3), 301–315.

Simon, H. A. (1957). *Models of man; social and rational*. Hoboken: Wiley.

Srivastava, A. K., & Nema, A. K. (2012). Fuzzy parametric programming model for multi-objective integrated solid waste management under uncertainty. *Expert Systems with Applications, 39*(5), 4657–4678.

Sumathi, V. R., Natesan, U., & Sarkar, C. (2008). GIS-based approach for optimized siting of municipal solid waste landfill. *Waste Management, 28*(11), 2146–2160.

Tavares, G., Zsigraiová, Z., & Semiao, V. (2011). Multi-criteria GIS-based siting of an incineration plant for municipal solid waste. *Waste Management, 31*(9), 1960–1972.

Torabi-Kaveh, M., Babazadeh, R., Mohammadi, S. D., & Zaresefat, M. (2016). Landfill site selection using combination of GIS and fuzzy AHP, a case study: Iranshahr, Iran. *Waste Management & Research*, 0734242X16633777.

TUIK. (2015). www.tuik.gov.tr/PreTablo.do?alt_id=1027. Last Accessed December 31, 2015.

Wang, S., Huang, G. H., & Yang, B. T. (2012). An interval-valued fuzzy-stochastic programming approach and its application to municipal solid waste management. *Environmental Modelling and Software, 29*(1), 24–36.

Xu, Y., Huang, G., & Li, J. (2016). An enhanced fuzzy robust optimization model for regional solid waste management under uncertainty. *Engineering Optimization*, 1–18.

Yesilnacar, M. I., Süzen, M. L., Kaya, B. S., & Doyuran, V. (2012). Municipal solid waste landfill site selection for the city of Şanliurfa-Turkey: An example using MCDA integrated with GIS. *International Journal of Digital Earth, 5*(2), 147–164.

Zimmermann, H. J. (1975). Description and optimization of fuzzy systems. *International Journal of General System, 2*(1), 209–215.

Zimmermann, H. J. (1978). Fuzzy programming and linear programming with several objective functions. *Fuzzy Sets and Systems, 1*(1), 45–55.

Part II
Disaster Response Management

Chapter 6
Application of Fuzzy Rules to the Decision Process in Crisis Management: The Case of the Silesian District in Poland

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Abstract In this chapter, the application of fuzzy rules to crisis management is proposed. The fuzzy notions are considered in all their nuances, defined by experts. Then, the usage of fuzzy rules in the HAZOP method applied to crisis management is considered. Examples stem from the crisis management centre in a Polish district. It is shown that the proposed approach allows us to identify events with serious or even disastrous consequences, which would not have been identified otherwise.

6.1 Introduction

In crisis situations (like earthquakes, industrial accidents, train accidents, terrorist attacks, floods etc.), the capacity to take fast, efficient and correct decisions is a very important challenge. The problem is that in such situations there is no time to analyse various scenarios and decisions; and the stress, emotions of both victims and policemen, first aid agents etc., weather conditions and other factors cause decision making to be still more difficult. Any wrong decision, error or delay may result in deaths or serious injuries, damage of important devices and environmental pollution (Traore et al. 2014; Acharyulu and Seetharamaiah 2015). This is why a computer system, adequate for the requirements of crisis management, is necessary.

In crisis situations, various groups of people have to cooperate, exchange information and take quick decisions. Because of stress, injuries and a lack of time, the information exchanged is incomplete, even if a computer system is used. All the

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same, the decisions and actions have to be taken immediately. Also, because of the incompleteness of information, the immediate future is uncertain—another terrorist attack may follow or not, we may have to send additional troops if the situation is more serious than it seems at the moment, but it is also possible that no additional forces will be necessary. This is why fuzzy modelling should be used in crisis management: it may model and measure both the uncertainty and incompleteness of information as well as the possibility of certain events or actions that may occur or may have to be pursued in the future.

In the present chapter we describe crisis management in a selected district in Poland, where, in the presently used crisis management system, only crisp modelling and decisions are possible. We give a literature review on the state-of-the-art of the use of fuzziness in crisis management and propose an application of fuzziness to decisions made by the crisis management system in the considered district. Then, in order to propose another application of fuzzy modelling to crisis management, we describe the traditional version of the HAZOP method, which can be used in risk and uncertainty management, and show how a fuzzy version of the method could be used in crisis management, in the considered Polish district, but also elsewhere.

6.2 Crisis Management—The Need for Flexibility and for Handling Incomplete Information

There are various models of crisis management, which can be divided into two groups (Pirozzi 2013):

1. A simplified two-stage model, used in Asian countries:
   - Actions before the crisis
   - Actions after the crisis
2. A three-stage model used mainly in Europe and USA:
   - Prevention and warning stage
   - Crisis stage
   - Crisis consequences removal stage.

The first system type does not distinguish the management of the crisis event itself. This is why the second system type is preferred in Europe, although the first also has its advantages (i.e. simplicity and the quality of data).

Many computer systems have been worked out for the (b) stage of the second Model type, thus the management and crisis itself.

The considered department in the south of Poland has a crisis management centre. Their computer system is based on a decision support system. Here is a typical function and decision that is performed and managed by this system:

1. Monitoring of a certain magnitudes (e.g. of water level, chemical substance concentration etc.);
2. If the value belongs to a (crisp) interval, the decision—a certain action—has to be performed.

The crisp intervals have of course crisp limits. Thus, values that are very close may lead to quite different actions. For example, if the water level is considered to be in the warning state, no constant duty in the crisis management centre is required, even if this warning state is very close to the alarming state, when such a constant duty is necessary. It is up to the humans to be more flexible in their decisions and to notify an adequate person to be ready to leave for the centre in the case of an alarming state, but the computer system itself offers no flexibility here. In fact, we have both lack of information and uncertainty: we only have information about the water level in selected points and do not know for certain whether the alarming state will be reached or not; not only because of the incomplete information, but also because of the uncertainty linked e.g. to the force and direction of the wind in the immediate future.

For such reasons it is important for crisis management systems to incorporate both lack of information and uncertainty. This is made possible by the fuzzy approach, presented shortly.

6.3 Fuzzy Approach in Decision Making

Zadeh (1983) introduced the possibility of mathematical modelling of adjectives, i.e. of such notions as “high”, “other” etc. This makes it possible to model their strengthenings, weakenings, and other nuances in such a way that we can use in computer systems a language similar to the natural one and have the computer make nuanced decisions, similar to those made by the human mind.

To define the necessary notions, a membership function is used, defined on the set of possible values that can be taken by the element being evaluated (for example, the element may be the water level in a river, possible values would then be all the non-negative values smaller than 15 m, which is a consequence of the dimensions of the river basin), and with values in the interval [0,1].

Let us thus define the space of the values of the element that is evaluated as U, and the evaluated notions as r. The membership function μ_r defined on U, with values in the interval [0,1], represents the expert opinion to which extent $x \in$ U is r.

For example, if we consider the notion “a major deviation from the highest accepted (i.e. highest normal, reference) level”, we can define, based on expert opinion, the notion “a major deviation”, by means of the membership function $\mu_{\mathrm{majordeviation}}$, defined on the set of non-negative numbers, representing the percentage of the difference (i.e. the actual value—the highest possible accepted value) with respect to the highest accepted value of the level.

$$\mu_{\text{majordeviation}}(x) = \begin{cases} 1 & \text{if} \quad x \geq 80\,\% \\ \frac{10x}{6} - \frac{1}{3} & \text{if} \quad 20\,\% \leq x \leq 80\,\% \\ 0 & \text{if} \quad x \leq 20\,\% \end{cases} \tag{6.1}$$

According to (6.1), a deviation is considered to be decisively major if it exceeds 80 % of the accepted value and to be decisively small if it is less than 20 % of the accepted value. The values in between are considered to be between major and small, and it is possible to differentiate the degree to which the deviation is big. The function μ_r allows differentiation of the level of possessing the feature r, which the human mind normally does.

Furthermore, exactly as done by the human mind (Zadeh 1983), it considers different nuances of basic features or notions. For example, we can consider a strengthening of a basic notion r, denoted as r^2, r^3 etc., which corresponds to the following notions in the natural language: "very r", "exceptionally r" etc. The strengthenings are functions of the basic notion or feature r. These functions are also determined on the basis of expert opinions. For example, function μ_{r^2} can be defined in the following ways:

(a) $\mu_{r^2}(x) = (\mu_r(x))^2$
(b) $\mu_{r^2}(x) = \mu_r(x - a)$, where a is a constant given by the expert.

In case (a), the set of elements having the feature r^2 (very r), to the degree higher than 0 is identical to the respective set for the feature r, only that it is more difficult for the element to possess the feature in a high degree. In case (b), the set of elements having the feature r^2 to the degree greater than 0 is different to the respective set for the feature r, and the following set is not empty: $\{x : \mu t_{r^2}(x) = 0 i \mu_r(x) > 0\}$. Which approach to use depends on the expert.

In an analogous way, we can define the notions representing weakenings of the notion r (e.g. "a little r", "little r". "about r") and its extensions (e.g. "approximately r", "r or p", where p is another notion etc.). An important nuance of each notion r is the notion "borderline r", defined for example as:

$$\mu_{borderlinemajordeviation}(x) = \begin{cases} 1 & \text{if} \quad \mu_{majordeviation}(x) \geq 0.9 \\ 5\mu_{majordeviation}(x) - 3.5 & \text{if} \quad 0.7 \leq \mu_{majorbigdeviation}(x) \leq 0.9 \\ 0 & \text{if} \quad \mu_{majorbigdeviation}(x) \leq 0.7 \end{cases}$$

6.4 Application of Fuzzy Rules to Crisis Management: State-of-the-Art

Fuzzy rules have found a wide application in decision making. Fuzzy rules are an extension of crisp rule of the type "If a condition is fulfilled (the possible states are yes or no), the something is true, or something should be done". The fuzzy rules are similar conditional statements, in which in both the conditional and conclusion parts there may exist more possibilities than just yes or no or true or false. An overview of various types of fuzzy decisions is given in Dubois and Prade (1996).

Here we consider a special type of fuzzy rules, which are defined as conditional sentences whose main close (conclusion) is expressed in the imperative, in a natural language, with two possible states ("true" or "false"), and whose premise is a conjunction of statements expressed by means of the fuzzy approach (e.g. Anooj 2012). For example, in a crisis management system in the considered department, we have the following rules, whose premises are at the moment crisp, but might also be expressed by means of fuzzy numbers:

- If the operator's qualifications are low and the rain is heavy, send another operator to help;
- If the rain is medium and the wind strong, start preparations for intervention.

The rules are generated on the basis of expert opinion or experiences from the past. Fuzzy rules can be applied in such a way that if the membership function of all the phrases in the premise is positive, the action contained in the basic clause is started. If there are two or more rules generating different actions, the rule is selected and applied whose membership functions in the premise have a higher value (the minimum of the values can be used to calculate the value in the composed premises).

The use of fuzzy rules in crisis management has been proposed elsewhere (Landry et al. 2008) for the crisis management decision support system in a French department. However, that proposal did not cover the nuances (e.g. strengthenings, weakenings etc.) of fuzzy notions, whose usage we consider necessary, and will show in Sect. 6.5. Other existing applications of fuzzy rules to crisis management use fuzzy numbers to express the possibility degree of actions (Traore et al. 2014; Nokhbeh Foghahaayee et al. 2010, 2014; Oztaysi et al. 2013).

We apply the approach of Landry et al. (2008) here to a Polish crisis centre, adding the usage of Nuancing fuzzy notions, presented in Sect. 6.3. First we will describe an element of the decision support system in the considered crisis management system in its present, crisp form, and then its fuzzification proposal.

6.5 Case Study—Hydrological Control of a Department

The case study presents a simplified version of a real-world case, stemming from the considered crisis management centre in Poland.

The Meteorology and Water Management Institute of the department, basing itself on various accessible data, systematically elaborates weather forecasts, which are composed of the following basic elements:

– The precipitation strength
– The precipitation intensity

Table 6.1 Precipitation strength—the thickness of the water layer that comes into being as a result of precipitation, on a horizontal surface (mm/m^2)

Precipitation	Rain (mm)	Snow (mm)
Small	0.0–5.0	0.0–2.5
Medium	5.1–10.0	2.6–5.0
Rather strong	10.1–20.0	5.1–10.0
Strong	>20.0	>10.0

Source Internal documents of the crisis management centre

– Wind force
– Water height in the water gauges of the department.

The aim is to be able to foresee such disasters as floods and hurricanes. If one of the listed parameters is too high, certain measures have to be taken.

The analysis of the data is performed according to tables that can be found in the internal documents of the crisis centre. Table 6.1 is an example. It consists of "classical" intervals corresponding to small, medium, rather strong and strong precipitation. The intervals cover the whole space of possible values, but are disjunctive.

Also for the other factors (b, c and d) listed above, the centre has corresponding tables, where cases of the factors being "small", "medium", "rather strong (rather high)". "strong (high)" etc., are defined. For wind we additionally have the features "gale", "hurricane", "storm". All the tables contain crisp intervals. The tables are used in the premises of (at the moment non-fuzzy) rules, for example:

- If the precipitation is medium, introduce the state of alert.
- If the precipitation is small, do not take any measures.
- If the respective value belongs to the corresponding interval, the imperative is put into action.

Let us have a look for example at rule (b). It may turn out to be ineffective and lead to undesired consequences. This may happen in case of the rain being "only" small according to Table 6.1, but in a fact being not so small—taking on for example the value of 4.9 mm. In such a case in fact rule (a) should be applied, maybe with some delay. At least the action from this rule should be prepared. Applying strictly rule (b), without taking into account that the rain is "almost medium", might be even dangerous.

Applying the approach described in Sect. 6.4, it would be necessary to reformulate the tables from the internal documentation of the crisis management centre. Table 6.1 for example could be reformulated in the following way (we discuss here only the second column, which refers to rain; the definition of individual notions would be given by experts).

In Fig. 6.1 we present graphically the fuzzification proposal of the features from the first column of Table 6.1, describing rain. These features would be represented by means of membership functions, marked in the way explained below:

- the membership function represented as ——— refers to the feature "small", μ_{small};
- the membership function represented as – – – – refers to the feature "medium", μ_{medium};

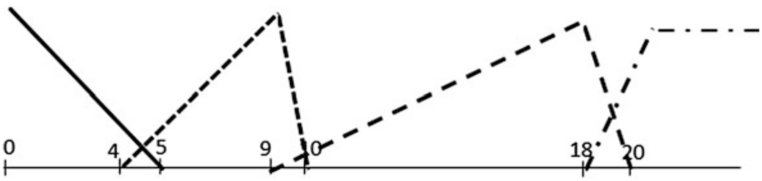

Fig. 6.1 Fuzzification proposal of rain features for Table 6.1

- the membership function represented as ▬ ▬ ▬ refers to the feature “rather strong”, $\mu_{ratherstrong}$;
- the membership function represented as ▬ ▪ ▬ ▪ refers to the feature “strong”, μ_{strong};

In such a case it would be possible to take into account nuances of the four features, either by distinguishing the small values of the membership functions, or (in order to be able to use natural-like language, without the necessity of referring to the values of the membership functions) by defining additional features, representing the nuances of the basic features. For example, function $\mu_{almoststrong}(x) = \mu_{ratherstrong}(x-2)$ might represent the notion “almost strong”. Tables like Table 6.1 would be completed and the resulting rules will be more efficient, because they would be more nuanced and would better adopt the action to be taken to the actual situation.

In the succeeding sections we will propose another application of fuzzy rules to crisis management. In order to introduce the basis for our new proposal, first we will introduce the HAZOP method, known above all from applications to risk and uncertainty management, but which can also be applied generally to decision making.

6.6 Crisp HAZOP Method in Decision Making

The crisp version of the HAZOP method is described in e.g. (de la O Herrera et al. 2015). It was elaborated for the needs of the chemical industry in the 1960s. Basic applications are presented for example in (Redmill et al. 1997) and in the standard from the British government (Ministry of Defence 1990). Figure 6.2 presents its basic functioning. The assumption is that we have a system in which it should be continuously checked whether any action is needed to repair it. This system may be, for example, a department in which it should be continuously checked whether a crisis has occurred or is approaching. This is carried out by checking certain parameters and evaluating deviations from reference values.

The elements of the system are selected spots, control points, and flows. The parameters of each element are its features, e.g. speed (e.g. of water flow in the river, of information flow), height (e.g. of water level), quality (e.g. of information),

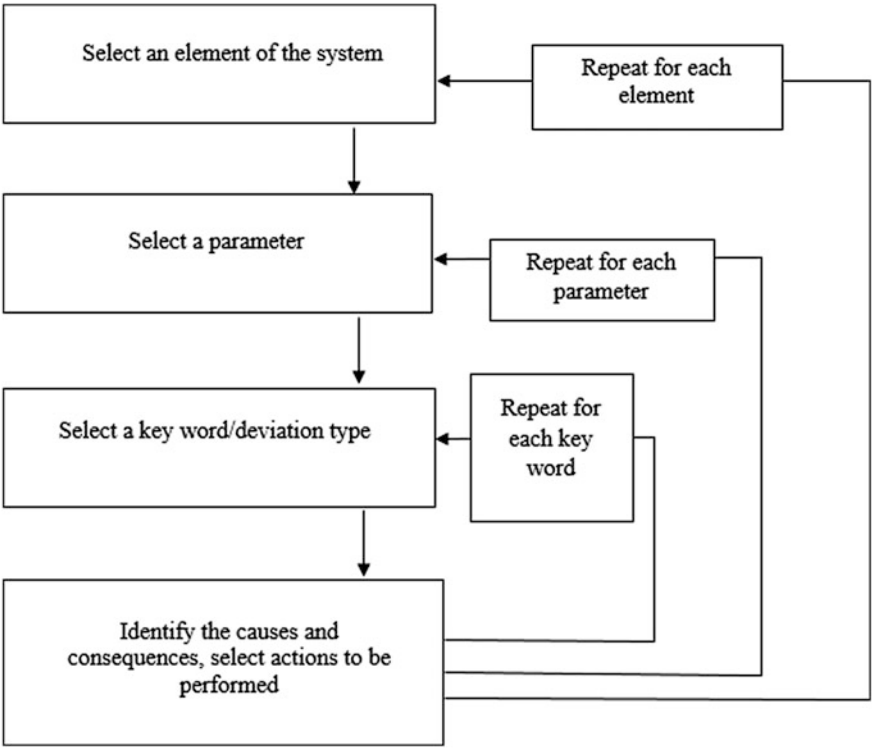

Fig. 6.2 The HAZOP method in its classical form. *Source* Ministry of Defence (1990)

direction (e.g. of wind), etc. The essence of the HAZOP method is the usage of keywords that help to identify serious deviations and anomalies of the parameters, in order to take necessary measures.

The list of potential key words is proposed in the literature, but it should be built up in each individual case on the basis of experience and adopted to the current needs. In Table 6.2 we give an example of the list with a proposal of interpretation.

To each keyword/deviation or anomaly of each parameter, a certain action is linked. Thus, we are dealing with the following rules: if a parameter has (to such and such degree) this or that anomaly, perform a certain action. The rules may have fuzzy premises (possessing a feature to such and such an extent).

The HAZOP method has been criticised in (Baybutt 2015). This author raises many negative aspects of the HAZOP method, but one of the most important is the fact that it does not consider complex deviations. i.e. combinations of deviations corresponding to various keywords. As Baybutt (2015) says, complex deviations may lead to such consequences that may remain undetected by the classical analysis of single deviations. It is true that complex deviations have sometimes a low probability, but in crisis management also low probability events with serious consequences should be considered, even if the effort needed for their identification

Table 6.2 Example of the list of keywords for the HAZOP method

Parameter	Keyword	Interpretation
Flow (of data, of information, of people, of water)	Lack	There is no flow
	More	The flow is larger than accepted
	Partial	The information, the data etc. that is flowing is incomplete
	The other way round	The flow goes in the wrong direction
	Differently	The flow contains wrong elements
	Earlier	The flow takes place earlier than expected
	Later	The flow takes place later than expected
Frequency of the occurrence of a phenomenon	More	The phenomenon occurs at a higher frequency than normally
	Less	The phenomenon occurs at a lower frequency than expected
Value of an indicator	More	The value of the indicator is too high
	Less	The value of the indicator is too low

Source Ministry of Defence (1990)

is high. A low probability is no reason for disregarding events that could lead to deaths or injuries. That is why we use here, for crisis management, a generalisation of the HAZOP method, proposed in (Kuchta et al. 2016), which considers complex deviations and additionally takes into account fuzzy notions and their nuances.

6.7 Generalised Fuzzy HAZOP Method

Taking into account the reproaches formulated in (Baybutt 2015) and the fuzzy theory of Zadeh (1983), we suggest that in crisis management combinations of deviations should be considered, and the deviations should be described as fuzzy notions, together with their nuances. We are aware that this will increase considerably the complexity of the method, but in crisis management effort should not be an excuse for disregarding crises dangerous for human beings and the environment. Of course, the problem of identification of important combinations is an open problem. Some combinations will have no meanings, others may seem impossible in a certain moment, but in another moment they may be quite possible. It may happen that the expert responsible for the selection of combinations is prone to his or her prejudices and fails to identify some important combinations. Still, even if it is difficult and the number of identified combinations is high, in crisis management it is essential to analyse all of them, excluding only those that really cannot occur or whose consequences are not so serious.

Table 6.3 Modification of the HAZOP method

STEP 1: Select n = 2
STEP 2: Select all n-element subsets of X that cannot be disregarded
STEP 3: Analyse the subsets and take the necessary actions
STEP 4: If n should be increased, increase it and go to STEP 2, otherwise STOP

As we mentioned above, in our opinion the notions in the keywords should be defined as fuzzy notions, as described in Sect. 6.3, and their nuances should be considered. For example, it is obvious that consequences in the case of 10 very small deviations may be as serious or even more serious than in case of two medium deviations. The combinations of fuzzy deviations with nuances will allow us to identify many events where actions have to be performed in order to avoid serious consequences, which would be impossible to be identified by means of the classic HAZOP method.

The only fuzzy version of the HAZOP method known in the literature is proposed by Tao et al. (2012), but these authors use fuzziness to express the possibility degree of an event, and not the degree of possessing features. We use fuzziness in the HAZOP method in order to express the nuances of various features of parameters, in order to identify all situations in which it is necessary to take some measure, even those that have a low probability.

The modified version of the HAZOP method is proposed in Table 6.3. The set X used is the set of all feasible (thus having a meaning and possible to occur) fours, composed as follows: element of the system, parameter, a keyword, a nuance of the keyword. An example of an element of X is the following four: water in river, water level, more, very. The symbol n represents the number of elements that may form a combination. The value of n will depend on the expert: it may have to be rather high if longer chains of small deviations may have serious consequences.

The fuzzy rules are hidden in Step 3: the analysis is based on fuzzy rules.

The application of the modified HAZOP method will be presented in the next section, on the example of decisions taken in the discussed crisis management centre.

6.8 Case Study—Terrorism or Bioterrorism Act in the Department

First we will describe the way a terrorist or bioterrorist event would be handled at present in the crisis management centre. Then we will describe how it should be handled using fuzzy notions and the modified HAZOP method.

Let us assume that a terrorist or bioterrorist event has occurred. Then in the department the following information flow has to take place:

A. Someone has to notify one of the units listed below (each, when it receives the message, has to notify all the other units):
   - Crisis management centre;
   - The nearest police station;
   - The local fire station;
   - The local hospital.

B. The crisis centre determines, at the maximum possible accuracy, on the basis of information received from the police and the firefighters, the scope, the exact time and the place of the event, the size and the type of the event and the number of deaths and injuries. On the basis of this information it prepares adequate forces and means in order to:
   - Secure the event place;
   - Steer the traffic in order to limit the number of vehicles at the spot and to control the vehicles entering and exiting;
   - Guarantee medical support;
   - Perform evacuation of the injured and of the inhabitants or the places nearby being in danger.

C. If necessary, make preparations for the following to arrive:
   - Specialised medical troops;
   - Negotiators and special police troops, if there are hostages;
   - Troops of chemical rescue, in case of the danger that harmful substances may be spread;
   - Specialist troops of minesweepers, in order to locate and neutralise explosives.

Now we will describe how the classical HAZOP (Fig. 6.2) method would be used and what disadvantages this might have. We will discuss two elements of the system, one parameter and one keyword for each element. In the classical HAZOP method, no combinations are considered.

The first element of the system is an information flow:

- The choice of the element of the system: the information flow from someone on the spot to one of the units (i), …, (iv) from A.
- Selection of the parameter: speed
- Selection of the keyword: “less”
- Interpretation: identification of causes and consequences, measures to be taken: the respective services have been notified too late, for example because of the lack of telephone reception or of people who would be in a sufficiently good condition to make a phone call. Consequences: there may be some injured persons who will get help too late—severe consequences;
- Taking measures minimising the consequences of the event—here rules would be applied.

The second element of the system is another information flow:

- The choice of the element: the information flow from the troops at the spot of the event to the crisis management center:
- Parameter choice: content;
- keyword choice: “less”
- Interpretation: identification of causes and consequences, measures to be taken: The information about the type and the scope of the danger is too optimistic. The reason might be the lack of experts, haste, emotions, the scope of the damage. Consequences: inadequate or too few rescue troops may be sent, the injured whom it would have been possible to help will get help too late, will not get help at all or will get unprofessional help; severe consequences;
- Taking measures minimising the consequences of the event—here rules would be applied.

As mentioned above, in the classical application of the HAZOP method the analyses of the elements, parameters and keywords are conducted independently. Furthermore, the variances are crisp and the nuances of their factors are not taken into account. Below we will present the application of the proposed generalisation of the HAZOP method. First we will present the use of nuances of the notions needed in crisis management (using both examples-elements presented above); then we will introduce the combinations and their role in the method.

6.8.1 Application of the Fuzzified HAZOP Method

The first element of the system is an information flow:

- The choice of the element of the system: the information flow from someone on the spot to one of the units (*i*), …, (*iv*) from step A.
- Selection of the parameter: speed
- Selection of the keyword: “a little bit less”, “a little less”, “significantly less”, “disastrously less”
- Interpretation: identification of causes and consequences, measures to be taken:
  - a little bit less: the reason might be momentary problems with the telephone reception or a momentary shock—medium consequences;
  - a little less: reasons as above or the time needed for an injured person to reach for the phone—serious consequences;
  - significantly less: the people on the spot are so injured, that only someone coming from outside can make a phone call—serious consequences;
  - disastrously less: nobody near the spot of the event is able to notify anybody —disastrous consequences;

- Taking measures minimising the consequences of the event—here fuzzy rules would be applied.

The second element of the system is another information flow:

- The choice of the element: the information flow from the troops at the spot of the event to the crisis management centre;
- Parameter choice: content;
- Keyword choice: “less”—“a little bit less”, “a little less”, “considerably less”, “disastrously less”;
- Interpretation: identification of causes and consequences, measures to be taken:
  - a little bit less: a tiny mistake in the assessment of the situation caused by haste and emotions, minor consequences, because the “almost” right troops will be sent—insignificant consequences;
  - a little less: a small mistake in the assessment of the situation because of the reasons listed above, which may result in sending a too small or poorly equipped team, which may in turn mean delayed help or a help without the necessary equipment: serious consequences;
  - significantly less: a serious mistake in the assessment of the situation, a consequence of the lack of expertise or of emotions, which can result in sending troops whose size and equipment would not be adequate to the event’s nature, which in turn may mean not providing the right assistance to a large group of people: serious consequences;
  - disastrously less: a completely erroneous (e.g. too optimistic) assessment of the situation, being a consequence of the size and the nature of the event, which made its proper assessment impossible. This will result in sending too few troops, maybe with inadequate qualifications, not asking for help from other departments, communities or even states. This will mean that most of the injured will not get help—disastrous consequences.
- Taking measures minimising the consequences of the event—here fuzzy rules would be applied.

In the fuzzy version of the HAZOP method with nuances proposed here, the analysis of individual deviations is performed individually, but the intensity of various features, described in a fuzzy way, is distinguished. This makes it possible to differentiate reasons, consequences and measures to be taken for deviations with various features and various degrees of possessing them, and to concentrate on really important aspects of the terrorist event. However, as mentioned above, in crisis management it is necessary to consider a combination of elements of the system, parameters and keywords. Below, we present how it might look like in the considered case.

6.8.2 Application of Generalised HAZOP Methods

Determination of the set X of fours (i.e. system element, parameter, keyword, nuance)

- Selection of a number n = 2
- Selection of 2-element subset of X: {(the information flow from someone on the spot to one of the units (a) … (d), speed, less, a little) (the information flow from the troops at the spot of the event to the crisis management centre, content, less, a little)}
- Check if the selected combination makes sense
- Interpretation: identification of cause and consequences, measures to be taken: If the services are notified a bit too late and if additionally the representatives of the services, once on the spot of the event, send a too optimistic assessment of the situation, there will be less time for correction of the number and type of troops sent to the spot of the event. As a result, a considerable number of the injured may not get any help—disastrous consequences;
- Taking measures minimising the consequences of the event—here fuzzy rules would be applied.

As can be seen in the above example, considering combinations from the set X has allowed us to identify serious consequences of events that would not have been identified in the traditional version of the HAZOP method. The combination analysed above has such serious consequences that it cannot be ignored. The classical approach would not have led to its identification.

6.9 Conclusions

A systematic consideration of the fuzzy approach with nuances in crisis management and the consideration of combinations of deviations and anomalies have been proposed. A generalisation of the HAZOP method has been formulated as well. All the discussion is illustrated by means of cases from the crisis management centre of a Polish department.

The proposed approach will considerably increase the effort needed for efficient crisis management. This is why it should be further investigated, especially as far as ways of minimising the number of combinations to be analysed are concerned, without diminishing the efficiency of the crisis management. It seems that there is no other way: in crisis management, a major effort needed cannot justify not considering serious cases. The consequences of such an omission may be disastrous.

However, the most important direction of further fuzzy research case studies in crisis management centres lies in different countries and modifications of the approach proposed here based on feedback from the practitioners. Actual crisis events should be analysed: it should be checked whether the right decisions were taken at the right time; and if not, why. A register of rule should be elaborated and shared among crisis management centres around the world.

References

Acharyulu, P. S., & Seetharamaiah, P. (2015). A framework for safety automation of safety-critical systems operations. *Safety Science, 77*, 133–142.

Anooj, P. K. (2012). Clinical decision support system: Risk level prediction of heart disease using weighted fuzzy rules. *Journal of King Saud University—Computer and Information Sciences, 24*(1), 27–40.

Baybutt, P. (2015). A critique of the hazard and operability (HAZOP) study. *Journal of Loss Prevention in the Process Industries, 33*, 52–58.

de la O Herrera, M. A., Luna, A. S., da Costa, A. C. A., & Lemes, E. M. B. (2015). A structural approach to the HAZOP–Hazard and operability technique in the biopharmaceutical industry. *Journal of Loss Prevention in the Process Industries, 35*, 1–11.

Dubois, D., & Prade, H. (1996). What are fuzzy rules and how to use them. *Fuzzy Sets and Systems, 84*(2), 169–185.

Kuchta, D., Gladysz, B., Stanek, S., & Drosio S. (2016). Risk management in critical computer systems on the example of a crisis management center (in Polish), to be published in Scientific Annals of University of Economics in Katowice.

Landry, J. F., Ulmer, C., & Gomez, L. (2008). Fuzzy distributed workflows for crisis management decision makers. *Intelligence and security informatics* (pp. 226–236). Berlin: Springer.

Ministry of Defence. (1990). HAZOP studies on systems containing programmable electronics.

Nokhbeh Foghahaayee, H., Menhaj, M. B., & Shafiee, M. (2010). Fuzzy decision support system for crisis management with a new structure for decision making. *Expert Systems with Applications, 37*(5), 3545–3552.

Nokhbeh Foghahaayee, H., Menhaj, M. B., & Torbati, H. M. (2014). Fuzzy decision support software for crisis management in gas transmission networks. *Applied Soft Computing, 18*, 82–90.

Oztaysi, B., Behret, H., Kabak, Ö., Sarı, I. U., & Kahraman, C. (2013). Fuzzy inference systems for disaster response. In B. Vitoriano, J. Montero, & D. Ruan (Eds.), *Decision aid models for disaster management and emergencies* (pp. 75–94). Paris: Atlantis Press.

Pirozzi, N. (2013). *The EU's comprehensive approach to crisis management*. Geneva: Geneva Centre for the Democratic Control of Armed Forces.

Redmill, F., Chudleigh, M. F., & Catmur, J. R. (1997). Principles underlying a guideline for applying HAZOP to programmable electronic systems. *Reliability Engineering and System Safety, 55*(3), 283–293.

Tao, C., Huabing, Z., Honglong, Z., Yufeng, Y., & Xin, W. (2012). Quantitative HAZOP risk analysis for oil tanks using the fuzzy set theory. In: *Proceedings of the Biennial International Pipeline Conference*, *IPC* (pp. 379–385).

Traore, M., Chatelet, E., Soulier, E., & Gaber, H. (2014). Diagnosis using incomplete model in fuzzy discrete event system: Application to crisis management. In: *Proceedings of 2014 13th International Conference on Machine Learning and Applications, ICMLA 2014* (pp. 432–440).

Zadeh, L. A. (1983). A computational approach to fuzzy quantifiers in natural languages. *Computers & Mathematics with Applications, 9*(1), 149–184.

Chapter 7
Maritime Environmental Disaster Management Using Intelligent Techniques

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Abstract The maritime environmental disasters are generally caused by collision, grounding, stranding heavy weather, explosion or fire. These disasters can cause spillage of oil, bunker, dirty water or chemical harmful substances. It is well known that the most known environmental disaster in maritime having serious impacts on marine life is oil spill. Although several intelligence techniques like heuristic search algorithms, machine learning, and fuzzy approach have been employed in maritime sector with various purposes, in the literature, applications of intelligent techniques for the solution of the maritime environmental disaster problems are quite limited. In this study, an intelligent system which consists of model-base, database, environmental disaster management actions, ship operation management actions, user interface, environmental disaster modelling, and decision support unit has been proposed. The proposed system, called as Maritime Intelligent Environmental Disaster Management (MIEDM), is aimed at strengthening operating mechanism along with the mitigation, preparedness, response, and recovery phases to eliminate the potential impacts of maritime environmental disasters.

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7.1 Introduction

Environmental sensitiveness is one of the fundamental aspects of sustainable maritime industry since carriage of cargoes by ships poses potential hazards to human life, marine ecology, and cargoes themselves. Specifically, transportation by ships may cause exhaust gas emissions and oil pollution which is absolutely one of the most catastrophic consequences of environmental disasters for marine habitat. The extensive oil spill may spread out hundreds of nautical miles from the source of incident and cause severe harms to maritime environment. The maritime authorities (IMO, Flag State Control, Port State Control, Classification Society, etc.) have been adopting a set of regulations and conventions such as MARPOL73/78 (International Convention for the Prevention of Pollution from Ships), AFS (The International Convention on the Control of Harmful Anti-fouling Systems in Ships), OPRC (International Convention on Oil Pollution Preparedness, Response and Co-operation) and etc. in order to prevent marine environmental pollution. Particularly, the MARPOL is one of the most contributory conventions to protect marine environment. It is the one of three most significant complementing key conventions of the IMO. The convention consists of six main annexes which cover the regulations for pollution caused by ships.

The primary aim of the MARPOL is to prevent pollution by oil and other harmful substances as well as accidental spillage from the ships (Lloyd Register 2005). Although the statistics show that these conventions and regulations assist in gradually reducing ship-sourced marine environmental pollution, the marine environmental disasters are still on-going (EMSA 2015).

Costa Concordia incident, for instance, is a fresh marine environmental disaster that was followed by millions of people. The luxury passenger ship tragically grounded at Giglio Island and flooded due to the tore about 50 m gash on her port side of hull. The ship lost her electrical and propulsion power. Although the weather was good and sea was calm, evacuation process couldn't be completed properly. According to the SOLAS, all passengers should be evacuated from the ship within 30 min. However, the evacuation operation took about 6 h due to insufficient disaster management. At the end of tragic accident, 32 people lost their life and a little amount of fuel and diesel oil spilled away from the ship bunker tanks. The wreck removal operation took place more than two years. In the course of wreck removal operation, numerous different pollutants such as scraps, plates, batteries, tonner, debris, etc. were spilled into the sea. Apparently, tourism was seriously affected.

The marine environment disaster including spillage of oil, bunker, dirty water or chemical harmful substances may be caused by collision, grounding, stranding heavy weather, explosion or fire. The findings show that the most significant maritime environmental disasters are due to oil spillage which is caused by either ship collision or grounding at sea (EMSA 2015; Samuelides et al. 2009). For instance; Torrey Canyon, Exxon Valdez, Erika, Prestige incidents are the most catastrophic maritime environmental disasters in the history (Celik and Topcu 2009). The effects of those disasters were severely harmful to not only marine habitat but also mainland shores due to excessive oil contamination. Thousands tons of crude oil cargo contaminated wide range of area and affected marine habitat, organisms, birds, mammals, coastlines, fresh water sources, etc. The long term effects of contamination can be destructive since harsh chemical solvent and clean-materials are used. In addition, economy and tourism may severely suffer from tremendous compensation and slowdown of tourists.

Most maritime environmental disasters are due to collision or grounding (Akyuz 2015; Chauvin et al. 2013). According to Graham (2012), collision is one of the most important issues in maritime environmental disasters. Moreover, almost three of four maritime accidents in European seas are related to collision and grounding incidents (EMSA 2015). When the vessels are collided, it is possible to damage each vessel's hull or engine room. Even though the vessel is ballast condition (i.e. no cargo on-board), there would be pollution damage since bunker remains on fuel/diesel oil tanks. The massive environmental damage may emerge if the liquid cargo on-board at tanker ship. Likewise, grounding may result with severe structural damage to ship hull in particular bottom of ship where ballast and fuel oil tanks are placed (Zhu et al. 2002). Due to the excessive loads upon ship hull, the bottom shall plates may be severely damaged by tearing and may cause huge oil spill. In order to minimize damage to the environment and ship hull, the IMO adopted double hull construction requirements for all types of ships in 2005 (IMO 2005). Basically, the convention requires ship owners to design their ship with two complete layers of hull surface which surrounds bottom and sides of the ship. There is some distance between inner and outer hull surface. In the event of low-intensity ship collision or grounding, double hull structure can prevent damage. Thus, the likelihood of oil spillage can be reduced as much as possible through a safety barrier. On the other hand, in the event of high-intensity collision or grounding incidents, double hull structure cannot prevent oil spillage completely but just mitigate collision intensity.

In the view of environmental disasters in maritime industry, the aim of this chapter is to present intelligent techniques in management of maritime environmental disasters since consequences may pose damages for human life, commodity, and marine habitat. In this context, the chapter organized as follows: this part gives motivation behind the research. The second part provides comprehensive literature overview about maritime environmental disasters. The part three introduces intelligent systems. The applications of intelligent techniques to maritime industry are provided in part four. The final part gives discussion and conclusion about the study.

7.2 Maritime Environmental Disasters

Although maritime environmental disasters rarely appear, the adverse effects may continue for long years. The consequences of a disaster such as oil spill are severely damaging to marine environment and ocean inhabitants. The adverse effects may extend to economy and tourism industry. The compensation cost may reach billion dollars. The local tourism may be severely damaged while most people keep away from polluted area. Since a marine environmental disaster may pose serious harms, marine and environmental safety practitioners have been attempting to seek proactive solutions to minimize potential dangers in advance. Although there have been some research papers on this topic, most of them cannot go beyond the theoretical workshop. In the context of maritime environmental disaster literature, limited studies have been performed. For instance, Yan et al. (2009) proposed a research paper for quick response to a maritime disaster. The authors made use of heuristic approach to acquire a rational framework for rescue during maritime disaster. The findings indicated that the proposed approach has high performance in making a baseline schedule, and quickly reschedule. Another original research on the basis of maritime environmental disasters investigated and analyzed the trend of fatalities in Danish ship fleet due to maritime disaster (Hansen et al. 2012). Indeed, the authors divided the study into two parts: first one focused on the crew fatalities that may occurred during a maritime disaster, the second part involved ship crew who abandoned the ship during a maritime disaster. The study used core data from various sources. Likewise, Anyanwu (2014) performed research on maritime disaster on passenger ships. In the paper, statistical data were transformed into useful information to analyze causes of maritime disasters in passenger ships. At the end of the research, the author made recommendations to minimize such maritime disasters in the future.

Comprehensive research with respect to the human factor in maritime disasters was conducted to define human behavior and role during maritime catastrophes (Lupanov et al. 2013). In the study, the authors investigated human role on the basis of medical treatment during a disaster. A different study has recently been introduced by Nova-Corti et al. (2015) to analyze economic consequences of maritime disaster in special areas. The study assessed the economic effect of M/T Prestige maritime disaster on environment and population. Furthermore, Molloy et al. (2016) have already investigated a special maritime disaster case: fire at MV Star Princess, an oceangoing passenger vessel. In the paper, the authors perform an elaborated analysis to reveal the causes of maritime disaster, pre-actions, actions and post-actions for it.

In the view of maritime disaster research, the marine oil spill case apparently becomes prominent topic where various studies have been performed. The most important reason is that the consequences of oil spill may severe damages to marine environment, mainland shore lines, and economy. Also, oil spill is one of the most common marine pollution causality (EMSA 2015). Figure 7.1 shows annual number of oil spills (>700 mtons) caused by ship since 1990 years. Therefore, the marine and environment safety practitioners have focused on seeking alternative solutions to minimize effects of oil spill. For example, economical effects of MT Prestige maritime disaster were discussed in a couple of papers (Loureiro et al. 2006; Garza-Gil et al. 2006; Negro et al. 2009) since responsibility of financial recovery may involve ship management company, P&I Club, government and local authority. Specifically, cleaning-up and recovery costs require huge financing. Also,

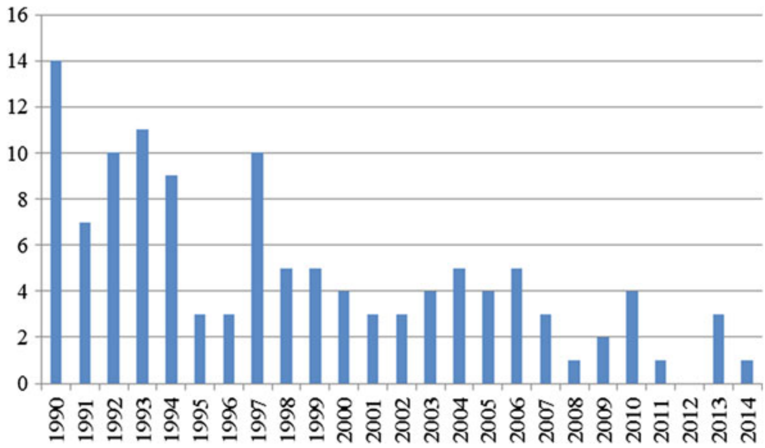

Fig. 7.1 Annual number of oil spills (>700 mtons) caused by ship since 1990 (ITOPF 2015)

socio-political and environmental effects of MT Prestige maritime disaster were analyzed to reveal how a severe marine environmental disaster affects people and oil industry (Perez 2003; Perry et al. 2010).

In the recent years, as the consequences of oil spill disaster on human life, marine ecology and environment are shown, a number of case studies have been undertaken. For instance, Dongdong et al. (2015) proposed a marine oil spill risk mapping (MOSRM) method to perform risk analysis for oil spill pollution. The aim of the method was to construct a risk indexing system and convenient quantitative model. The authors illustrated the proposed approach upon Dalian port where numerous big size crude oil tankers approach. Likewise another risk based study was performed to analyze oil spill accident (Lee and Jung 2015). The paper presented a model based approach focusing on the likelihood of oil spill and the first impact time. To validate the model, past oil spill accidents were analyzed under different conditions. Furthermore, Goerlandt and Montewka (2015) introduced another risk based modeling in marine transportation system. In the paper, authors utilized Bayesian Network approach to conduct probabilistic risk quantification. Oil spills due to tanker ships collision in the Gulf of Finland were applied to demonstrate the model. Another research has been made upon international compensation regime in case oil spill pollution occurs (Dong et al. 2015). The authors used two methods to compare the inputs: fuzzy-set qualitative comparative analysis and an ordered probit model. The findings of this study showed that accepting compensation regime for the high risk of exposure of tanker oil spills was necessary to provide better protection for marine environment and pollution victims in case of oil spill disaster.

In order to predict potential range, effect, recovery range, and direction of oil spill, some elaborative researchers extended the use of simulation systems and modeling to undertake prompt response during oil spill (Reed et al. 1999;

French-McCay 2004; Guo et al. 2009). As the oil spill incidents have catastrophic consequences for marine environment and human life, marine and environment safety practitioners is able to assess oil spill risk in advance by adopting simulation systems and modeling. Thus, simulation modeling can give potential damages in advance. In this context, necessary clean-up equipment and recovery measures can be taken. However, it should be noted that the simulation modeling applications use instant data rather than real one. In other words; sea, weather or environmental conditions onboard ship may quickly change. Therefore, the input data should be dynamic not static.

In the light of comprehensive overview of the maritime environmental disasters, it is noted that there are some theoretical studies associated with oil spill disaster to avoid pollution and enhance safety in marine environment. However, most of them are not applicable in practice and far beyond the reality. To remedy the gap, this chapter proposes an alternative solution by adopting intelligent techniques in management of maritime environmental disaster.

7.3 Intelligent Systems

The main purpose of intelligence system is to create machines or systems which represent thought processes or behaviors of humans. For this, an intelligent system presents smart proactive solutions for the real world problem based on the data obtained from the past experiences. According to Turban et al. (2010), a system or machine can be called as intelligent if it has at least one characteristic of following behaviors; It can be able *(i) to learn from experience, (ii) to infer under uncertainty, (iii) to use knowledge to respond dynamic environment, (iv) to understand natural language, (v) to solve complex problem, (vi) to present reasoning, (vii) to recognize shape or image in a situation, (viii) to percept physical changes.* Although developing an intelligence system is quite difficult because of the dynamic structure of the world, there are perfect applications on various sectors such as manufacturing, entertainment, education, transportation, communication etc. An intelligent system consists of two components, namely software and hardware. In particular, software presents the behavioral characteristics of an intelligent system or a machine.

In intelligent system applications, researchers face numerous challenges while a dynamic environment is being represented. While creating an intelligent system, the most common tools are as follows (Castillo and Melin 2014; Teymourian et al. 2016; Satunin and Babkin 2014; Erkaymaz et al. 2012; Gómez-Vallejo et al. 2016; Koch et al. 2015; Bateman et al. 2010).

- Fuzzy Logic
- Search algorithms

- Uninformed (blind) search algorithms

  Depth-First Search
  Breadth-First Search
  Uniform-cost search

- Informed search algorithms

  Best-first search
  A* search

- Heuristic search algorithms

  Hill-climbing search
  Simulated annealing search
  Genetic algorithms
  Ant colony
  Tabu search
  Particle swarm optimization
  Bee colony

* Expert systems
* Artificial neural networks
* Reasoning
* Cased based reasoning
* Machine Learning
* Natural Language Processing
* Image processing

The most known environmental disaster in maritime having serious impacts on marine life is oil spill frequently caused by shipwrecking or vessel collision. In the literature, applications of intelligent techniques for the solution of the problem are limited. Wirtz and Liu (2006) used decision support system in order to rank different response actions to a chemical or oil spill and to estimate short-mid-term economic and ecological consequences of different mitigation measures by integrating the state-of-the-art oil spill contingency simulation system with wind and current forecasts, environmental geographic system (GIS) data and multi-criteria analysis techniques. Liu and Wirtz (2006) utilized the fuzzy comprehensive evaluation method to put forward an efficient strategy for the oil spill contingency management. In another study, Wirtz et al. (2007) presented an integrated framework to develop a rationale for conflicts which arise in the context of oil spill contingency policies. Then, Liu (2010) proposed monetary evaluation model combined with simulation technique to assess performances of using the response strategies. Although there have been limited studies on the applications of intelligent system in maritime environmental disasters, a wide range of techniques using intelligence techniques become applicable into marine industry. In the next section, applications of intelligent techniques to marine industry will be presented.

7.4 Applications of Intelligent Techniques to Maritime Industry

Several intelligence techniques like heuristic search algorithms, machine learning, and fuzzy approach have been employed in maritime sector with various purposes. Ant colony optimization, artificial neural networks, tabu search, simulated annealing, genetic algorithm, particle swarm optimization and support vector machines are commonly used techniques in the literature for the applications of intelligence techniques to marine industry.

7.4.1 *Applications of Simulated Annealing*

Simulated annealing has extensively been utilized to solve the problems of maritime industry. In the literature, it was employed to investigate some essential topics like port throughput forecasting, optimal ship routing, and berth scheduling.

Geng et al. (2015) utilized the multivariable adaptive regression splines-robust v-support vector regression (MARS-RSVR) with chaotic simulated annealing particle swarm optimization (CSAPSO) for port throughput forecasting. The proposed method which is a combination of MARS, RSVR and CSAPSO was compared with ARIMA (the autoregressive moving integrated moving average), MBPNN (the multivariable adaptive regression splines BP neural network), RSVR-CSAPSO, MSVR-CSAPSO (the multivariable adaptive regression splines SVR-CSAPSO), MRSVR-PSO, and MRSVR-SAPSO. It was concluded that the proposed MRSVR-CSAPSO provides better predictions than the other six models in terms of forecasting error.

Kosmas and Vlachos (2012) investigated optimal ship routing by using simulated annealing. The proposed algorithm was used to perform discretization for a primary route and to obtain the optimal routes by taking small deviations into account. When the proposed algorithm was compared with genetic algorithm, it was found that although the differences are not important, some new characteristics of the optimal route are uncovered with the proposed algorithm.

Kim and Moon (2003) studied the berth scheduling problem by employing the simulated annealing algorithm. As a result of the experiments, it was stated that simulated annealing provides quite similar solutions that are obtained through MIP model. Furthermore, it was indicated that the computational time and the quality of solutions are influenced by the number of vessels and the ratio of the overlapped area of rectangles to the total area of rectangles.

7.4.2 Applications of Genetic Algorithm

Genetic algorithm has been utilized to address several issues and some of them are as follows: forecasting container throughputs at ports, storage management and vehicle scheduling at container terminals, sea water level forecasting, and real-time wave forecasting. It is broadly qualified as a promising tool in maritime industry.

Wu et al. (2013) employed a linear mixed integer programming for storage management and vehicle scheduling at container terminals while using a nonlinear mixed integer programming model to decrease the number of constraints and the computational time. Furthermore, genetic algorithm was utilized to schedule equipment and container storage in an integrated way. It was concluded that genetic algorithm provides a solution to such a large scale scheduling problem in a reasonable computation time.

In the study of Ali Ghorbani et al. (2010), the genetic programming was employed to forecast sea level variations. A comparison with an artificial neural network model was performed. It was concluded that the performances of the genetic programming and the artificial neural network model are quite adequate, and either of them may be used as an alternative to the harmonic analysis. Gaur and Deo (2008) utilized genetic programming for real-time wave forecasting, and they also concluded that genetic programming can be qualified as a promising tool.

Chen and Chen (2010) examined the use of genetic programming in forecasting container throughputs at ports. The predictions of the genetic programming were compared with decomposition approach (X-11), and seasonal auto regression integrated moving average (SARIMA). It was concluded that genetic programming provides better predictions than X-11 and SARIMA.

7.4.3 Applications of Ant Colony Optimization

Ant colony optimization approach is used for many purposes such as constructing a navigational decision support system, solving a cross-docking network transportation problem, optimizing autonomous ship maneuvers, ship steering control and cruising vessel on river.

Jiang et al. (2015) proposed an algorithm for solving ship multi and branch pipe route design. The proposed algorithm aims at planning suitable pipe routes in order to make the starting and ending points connected under several constraints. In the study, ant colony optimization algorithm was enhanced with respect to ship pipe routing features by modifying some steps of the algorithm. Furthermore, the pheromone direction information and pheromone extension process were advanced through the proposed algorithm to make calculation performance better. The efficiency of the proposed algorithm was indicated with simulation results.

Tomera (2014) used ant colony optimization algorithm to investigate the optimal parameters of the ship course controller. The process of finding parameters was performed for the case in which the controller changes the ship's course and the integral action was turned off. In the process, the course error based objective function and a given rudder deflection was utilized by the ant colony optimization algorithm. The results obtained through the ant colony algorithm were compared with the results of genetic algorithm, and it was indicated that the ant colony algorithm reaches the final solution quite fast. To sum up, it was concluded that the ant colony algorithm is a quite useful tool to optimize parameters of ship course controller.

Lu and Liu (2013) utilized a controller to cruise a vessel along a river. The developed controller consists of an ant colony algorithm, a fuzzy neural network controller, and a switching law. In the study, ant colony algorithm was used to find an approximately optimal sailing line. Within this process, the search pattern of the algorithm s formed by utilizing the tidal current, river current, vessel velocity, and position of the coordinate. Then, fuzzy neural network controller makes the vessel come nearer to the approximately optimal sailing line. Then, the switching law is finally employed to decide whether ant colony algorithm seeks for a new approximately optimal sailing line with respect to the error of sailing line.

Escario et al. (2012) aimed to obtain optimal maneuvers for an Autonomous Surface Vessel by employing ant colony optimization algorithm. For this study, some modifications were made on the ant colony optimization algorithm while its main structure is maintained. The modified version can be employed for the problems that can't be graphically represented. Moreover, modifications made enable the algorithm to self-regulate the search, and in this manner it is possible to stay away from local minima. When the developed algorithm is utilized in Autonomous Surface Vessel maneuvering problems, it provides feasible path that meet the requirements of the desired maneuver, and then by improving, near to the optimal maneuver is generally achieved.

In the study of Musa et al. (2010), an algorithm was developed to minimize the total shipping cost for a cross-docking network transportation problem where the loads aren't stored in a distribution center. Ant colony optimization algorithm was utilized to handle this problem. After a numerical example, it was concluded that the developed algorithm provides solutions which considerably decrease the shipping cost. Furthermore, it was stated that the developed algorithm provides better results particularly for large problem instances than Branch-and-Bound.

Lazarowska (2014) used ant colony optimization to develop a navigational decision support system. The collective behavior of ants was highly influential on the development of this decision support system. The developed system is able to perform path planning and is able to avoid collisions in the open sea and in restricted waters. Moreover, it improves automation of the safe ship control process. Furthermore, it can be utilized for the control system of Unmanned Surface Vehicles to make improvements on their autonomy. It was thus concluded that a useful and innovative navigational decision support system was obtained by using ant colony optimization.

7.4.4 Applications of Tabu Search

Tabu search has been utilized to come up with a solution to various problems such as industrial ship routing problem, single liner long-haul service route design problem, dynamic and stochastic routing in industrial shipping, and the inland container transportation problem.

Lee and Kim (2015) investigated an industrial ship routing problem of a steel manufacturing company. The problem in the study was stated as determining route of a fleet of heterogeneous ships to carry cargoes. In the problem, the fleet of heterogeneous ships included company-owned ships and tramp ships. A company-owned ship was able to transport cargoes from multiple supply ports to multiple delivery ports throughout a route whereas a tramp ship was able to transport a cargo directly to a delivery port from a supply port. A mixed integer programming model for this problem was provided and an adaptive large neighborhood search-based heuristic was utilized. It was stated that in order to decrease the operation cost the two types of ships needs to be effectively arranged.

Song and Dong (2013) examined a single liner long-haul service route design problem including route structure design, empty container repositioning, and ship deployment. The study aimed to make the total cost of a liner long-haul service route minimum where the total cost of a liner long-haul service route involves ship related costs, fuel consumption costs, port related costs, laden containers and empty container inventory-in-transition costs. A three-stage optimization method was formed to handle this problem. Moreover, the concept of topological structure and ship load factors were included. It made the decisions on the route structure design at the first stage easier and allowed introducing an efficient heuristic algorithm for repositioning empty containers at the second stage. At the third stage, the ship deployment problem regarding the number of ships, capacity of ships and sailing speeds were examined.

Tirado et al. (2013) investigated a dynamic and stochastic maritime transportation problem in industrial shipping. Three heuristics including the myopic dynamic heuristic, the multiple scenario approach with consensus, and the branch-and-regret heuristic, were utilized in the study in order to evaluate performance of these heuristics' on minimizing transportation costs. It was concluded that existence of stochastic information in the proposed method provided considerable savings to the shipping company. Moreover, it was stated that the branch-and-regret heuristic and the multiple scenario approach with consensus were better than the myopic dynamic heuristic.

Sterzik and Kopfer (2013) proposed a solution to the problem of moving full and empty containers among several terminals, depots and customers. In this study, the aim was making the total operating time of the trucks minimum. A Tabu Search Heuristic was proposed to obtain a solution for the composed mathematical formulation handling vehicle routing, scheduling and empty container repositioning.

7.4.5 Applications of Particle Swarm Optimization

Particle swarm optimization has been preferred to present a solution for various problems like freight transport network design, damage level prediction of non-reshaped berm breakwater, and the berth allocation problem. In the applications, computational efficiency of the particle swarm optimization was emphasized.

Harish et al. (2015) utilized support vector machine (SVM) and hybrid Particle Swarm Optimization tuned support vector machine PSO–SVM to predict damage level for non-reshaped berm breakwater. The comparisons of PSO–SVM with SVM, artificial neural network (ANN) and adaptive neuro fuzzy inference system (ANFIS) models were made. It was concluded that PSO–SVM and ANFIS provides a better performance than ANN and SVM. Furthermore, PSO–SVM is better than ANFIS in terms of computationally efficiency.

In the study of Ting et al. (2014), the discrete and dynamic berth allocation problem (BAP) was investigated by a mixed integer programming (MIP) model. The problem involved assigning ships to discrete berth positions and making the total waiting times and handling times for all ships minimum. Since it was an NP-hard problem, a particle swarm optimization (PSO) approach was adopted to come up with a solution to this problem. The comparison of the PSO's performance with tabu search, population training algorithm with linear programming, and clustering search approach was performed. As a result, PSO was found better than the other algorithms in terms of computation time and solution quality.

Yamada and Febri (2015) employed PSO approach to solve a freight transport network design problem. After the examination of the several variants of PSO, it was shown that the approach provided a superior performance.

7.4.6 Applications of Artificial Neural Networks

Some important topics in the literature like improving ship operations, predicting behavior of ship, providing automation in berthing, assessing port operability and port planning had been addressed with artificial neural networks and quite efficient solutions had been obtained.

Bal Beşikçi et al. (2016) developed a decision support system which was based on an artificial neural network in order to perform energy efficient ship operations. Artificial neural network was used to predict the fuel consumption of ship under several operational conditions. As the parameters in the prediction process, ship speed, revolutions per minute, mean draft, trim, cargo quantity on board, wind and sea effects were utilized. In the study, performance of the proposed method was compared with the performance of multiple regression analysis, and it was concluded that artificial neural network was better than multiple regression analysis. Therefore, a decision support system taking both the economic and environmental issues into consideration while making decisions at operational level was developed by using artificial neural network.

Praczyk (2015) used evolutionary neural networks in order to predict behavior of ship. Ship spatial orientation was provided by inertial navigational systems for the prediction. In the study, Assembler Encoding with Evolvable Operations method was employed to train neural networks. Linear Regression with Correction and Autoregressive Integrated Moving Average were also used as a reference point for the networks. It was stated that when these methods are compared, evolutionary neural networks provide more accurate predictions.

Ahmed and Hasegawa (2013) employed artificial neural networks to provide automation in berthing. By adopting nonlinear programming method, teaching data was created in order to guarantee optimal steering. Lavenberg–Marquardt algorithm in back propagation technique was employed to train neural networks for command rudder angle and propeller revolution output.

In the study of López et al. (2015), artificial neural networks were utilized to predict the values of wave height inside a harbor basin and its impacts on port operability by using deep-water buoy observations. Moreover, because of its generalization capabilities, multilayer feed-forward back-propagation neural networks were employed. In the study, the Levenberg–Marquardt algorithm was employed to train neural networks whereas Bayesian regularization was used to avoid over-fitting. It was concluded by using artificial neural networks that most influential variables on wave agitation inside the basin are wave height and period.

García et al. (2014) investigated the behavior of neural networks for the process of port planning, especially for the possible traffic growth and the requirements from the point of equipment and installations. It was stated that the traffic levels in the terminals could be efficiently examined with their method. In the study, a momentum descending gradient was employed to train neural networks. The results indicated that artificial neural networks are effectively utilized for the matters related to port planning and container terminals.

7.4.7 Applications of Support Vector Machines

Support vector machines like other intelligent techniques have been used in maritime industry. Maneuvering simulation and prediction of wave transmission of horizontally interlaced multilayer moored floating pipe breakwater can be given as the examples of its applications.

Luo et al. (2014) employed support vector machines for maneuvering simulation. Implicit models of maneuvering motion were acquired through support vector machines regression. Based on the regression maneuvering models, a simulation was conducted for the turning circle maneuver. Patil et al. (2012) proposed a genetic algorithm based support vector machine regression model (GA-SVMR) in order to predict wave transmission of horizontally interlaced multilayer moored floating pipe breakwater. Genetic algorithm was utilized to identify optimal SVM and kernel parameters of GA-SVMR models. The obtained results were compared with Artificial Neural Network (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS) with respect to their correlation coefficient, root mean square error, and scatter index. It was found that GA-SVMR outperforms ANN and ANFIS in terms of reliability.

7.4.8 Applications of Branch-and-Bound

Branch-and-bound technique has also been employed in maritime industry. In the literature, by using this technique, a safe ship trajectory in fuzzy environment was determined, the intermodal hub location and single-allocation ordered median hub location problems are solved.

Mostefa (2014) utilized the branch-and-bound method, dynamic programming, and genetic algorithm in order to identify safe ship trajectories in the case of collision in fuzzy environment. Optimal safe ship trajectory in the case of collision was considered as multistage decision-making in a fuzzy environment. The maneuverability parameters of the ship and the navigator's subjective assessments in making a decision were taken into account while building the model. As a result, genetic algorithm was found to provide the best output while the ship was controlled by navigator's subjective assessment.

He et al. (2015) proposed an MIP heuristic including branch-and-bound, Lagrangian relaxation, and linear programming relaxation. In the proposed heuristic, the branch-and-bound and Lagrangian relaxation methods were employed to produce a population of initial feasible solutions whereas the linear programming relaxation method was used to obtain a linear-relaxed solution. The proposed method was implemented to the intermodal hub location problem. According to the obtained results, the proposed heuristic approach provided better than the other methods.

Puerto et al. (2013) proposed a branch-and-bound-and-cut based algorithm to solve the Single-Allocation Ordered Median Hub Location problem. It was concluded that the branch-and-bound-and-cut based algorithm display a sufficient performance for small to medium sized problems.

Nishi and Izuno (2014) utilized column generation heuristic to come up with a solution to a ship routing and scheduling problem for international crude oil transportation with split deliveries. In the study, the column generation heuristic was compared with the branch and bound algorithm. As a result of the computations, it was stated that the performance of the column generation heuristic was more effective than the other one.

7.4.9 Applications of Fuzzy Logic

Fuzzy logic is one of the most preferable intelligent techniques since it helps to integrate uncertainty which commonly exists in real life to the models.

A multi-objective mathematical model was proposed by Ghodratnama et al. (2015) in order to come up with a solution to a capacitated single allocation hub location problem. Some parameters in the model were considered as uncertain parameters to make the model more realistic. Moreover, fuzzy multi-objective goal programming and the Torabi and Hassini's method were adopted to provide a solution to this problem. It was stated that fuzzy goal programming method provided solutions with higher quality than the Torabi and Hassini's (TH) method. Yet, fuzzy goal programming necessitates more computational times.

As we stated in previous sections, Harish et al. (2015), Lu and Liu (2013), Patil et al. (2012) incorporated fuzzy approach in their studies on damage level prediction, cruising vessel on river, and predicting wave transmission, respectively.

7.5 Maritime Intelligent Environmental Management Framework

An expert system consists of a knowledge base, an inference engine, and user interface. The structure of an expert system is given in Fig. 7.2. The factual and heuristic knowledge forms the knowledge base of expert systems. If the knowledge is widely shared (for instance, typically found in textbooks or journals), it is called as factual knowledge. On the other hand, the knowledge is called heuristic knowledge if it is more experiential and more judgmental. Knowledge is generally represented by a rule or a unit (also known as frame, schema, or list structure). A unit is a kind of property list of the entity and it is an assemblage of associated symbolic knowledge about the entity (Engelmore and Feigenbaum 1993). The task of an inference engine in the system is to organize and control the steps to obtain solution the problem. There are two types of inference engine also known as

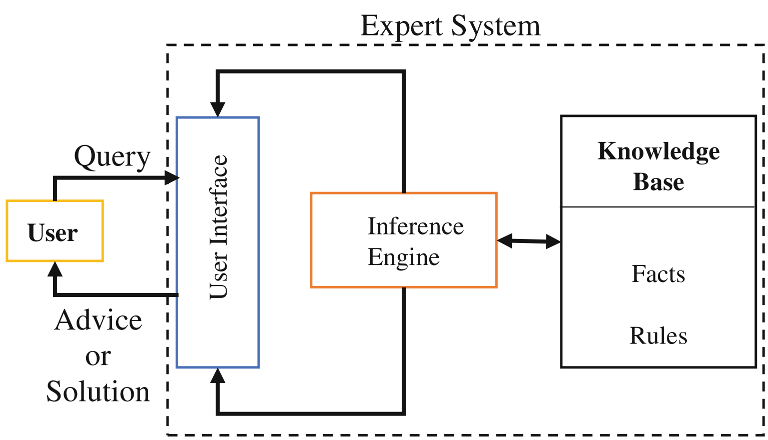

Fig. 7.2 Structure of an expert system

forward chaining and backward chaining. The forward chaining starts from a set of conditions and moves toward some conclusion while backward chaining starts from conclusion and produce a path to the conclusion. The user interface, the third component of expert system, interacts the user with the system. The effectiveness of the user interface design is vital since the quality of the user interface affects the acceptability of the expert system (Merritt 1989).

It is possible to develop an expert system which presents decision aid on maritime environmental disaster. For this, Fig. 7.3 presents Maritime Intelligent Environmental Disaster Management Framework. The proposed system includes model-base, database, environmental disaster modelling and decision support unit, environmental disaster management actions, ship operation management actions, user interfaces, and corresponding users. The model base incorporates the intelligent techniques such as Search Algorithms, Genetic algorithms, Artificial Neural Networks, and etc. The data sets along with the ship systems, processes, operating

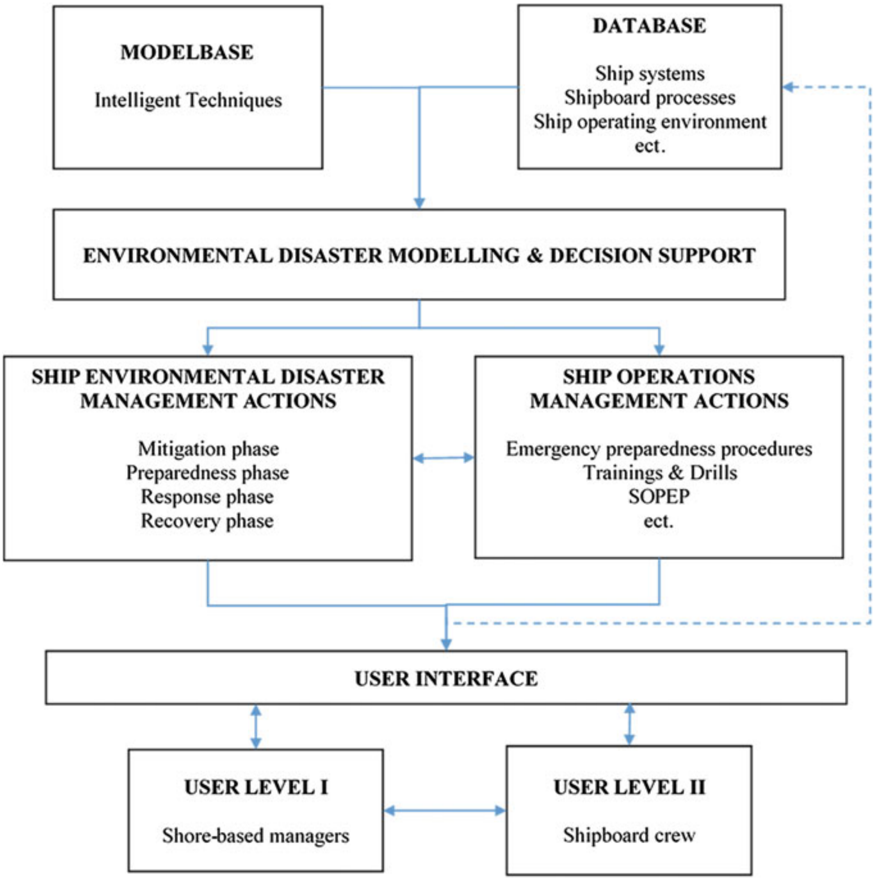

Fig. 7.3 Maritime intelligent environmental disaster management framework

environment, other facts and figures. The model-base and database enable structuring of environmental disaster model to provide decision support both to ship operation control and to disaster management concept. For instance, increasing the effectiveness of The Ship Oil Pollution Emergency Plan (SOPEP) can be addressed. Moreover, the arisen problems and uncertainties along with the mitigation, preparedness, response, and recovery phases can be treated. The mentioned analysis and relevant outcomes are also extended information through ship operating conditions and disaster monitoring database. The user interface can be controlled by shore based organization personnel and shipboard crew.

The Maritime Intelligent Environmental Disaster Management mainly consists of two fundamental actions: ship environmental disaster management actions which provide utmost acts to avoid risk; and ship operations management actions which support practical applications in the event of disaster.

The aim of the ship environmental disaster management actions is to cope with risks before environmental disasters. There are totally four main phases of actions in the ship environmental disaster management. These are mitigation, preparedness, response, and recovery, respectively. In the mitigation phase, it is aimed to reduce the effect of disaster. It primarily focuses on long-term actions. For instance, absorbent pads and sorbents are the materials to build up temporary barriers for avoiding spillage away. Another good example to mitigation phase is to get weather forecasting to avoid swell or high wave strikes in the event of spillage. The second phase is preparedness which includes a specific plan to be addressed in the event of disaster. This plan may include creative solutions to prevent disaster effects. The other phase is response which involves necessary emergency services and responders. For instance, urging emergency response team on-board ship or regional response team from the shore-based company is an alternative solution to avoid harmful substances or spillage during the disaster. Recovery phase is the final main phase of actions. The objective of the recovery phase is to restore the affected region and try to bring things back like before. Recovery phase should provide maximum efforts to bring things back such as marine ecology, mainland shores and climate. Cleaning up the affected area, giving non-hazardous chemical aid, restore the marine environment or cleaning up mainland shores are practical examples of recovery phase after disaster.

The aim of the ship operations management action is to carry out practical applications in the event of disaster such as oil spill. This may involve SOPEP, oil spill drills and trainings. The main aim of the SOPEP is to provide necessary guidance to be taken during an oil spill incident. The SOPEP contains chemical solvents, dispersants, absorbent, disposable bags, buckets, chemical protective suits, scuppers, sawdust, gloves, etc. The oil spill drills and trainings enable shipboard crew to become aware of the spillage and become proficient in the event of oil spill. Moreover, these practical applications bring a ship crew to an agreed standard of proficiency in the event of oil spill pollution.

7.6 Conclusion

Safety culture and environmental stewardship, cited within critical actions, need for a new sustainable transportation concept defined by IMO. The environment related actions are also associated with the innovative shipboard technologies, energy efficiency studies, and other operational and managerial aspects. Controlling the potential impacts in the complex operational environment requires advance action plans with high compliance level. The plans against environmental disasters can be effective by providing those three key aspects; (i) systems functionality, (ii) system interfaces design and installation, (iii) operator behaviors. At this insight, this chapter promotes to support environmental disaster prevention efforts at sea via integrating intelligent techniques. The proposed MIEDM framework is based on disaster management principles and intelligent techniques to provide decision support through users in both ashore executives and onboard personnel. The main idea is to enhance the ships and other marine systems' operating mechanism along with the mitigation, preparedness, response, and recovery phases to eliminate the potential impacts of maritime environmental disasters. In the operation of existing marine systems, the preparedness phase is more emphasized. Besides considering the overall phases, the intelligent systems are capable of strength each phase via taking the dependencies among the actions. Moreover, the benefits of the intelligent systems in disaster management are highlighted as follows: (*i*) The system has the ability to collect the data, to control environment, to report, and to communicate with other systems, (*ii*) It has the ability to forecast unexpected changes in the environment and to take action against them. (*iii*) The system may decide or select suitable actions among prevention measures regardless of human operators and other systems. (*iv*) It has the ability of learning or updating its prevention measures in its database. Furthermore, the MIEDM framework can be extended to practical demonstrations subsequent points for operational improvements in different marine systems (i.e. ship platform, offshore structures, port and terminals, etc.).

References

Ahmed, Y. A., & Hasegawa, K. (2013). Automatic ship berthing using artificial neural network trained by consistent teaching data using nonlinear programming method. *Engineering Applications of Artificial Intelligence, 26*(10), 2287–2304.

Akyuz, E. (2015). A hybrid accident analysis method to assess potential navigational contingencies: The case of ship grounding. *Safety Science, 79*, 268–276.

Ali Ghorbani, M., Khatibi, R., Aytek, A., Makarynskyy, O., & Shiri, J. (2010). Sea water level forecasting using genetic programming and comparing the performance with artificial neural networks. *Computers & Geosciences, 36*(5), 620–627.

Anyanwu, J. O. (2014). The causes and minimization of maritime disasters on passenger vessels. *Global Journal of Researches in Engineering: Industrial Engineering, 14*(2), Version 1.0.

Bal Beşikçi, E., Arslan, O., Turan, O., & Ölçer, A. (2016). An artificial neural network based decision support system for energy efficient ship operations. *Computers & Operations Research, 66*, 393–401.

Bateman, J. A., Hois, J., Ross, R., & Tenbrink, T. (2010). A linguistic ontology of space for natural language processing. *Artificial Intelligence, 174*(14), 1027–1071.

Castillo, O., & Melin, P. (2014). A review on interval type-2 fuzzy logic applications in intelligent control. *Information Sciences, 279*, 615–631.

Celik, M., & Topcu, Y. I. (2009). Use of an ANP to prioritize managerial responsibilities of maritime stakeholders in environmental incidents: An oil spill case. *Transportation Research Part D, 14*, 502–506.

Chauvin, C., Lardjane, S., Morel, G., Clostermann, J.-P., & Langard, B. (2013). Human and organisational factors in maritime accidents: Analysis of collisions at sea using the HFACS. *Accident Analysis and Prevention, 59*, 26–37.

Chen, S., & Chen, J. (2010). Forecasting container throughputs at ports using genetic programming. *Expert Systems with Applications, 37*(3), 2054–2058.

Dong, B., Zhu, L., Li, K., & Luo, M. (2015). Acceptance of the international compensation regime for tanker oil pollution—And its implications for China. *Marine Policy, 61*, 179–186.

Dongdong, L., Bin, L., Chenguang, B., Minghui, M., Yan, X., & Chunyan, Y. (2015). Marine oil spill risk mapping for accidental pollution and its application in a coastal city. *Marine Pollution Bulletin, 96*, 220–225.

EMSA. (2015). Annual overview of marine casualties and incidents, 2015.

Engelmore, R. S., & Feigenbaum, E. (1993). Knowledge-based systems. In: Japan, WTEC Hyper-Librarian.

Erkaymaz, O., Özer, M., & Yumuşak, N. (2012). Performance analysis of a feed-forward artificial neural network with small-world topology. *Procedia Technology, 1*, 291–296.

Escario, J., Jimenez, J., & Giron-Sierra, J. (2012). Optimisation of autonomous ship manoeuvres applying ant colony optimisation metaheuristic. *Expert Systems with Applications, 39*(11), 10120–10139.

French-McCay, D. P. (2004). Oil spill impact modeling: Development and validation. *Environmental Toxicology and Chemistry, 23*, 2441–2456.

García, T., Cancelas, N., & Soler-Flores, F. (2014). The artificial neural networks to obtain port planning parameters. *Procedia—Social and Behavioral Sciences, 162*, 168–177.

Garza-Gil, M. D., Suris-Regueiro, J. C., & Varela-Lafuente, M. M. (2006). Assessment of economic damages from the prestige oil spill. *Marine Policy, 30*(5), 544–551.

Gaur, S., & Deo, M. C. (2008). Real-time wave forecasting using genetic programming. *Ocean Engineering, 35*, 1166–1172.

Geng, J., Li, M., Dong, Z., & Liao, Y. (2015). Port throughput forecasting by MARS-RSVR with chaotic simulated annealing particle swarm optimization algorithm. *Neurocomputing, 147*, 239–250.

Ghodratnama, A., Tavakkoli-Moghaddam, R., & Azaron, A. (2015). Robust and fuzzy goal programming optimization approaches for a novel multi-objective hub location-allocation problem: A supply chain overview. *Applied Soft Computing, 37*, 255–276.

Goerlandt, F., & Montewka, J. (2015). A framework for risk analysis of maritime transportation systems: A case study for oil spill from tankers in a ship–ship collision. *Safety Science, 76*, 42–66.

Gómez-Vallejo, H. J., Uriel-Latorre, B., Sande-Meijide, M., Villamarín-Bello, B., Pavón, R., Fdez-Riverola, F., et al. (2016). A case-based reasoning system for aiding detection and classification of nosocomial infections. *Decision Support Systems, 84*, 104–116. doi:10.1016/j.dss.2016.02.005

Graham, P. (2012). Casualty and world fleet statistics at 01.01.2012. Communication presented at IUMI 2012. St Petersburg.

Guo, W. J., Wang, Y. X., Xie, M. X., & Cui, Y. J. (2009). Modeling oil spill trajectory in coastal waters based on fractional Brownian motion. *Marine Pollution Bulletin, 58*, 1339–1346.

Hansen, H. L., Jepsen, J. R., & Hermansen, K. (2012). Factors influencing survival in case of shipwreck and other maritime disasters in the Danish merchant fleet since 1970. *Safety Science, 50*, 1589–1593.

Harish, N., Mandal, S., Rao, S., & Patil, S. (2015). Particle swarm optimization based support vector machine for damage level prediction of non-reshaped berm breakwater. *Applied Soft Computing, 27*, 313–321.

He, Y., Wu, T., Zhang, C., & Liang, Z. (2015). An improved MIP heuristic for the intermodal hub location problem. *Omega, 57*, 203–211.

IMO. (2005). Construction requirements for oil tankers—double hulls, 2005.

ITOPF. (2015). *Oil tanker spill statistics 2014*. London: United Kingdom.

Jiang, W. Y., Lin, Y., Chen, M., & Yu, Y. Y. (2015). A co-evolutionary improved multi-ant colony optimization for ship multiple and branch pipe route design. *Ocean Engineering, 102*, 63–70.

Kim, K., & Moon, K. (2003). Berth scheduling by simulated annealing. *Transportation Research Part B: Methodological, 37*(6), 541–560.

Koch, P., Wagner, T., Emmerich, M. T. M., Back, T., & Konen, W. (2015). Efficient multi-criteria optimization on noisy machine learning problems. *Applied Soft Computing, 29*, 357–370.

Kosmas, O., & Vlachos, D. (2012). Simulated annealing for optimal ship routing. *Computers & Operations Research, 39*(3), 576–581.

Lazarowska, A. (2014). Ant colony optimization based navigational decision support system. *Procedia Computer Science, 35*, 1013–1022.

Lee, M., & Jung, J.-Y. (2015). Pollution risk assessment of oil spill accidents in Garorim Bay of Korea. *Marine Pollution Bulletin, 100*, 297–303.

Lee, J., & Kim, B. (2015). Industrial ship routing problem with split delivery and two types of vessels. *Expert Systems with Applications, 42*(22), 9012–9023.

Liu, X. (2010). Integrated modeling of oil spill response strategies: A coastal management case study. *Environmental Science & Policy, 13*, 415–422.

Liu, X., & Wirtz, K. W. (2006). Consensus oriented fuzzified decision support for oil spill contingency management. *Journal of Hazardous Materials, A134*, 27–35.

Lloyd Register Rulefinder. (2005). MARPOL—International Convention for the Prevention of Pollution from Ships Amended by Resolution MEPC.111(50) Amended by Resolution MEPC.115(51) Amended by Resolution MEPC.116(51), 2005.

López, I., López, M., & Iglesias, G. (2015). Artificial neural networks applied to port operability assessment. *Ocean Engineering, 109*, 298–308.

Loureiro, M. L., Ribas, A., Lopez, E., & Ojea, E. (2006). Estimated costs and admissible claims linked to the prestige oil spill. *Ecological Economics, 59*(1), 48–63.

Lu, H. C., & Liu, H. K. (2013). Ant colony fuzzy neural network controller for cruising vessel on river. *Applied Ocean Research, 42*, 43–54.

Luo, W., Moreira, L., & Guedes Soares, C. (2014). Manoeuvring simulation of catamaran by using implicit models based on support vector machines. *Ocean Engineering, 82*, 150–159.

Lupanov, A. I., Chermianin, S. V., & Logunov, K. V. (2013). The human factor in maritime disasters. *Archives des Maladies Professionnelles et de l'Environnement, 74*(5), 553–554.

Merritt, D. (1989). *Building expert systems in prolog*. Berlin: Springer.

Molloy, M. S., Mulhern, J., & Gans, L. (2016). Maritime disasters. *Ciottone's disaster medicine* (2nd ed., pp. 945–948). Amsterdam: Elsevier.

Mostefa, M. (2014). The branch-and-bound method, genetic algorithm, and dynamic programming to determine a safe ship trajectory in fuzzy environment. *Procedia Computer Science, 35*, 348–357.

Musa, R., Arnaout, J., & Jung, H. (2010). Ant colony optimization algorithm to solve for the transportation problem of cross-docking network. *Computers & Industrial Engineering, 59*(1), 85–92.

Negro, M. G., Villasante, S., Penela, A. C., & Rodriguez, G. R. (2009). Estimating the economic impact of the prestige oil spill on the death coast (NW Spain) fisheries. *Marine Policy, 33*(1), 8–23.

Nishi, T., & Izuno, T. (2014). Column generation heuristics for ship routing and scheduling problems in crude oil transportation with split deliveries. *Computers & Chemical Engineering, 60*, 329–338.

Nova-Corti, I., Gonzalez-Laxe, F., & Pociovalisteanu, D.-M. (2015). The economic analysis of maritime catastrophes in sensitive areas: The assessment and calculation of damages in the environment and population's way of life. *Journal of Cleaner Production, 107*, 267–278.

Patil, S., Mandal, S., & Hegde, A. (2012). Genetic algorithm based support vector machine regression in predicting wave transmission of horizontally interlaced multi-layer moored floating pipe breakwater. *Advances in Engineering Software, 45*(1), 203–212.

Perez, J. (2003). Early socio-political and environmental consequences of the prestige oil spill in Galicia. *Disasters, 27*(3), 207–223.

Perry, R. I., Barange, M., & Ommer, R. E. (2010). Global changes in marine systems: A social-ecological approach. *Process in Oceanography, 87*(1), 331–337.

Praczyk, T. (2015). Using evolutionary neural networks to predict spatial orientation of a ship. *Neurocomputing, 166*, 229–243.

Puerto, J., Ramos, A., & Rodríguez-Chía, A. (2013). A specialized branch & bound & cut for single-allocation ordered median hub location problems. *Discrete Applied Mathematics, 161* (16–17), 2624–2646.

Reed, M., Johansen, O., Brandvik, P. J., Daling, P., Lewis, A., Fiocco, R., et al. (1999). Oil spill modeling towards the close of the 20th century: Overview of the state of the art. *Spill Science and Technology Bulletin, 5*, 3–16.

Samuelides, M. S., Ventikos, N. P., & Gemelos, I. C. (2009). Survey on grounding incidents: Statistical analysis and risk assessment. *Ships and Offshore Structures, 4*(1), 55–68.

Satunin, S., & Babkin, E. (2014). A multi-agent approach to intelligent transportation systems modeling with combinatorial auctions. *Expert Systems with Applications, 41*(15), 6622–6633.

Song, D., & Dong, J. (2013). Long-haul liner service route design with ship deployment and empty container repositioning. *Transportation Research Part B: Methodological, 55*, 188–211.

Sterzik, S., & Kopfer, H. (2013). A Tabu search heuristic for the inland container transportation problem. *Computers & Operations Research, 40*(4), 953–962.

Teymourian, E., Kayvanfar, V., Komaki, G. H. M., & Zandieh, M. (2016). Enhanced intelligent water drops and cuckoo search algorithms for solving the capacitated vehicle routing problem. *Information Sciences, 334–335*, 354–378.

Ting, C., Wu, K., & Chou, H. (2014). Particle swarm optimization algorithm for the berth allocation problem. *Expert Systems with Applications, 41*(4), 1543–1550.

Tirado, G., Hvattum, L., Fagerholt, K., & Cordeau, J. (2013). Heuristics for dynamic and stochastic routing in industrial shipping. *Computers & Operations Research, 40*(1), 253–263.

Tomera, M. (2014). Ant colony optimization algorithm applied to ship steering control. *Procedia computer science, 35*, 83–92.

Turban, E., Sharda, R., Delen, D., & King, D. (2010). *Business intelligence* (2nd ed.). Upper Saddle River: Prentice Hall.

Wirtz, K. W., Baumberger, N., Adam, S., & Liu, X. (2007). Oil spill impact minimization under uncertainty: Evaluating contingency simulations of the prestige accident. *Ecological Economics, 61*, 417–428.

Wirtz, K. W., & Liu, X. (2006). Integrating economy, ecology and uncertainty in an oil-spill DSS: The prestige accident in Spain, 2002. *Estuarine, Coastal and Shelf Science, 70*, 525–532.

Wu, Y., Luo, J., Zhang, D., & Dong, M. (2013). An integrated programming model for storage management and vehicle scheduling at container terminals. *Research in Transportation Economics, 42*(1), 13–27.

Yamada, T., & Febri, Z. (2015). Freight transport network design using particle swarm optimisation in supply chain–transport supernetwork equilibrium. *Transportation Research Part E: Logistics and Transportation Review, 75*, 164–187.

Yan, L., Jinsong, B., Xiaofeng, H., & Ye, J. (2009). A heuristic project scheduling approach for quick response to maritime disaster rescue. *International Journal of Project Management, 27*, 620–628.

Zhu, L., James, P., & Zhang, S. (2002). Statistics and damage assessment of ship grounding. *Marine Structures, 15*, 515–530.

Part III
Energy Management

Chapter 8
Modelling Solar Energy Usage with Fuzzy Cognitive Maps

Veysel Çoban and Sezi Çevik Onar

Abstract Solar energy is a reliable and sustainable energy resource but its usage is still limited. Modeling solar energy generation capacity can help increasing solar energy usage. In this chapter, the factors that affect solar energy usage and the relations among them are defined by a comprehensive literature review. These factors are complex and the relations between them are ambiguous. Fuzzy cognitive maps are used for modelling solar energy generation capacity. Fuzzy cognitive maps are excellent tools for modelling such complexity and ambiguity. The relations among the factors are defined based on the experts' opinions. Different scenarios are developed and the changes in the solar energy generation capacity have been analyzed.

8.1 Introduction

Energy is a scare resource and has been important for over several centuries. Fossil fuels are the main energy resources. Fossil fuels are known to be one of the major contributors to the greenhouse effect that heat earth, disrupt its energy balance and cause climate change (United States Environmental Protection Agency (USEPA) 2016). Renewable energy resources are considered as the alternative for fossil fuels. Usage of renewable energy resources has been increased over the last two decades since they cause less damage to the environment. The renewable energy resources such as wind, solar, geothermal and tidal energy are starting to get global attention on almost any level possible.

Solar energy was the only source of energy until fossil fuels has been discovered (Silvi 2008). Over the last century, using solar power to generate energy has been

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considered many times but due to the relatively high costs and low efficiency, these attempts were not successful until the last decade. Electricity generated from solar sources are not considerably significant when it comes to comparing with other sources of electricity but solar energy investments are increasing. Solar energy is widely being considered as a reliable source of electricity generation. According to British Petroleum, the world has added 40.2 GW of solar power generating capacity which results in total of 180 GW. Total installed base of solar electricity generation capacity has quadrupled in the past four years. In 2014, solar generation capacity grew by 38 % (BP 2015). According to Renewable Energy Policy Network, total installed capacity of solar energy reached 177 GW of photovoltaics and 4.4 GW of concentrated solar power systems (REN21 2015). Germany is the number one country when it comes to solar electricity consumption with 18.8 % of global total. Germany is being followed by China (15.7 %), Italy (12.7 %), Japan (10.4 %), and United States of America (10 %) (BP 2015).

The usage of solar energy depends on several factors such as incentives provided by government, physical conditions, and energy prices. Germany is the world leader in deploying renewable energy to the grid. Germany investing heavily on renewable energy and eliminating nuclear (REN21 2015). Germany has a successful energy policy provided by using feed-in-tariff mechanisms, revised ownership structure and reduced dependence on fossil fuels (REN21 2015). Although many countries focus on solar energy, solar energy usage is still limited and remain very low compared to its potential. Defining the factors that affect solar energy usage and the relations among them will show the ways to increase solar energy usage. These factors are complex and the relations between them are ambiguous. Fuzzy cognitive maps are excellent tools for modelling such complexity and ambiguity. In this chapter, fuzzy cognitive maps are used for modelling solar energy generation capacity. The factors and the relations among the factors are revealed based on both a comprehensive literature review and experts' opinions.

The rest of the chapter is organized as follows. In Sect. 8.2, renewable energy and the main concepts of solar energy are given. Section 8.3 presents basic concepts of fuzzy cognitive maps and a literature review of fuzzy cognitive map. Section 8.4 gives the proposed solar energy model which is based on fuzzy cognitive maps. The last section concludes the paper and gives some perspectives.

8.2 Renewable Energy

Energy is the key factor in the generation of social and economic life for all countries in world. The historical developments of the industrialization and urbanization of the countries have been reflecting a strong relationship with their energy consumption. The general tendency of the countries to the industrialization has caused to increase the energy demand and consumption all around the world. While energy demand of the European Union is expected to increase by 0.5 %/year, energy demands of the Asia countries are expected to increase by 3 %/year such that the average expecting energy demand of the world is % 1.8 %/year in the period from 2000 to 2030 (Commision 2003).

The energy is provided by two inverse channels that are named as a renewable and a non-renewable source that is the conventional and primary energy sources. Non-renewable energy sources based on consumption of fossil fuels such as are coal, oil, natural gas release air-pollutant gases (CO_2, NO_x) that have adverse effects on the environment and human health with the greenhouse effect. Increasing trend of the fossil fuel consumption in the period from 2007 to 2030 (Agency 2009) is likely to lead to global warming, climate change and increases in human damages. On the other side, fossil fuel energy sources are finite and becoming scarce that this causes to increase energy prices and decrease economic developments. The world's increasing energy demand based on industrialization and population growth causes countries to tend to the alternative energy sources that will be different from rapidly depleting fossil fuel energy sources.

Renewable energy that generates the energy from infinite natural sources such as sun, water, wind, geothermal heat is one of the alternative energy sources. Renewable energies that do not use any other production processes have some important advantages against the fossil fuel sources such as using domestic resources, not emitting air-pollutant gases, providing sustainable and safety energy, and decreasing greenhouse effect. Also, they cause to increase of the economic activities by decreasing energy prices and providing new businesses in energy sector. For these reasons, governments from different regions around the world tend to develop their renewable energy technologies and utilize from their renewable energy sources. Therefore, the developing the renewable energy technologies and utilizing from renewable energy sources are having critical importance for the sustainable economic development and social wealth of all countries.

Based on the definition of the renewable energy used by the UK government, renewable energy technologies can be divided into eight classes as: solar photovoltaic, micro-wind, micro-hydro, large-scale wind, large-scale hydro, energy from waste, landfill gas and biomass (Kahraman et al. 2009). These differences among the renewable energy technologies reflect the different requirements based on economic, ecologic, technical, and social in order to efficiently utilize from different renewable energy sources. In order to install the most suitable renewable energy alternative that affects the economic growth and social wealth of the countries, many factors are defined according to their specific properties and the relationships among them are evaluated by experts. In this aims, governments can provide economic, social and political supports such as incentives, regulations, and international treaties.

8.3 Solar Energy

When world's energy demand is increasing with improving industry and growing population, conventional energy supply methods based on fossil fuel will remain incapable because of their non-renewable and finite sources. Besides, the scarcity of the fossil based energy sources triggers the irregular change and rise of the energy price that cause the unstable economies and social unrests. Therefore, the world tends toward the alternative energy supply sources such as sun, wind, geothermal that are called as renewable sources and their efficiently obtaining methods by improving new technologies (Mackay 2015; Ameta 2016). Improving new technologies in the alternative energy methods and their spreading among society cause to decrease of the cost of energy production and energy price that affect economic and social conditions.

Sun is the primary and origin source of many renewable energies such as solar, wind, and wave by provided atmospheric movements and ecologic formations. Solar energy generated by sun can also be accepted as a basic and the most important energy source among alternatives against the threats of the fossil fuel resources depletion. Solar energy is used in heating, enlightenment, and electricity with its modern technologies such as solar heating, photo-voltaic, concentrated solar power (Ameta 2016). It has some advantages and disadvantages compared with renewable and fossil based energy sources that they affect the selection of the solar energy sources by investors.

Solar energy has an environmental sensitivity such that it does not emit any waste, air-pollutant and greenhouse gases, and noise, but it has the indirect effects on environment with its production materials like cadmium telluride. Although its initial costs for purchasing and constructing that consist of solar panels, wiring, inverter, and batteries are fairly high such that governments try to encourage the investors by incentives such as feed-in tariff and regulations, it has not any production cost and has a little maintenance cost with providing long term warranties and services (Kalogirou 2014a). Improvements in solar energy technology that is cooperate with nanotechnology, chemistry, and physic give hope to decrease the initial costs and increase the efficiency of the solar energy production. Availability of the solar technology that consists of technical infrastructure such as distance to grid and land usage that solar panels need to use a lot of space and weather conditions like number of cloudy and rainy days affect the feasibility and efficiency of the solar energy sources (Kalogirou 2014b; Mackay 2015).

In this study, we define the factors (Table 8.1) that affect and are affected by "New Solar Energy Generation Capacity" that are based on their advantages and disadvantages against alternative renewable energies and fossil based energy sources. This study aims to verify the basic factors and ascertain their effects on the solar energy sources that they reflect the main tendencies of the investors.

8.4 Fuzzy Cognitive Maps

Axelrod (1976) introduced the Cognitive Map (CM) as a directed graph that is presented to visually model causal relationships (direct or indirect—hidden relationships) among concepts. Causal relationships are defined with binary numeric (crisp) values in CM that can be defined as Crisp Cognitive Maps (CCMs). An

Table 8.1 Factors related to installing solar energy sources

Factors	Definitions
Energy demand (ED)	The requirement for energy as an input to provide products and/or services (EIA 2016)
Energy price (EP)	The amount of money or consideration-in-kind for which an energy is bought, sold, or offered for sale. There is an inverse relation between non-renewable energy cost and attraction of renewable energy investments (Zhang et al. 2014)
Energy supply (ES)	Energy made available for future disposition. Supply can be considered and measured from the point of view of the energy provider or the receiver (EIA 2016)
Availability of alternative renewable energies (AARE)	Energy resources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy resources include biomass, hydro, geothermal, solar, wind, ocean thermal, wave action, and tidal action. The availability of renewable energy sources shall be governed by the physical capabilities of these sources and by limitations imposed by local or global regulatory agencies
New solar energy generation capacity (NSEC)	The amount of energy that is generated with the process of producing energy by transforming solar energy; also, the amount of energy produced, expressed in kilowatt-hours for electric (EIA 2016)
Cost of solar energy (CSE)	The total cost of producing and/or transmitting solar energy above some previously determined base cost. The cost of solar energy has a declining trend rapidly in the last decades, but its cost is still higher than the cost of conventional energy technologies (Adaramola 2015)
Solar energy incentives (SEI)	The programs that offers monetary or non-monetary awards to encourage producers to buy energy-efficient equipment and to participate in programs designed to reduce energy usage. Examples of incentives are zero or low-interest loans, rebates, and direct installation of low cost measures. Renewable energy development policies which are consist of law, supportive policies (tax relief, subsidized loans, feed-in tariff) and development plans complement each other and support the generation of new renewable energy (Zhang et al. 2014)
Technical applicability of solar technology (TAST)	The feasibility of the solar technologies that are usable in the given geological and operational conditions for production, processing, and sales of the solar energy (Bogetoft 2007)
Regulations (RG)	The governmental function of controlling or directing energy entities through the process of rulemaking and adjudication. In some conditions, laws and regulations could constrain or release the deployment of solar energy (Adaramola 2015)

(continued)

Table 8.1 (continued)

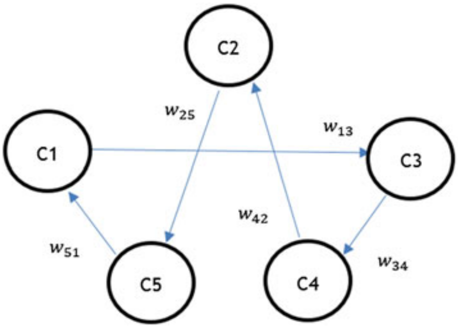
Factors	Definitions
Global treaties (GT)—Kyoto protocol	A written statement signed by two or more parties that specifies the terms for controlling energy. The Kyoto Protocol sets binding greenhouse gas emissions targets for countries that sign and ratify the agreement. The gases covered under the Protocol include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), per fluorocarbons (PFCs) and sulfur hexafluoride. The clean development mechanism (CDM) of the Kyoto Protocol has a very small role in solar energy generation among the renewable energy technologies because of its weak cost competitiveness (Adaramola 2015)

extension of the CMs with representing the causal relationships by linguistic values instead of the binary values were introduced as Fuzzy Cognitive Maps (FCMs) by Kosko (1986). FCMs are used as a tool in describing the degree of the relationship between concepts in linguistic terms (fuzzy numbers).

FCMs have been applied in many different scientific fields such as strategic planning (Diffenbach 1982), environmental management (Özesmi and Özesmi 2004), and decision making (Zhang et al. 1989). FCMs represent knowledge in a symbolic form for the modelling complex and dynamic systems. FCMs consist of concepts (nodes) and connections (arcs/edges) that represent the strengths of the interactions among concepts and show the dynamism of the system. Causal relationships among the concepts are modelled in directed graph with feedback and weighted in the interval [−1, 1] as positive, negative or neutral (Kosko 1986) by fuzzy numbers. Signed weighted edges connect the concept and represent the causal relationship among the concepts.

Nodes and weighted edges in graphic display are assigned the concepts (C_i) and relationships among concepts (w_{ij}) respectively. Initially experts' suggested weights of all the interconnections among the concepts in FCMs are shown in the weight matrix (W). There is no self-loops (no concept connects itself) in FCMs, so the diagonal of the matrix is defined as zero ($w_{ii} = 0$). A simple FCMs is drawn with five concepts (C_1, C_2, C_3, C_4, C_5) and five directed weighted edges and its weighted matrix is shown in Fig. 8.1.

Concepts, cause-effect connections among them and initial state of system are determined by expert(s). Initial state values of the concepts and edges can be obtained from the knowledge and experiments of the expert(s), simulation results or recorded data. Concepts are also described with their activation level in the related time as A_i^t that is defined in the interval [0, 1] as a degree of presence of a given concept in the system. The initial state vector A^0 can be defined as binary or rational values such as respectively:



$$W = \begin{bmatrix} 0 & 0 & w_{13} & 0 & 0 \\ 0 & 0 & 0 & 0 & w_{25} \\ 0 & 0 & 0 & w_{34} & 0 \\ 0 & w_{42} & 0 & 0 & 0 \\ w_{51} & 0 & 0 & 0 & 0 \end{bmatrix}$$

Fig. 8.1 A simple FCMs and its weight matrix

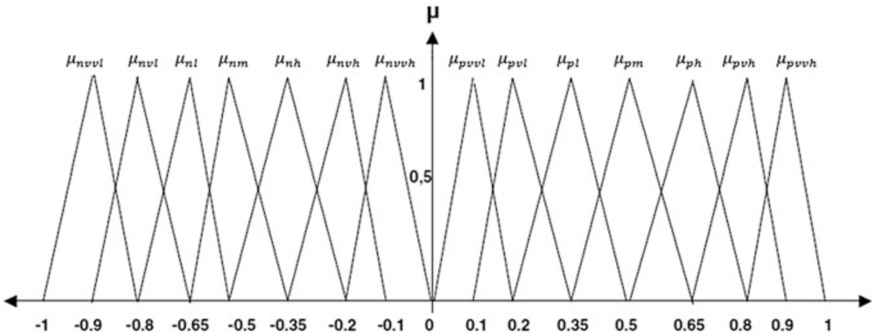


Fig. 8.2 Triangular membership functions of the linguistic variables (Xirogiannis et al. 2010)

$$A^0 = [0\,1\,0\,0\,1\,0\,0\,1\,0\,0] \quad A^0 = [0.42, 0.16, 0.34, 0.66, 0.35, 0.41]$$

The expert can define the causal relationships between concepts in FCMs with linguistic statements that allow to experts to express their knowledge naturally and easily. The experts' linguistic expressions used into evaluate the causality among factors include the sign and size of the influence such as positive high, negative medium, and positive very high that can be described within triangular membership functions of the fuzzy sets (Fig. 8.2). Linguistic variables are transformed (defuzzified) in the [−1, 1] interval as a crisp value by different defuzzification methods such as Weighted Average Method, Center of Gravity. Crisp values transformed from linguistic evaluations are defined as a weight matrix of the concepts in FCM and used to calculate the new state of the system. In this study, negative/positive very very low, very low, low, medium, high, very high, and very high linguistic terms are used as a linguistic variable in order to define the causal relationships around the "installing solar energy" and applied to triangular fuzzy membership function in order to transform them into crisp values.

Feedback mechanism in FCMs that represents the butterfly effect among concepts provides a dynamic system. Operations in FCMs start with defining the initial value (current state) of each concept based on the experts' evaluations, and then concepts (factors or nodes) interact with each other until an equilibrium point (Kosko 1997). The activation levels of all concepts of the FCMs in time t is showed in an initial state vector as $A^t = [A_1^t, A_2^t, \ldots, A_n^t]$. The new values of concepts at the new time step is calculated as;

$$A_i^{t+1} = f\left(\sum_{j=1}^{n} A_j^t w_{ij} + A_i^t\right) \tag{8.1}$$

In the equation, the previous state value (A_i^t) of concept C_i and the total causal effects of other concepts on the concept C_i (weighted activation sum of C_i) are summed and used in the $f(\cdot)$ transformation (threshold) function.

The thresholds function is used to transform the weighted activation sum $\left(\sum_{j=1}^{n} A_j^{t-1} w_{ji} + A_i^{t-1}\right)o$ to the interval [0, 1] or [−1, 1] and determines the activation level of each concept. The most commonly used threshold functions which sigmoid and hyperbolic tangent functions are continuous transformation functions are shown below (Tsadiras 2008; Haykin 1998):

- Bivalent (step) function: This function transforms the activation level of each concept to 1 (activated) or 0 (inactivated) and obtained a binary FCMs.

$$f(x) = \begin{cases} 0, x \leq 0 \\ 1, x \geq 0 \end{cases} \tag{8.2}$$

- Trivalent function: This function defines the activation levels in three part as −1, 0, and 1 and these values refer the decreasing, remain stable and increasing of the concept respectively.

$$f(x) = \begin{cases} -1, x \leq -0.5 \\ 0, -0.5 < 0 < 0.5 \\ 1, x \geq 0.5 \end{cases} \tag{8.3}$$

- Sigmoid function: This function is commonly used function in the FCM that transforms the sum of the weights in the interval $[0, 1]$. Logistic function is the special case of the sigmoid function that δ parameter in sigmoid function is accepted as 1.

$$f(x) = \frac{1}{1 + \mathrm{e}^{-\delta x}} \tag{8.4}$$

$$Logistic\ function: f(x) = \frac{1}{1 + \mathrm{e}^{-x}} \tag{8.5}$$

- Hyperbolic Tangent function: This function transforms the sum of the weights in the interval $[-1, 1]$ whose initial state vector can include the negative state.

$$f(x) = \tan h(\delta x) = \frac{e^{\delta x} - e^{-\delta x}}{e^{\delta x} + e^{-\delta x}} \tag{8.6}$$

where x is the activation level of concept at related time. Parameter δ is the positive real number that is used to determine the shape of the function curve. Delta value (δ) is the problem-specific parameter and might be defined by researcher. When delta value takes large values as $\delta \geq 10$, the sigmoid function closes to the discrete function and activation levels are defined in the interval (0, 1). If delta value is defines with smaller values such as $\delta \leq 1$, the sigmoid function resembles to a linear function. If scholar wants to define a good degree of fuzzification in the interval [0, 1], delta value should be defined closer to five (Bueno and Salmeron 2009).

Activation level that is the value assigned to each concept is updated until convergence at a steady state. The concepts whose edge values are different from zero have an effect on the updating process of the activation level from A^t to A^{t+1}. In order to stop the iteration (updating), a limit value can be defined as $A^{t+1} - A^t \leq e$ that can be change according to study type and generally it is accepted as 0.001. Fixed-point equilibrium, limit cycle and chaotic behavior are another states that terminate the iterations (Tsadiras and Margaritis 1997; Kosko 1997; Dickerson and Kosko 1994).

Causal and interactive relationships among concepts within different aspects define the dynamic fuzzy system. Relationships represent the experts' knowledge and experience with linguistic or numerical values. FCMs are realistic and simple tool in the analyzing and decision making of the uncertain real world problems such as social, managerial, biological, economical, and energy problems.

8.5 Application

In this study, we defined the nine different factors around the "New Solar Energy Generation Capacity" and their causal relationships in the systems are graphically represented with FCMs that also analyzed the strengths of factors. The weight of the relationships are linguistically described by experts and defined as weight matrix.

The basic factor of the system is the New Solar Energy Generation Capacity (NSEC) and the other factors can be named as affecting factors that have effects on basic factor. The weights between the factors are defined according to importance level of relationships by experts who work academically in the field of renewable and solar energy. The effect of a specific factor on the other factors was determined by using linguistic terms, very low, low, medium low, medium, medium high, high, and very high in the interval [−1, 1] as "negative" or "positive" (Fig. 8.2). Dotted

Table 8.2 Linguistic terms of the causal relationships among the concepts

	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
Energy demand (ED)		VH			H					
Energy price (EP)	NM		VH		VVH					
Energy supply (ES)		NVH					NM			
Availability of alternative renewable energies (AARE)			H							
New solar energy generation capacity (NSEC)			H							
Cost of solar energy (CSE)					NVVH					
Solar energy incentives (SEI)				M		NVH				
Technical applicability of solar technology (TAST)					M	NVH				
Regulations (RG)							VVH			
Global treaties (GT)									M	

lines in the constructed FCM represent a negative causality, where the solid lines represent a positive causality among the relevant factors. For example, relationship degree between “Energy Price” and “New Solar Energy Generation Capacity” was linguistically defined as “Positive Very High” by experts’ consensus. Table 8.2 represents the relationship degrees (i.e., the relationship matrix) among the factors affecting Installing Solar Energy. Then, these linguistic terms were transformed into numerical values by using the fuzzy membership functions given in the Center of Gravity (also called Center of Area) defuzzification method (Fig. 8.3) by using Eq. 8.1 that the weights of the relationships (Table 8.3) are obtained in the [−1, 1] crisp interval (Lee 1990; Sugeno 1985).

$$z^* = \frac{\int u_{\underline{c}}(z) \cdot z dz}{\int u_{\underline{c}}(z) dz} \tag{8.7}$$

where $\int$ denotes an algebraic integration.

There are 31 connections in FCM based on the installing solar energy that consists of 10 different factors whose two are transmitters and eight are ordinary factors. Direction degrees of the causal relationships among factors can be expressed as in-degree that directs into a node and out-degree that directs out from a node. The other concept is centrality value that is measured with summation of the in- and out-degree of a node and reflects the importance of factors on the map

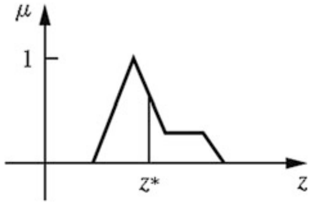


Fig. 8.3 Centroid defuzzification method

(Fig. 8.4). Figure 8.4 shows that Energy Price, Energy Supply, and New Solar Energy Generation Capacity are a central factor of the map with five total degrees and it is followed by Incentives with four degree values. Also New Solar Energy Generation Capacity is an receiver factor and Global Treaties are transmitter factors of the FCM.

In this study, FCM model was simulated under different scenarios with initial state of the system in order to evaluate the effects of the possible changes of the factors in the system. Scenarios were design based on the existence or lack of the specific factors in the system in the initial state vector; and behavior of the system was observed in the last state after the consecutive iterations. In this way, factors at each new states can be represented graphically and the active, inactive, influential and ineffective factors can be determined by observing the last state vector in the system. And then changes are observed whether the system converged towards a steady state and made a decision about factors in FCM.

First of all, initial state vector, A^0, was represented and then multiplied by the weight matrix that was defined by experts' common views about the relationships among factors (Eq. 8.1). In the following iterations, calculated state vector was added to the multiplied values and the hyperbolic tangent function with $\lambda = 0.50$ were used to recalculate an outcome new state vector at the each iterations. A Lambda value reflects the shape of the changes of the new state values in the hyperbolic tangent functions, therefore lambda (λ) was selected as 0.50 in order to see clearly the changes at the each iteration. The iterations were terminated when the difference between the two calculated new state vectors was smaller than or equal to 0.0001 (i.e., $A^{t+1} - A^t \leq 0.0001$). The last state vector also called as the final states or steady state vector of the factors (A^l).

Scenarios based on the initial state were designed as the existence or lack of one or more specific factors in the system that include the worst, best and random cases whose notations are shown as "1", "0" or "−1"; for example if there is any incentive provided by governments and energy prices are decreasing, initial state vector will be defined as $A^0 = [0 - 1\,0\,0\,0\,0\,1\,0\,0\,0]$ that "0" values represents the inactive factors. After that FCM is operated and new states of the concepts are observed at each iteration and reached at the last state in time. In the new solar energy generation capacity model that reflects the real life conditions can be expected to converge at the steady states that represents the long term predictions of the concepts in the system.

Table 8.3 Weight matrix of the linguistic relationships among concepts after using CoG defuzzification method

	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
ED		VH			H					
EP	NM		VH		VVH					
ES		NVH					NM			
AARE			H							
NSEC			H							
CSE					NVVH					
SEI				M		NVH				
TAST					M	NVH				
RG							VVH			
GT									M	

	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
ED		0.783			0.650					
EP	−0.500		0.783		0.900					
ES		−0.783					−0.500			
AARE			0.650							
NSEC			0.650							
CSE					−0.900					
SEI				0.500		−0.783				
TAST					0.500	−0.783				
RG							0.900			
GT									0.500	

Case 1. Existence of only one factor

In this case, one specific factor that is thought as a key concept of the solar energy generation model was accepted to exist in the system and other factors were accepted as lack. So, based on these assumptions, "energy price", "energy supply", "energy demand", "global treaties" such as Kyoto Treaty, and "technical applicability of solar technology" are accepted as the trigger factors and the influences of their individual existence was observed in the system. For example, the "energy price" was accepted to increase in the model that is defined as "1" and other factors were accepted as ineffective that was defined as "0" in the initial state like $A^0 = [0\,1\,0\,0\,0\,0\,0\,0\,0\,0]$. Also the worst scenarios can be defined based on the existence of the individual factor in the system such as decreasing of the energy supplies that was showed as "−1" in the initial state like $A^0 = [0\,0 - 1\,0\,0\,0\,0\,0\,0\,0]$ (Fig. 8.5).

In this case, four different scenarios were designed and observed the behaviors of the concepts at each iteration and the convergence states were evaluated according to initial state of the system.

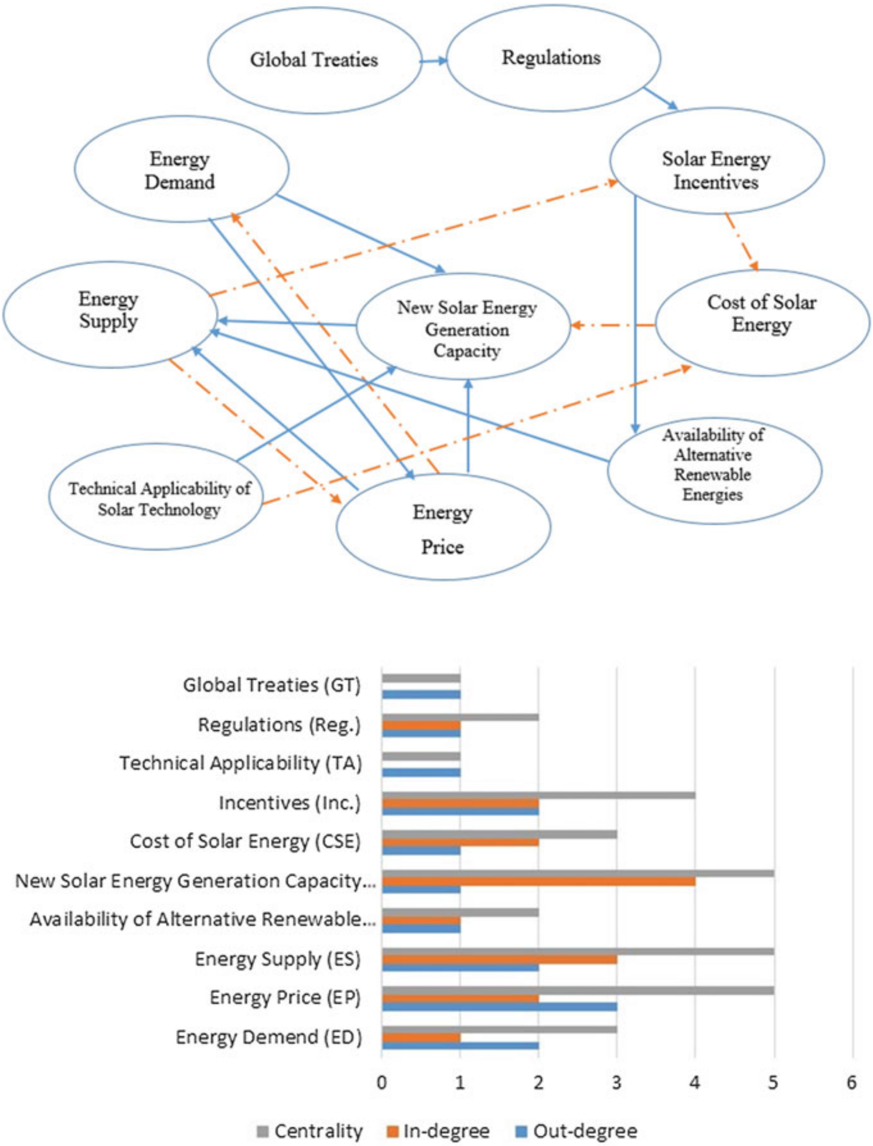


Fig. 8.4 Fuzzy cognitive map of solar energy usage (Graphical representation of the relational fuzzy cognitive map) and In-degree, out-degree, and centrality values of factors

i. **Scenario 1.1**: In this worst scenario, it is accepted that energy demand was decreasing that can be based on the change of the nations' or households' energy using habits by governmental regulations, energy price, environmental laws, environmental sensitivity and many other different and latent effects.

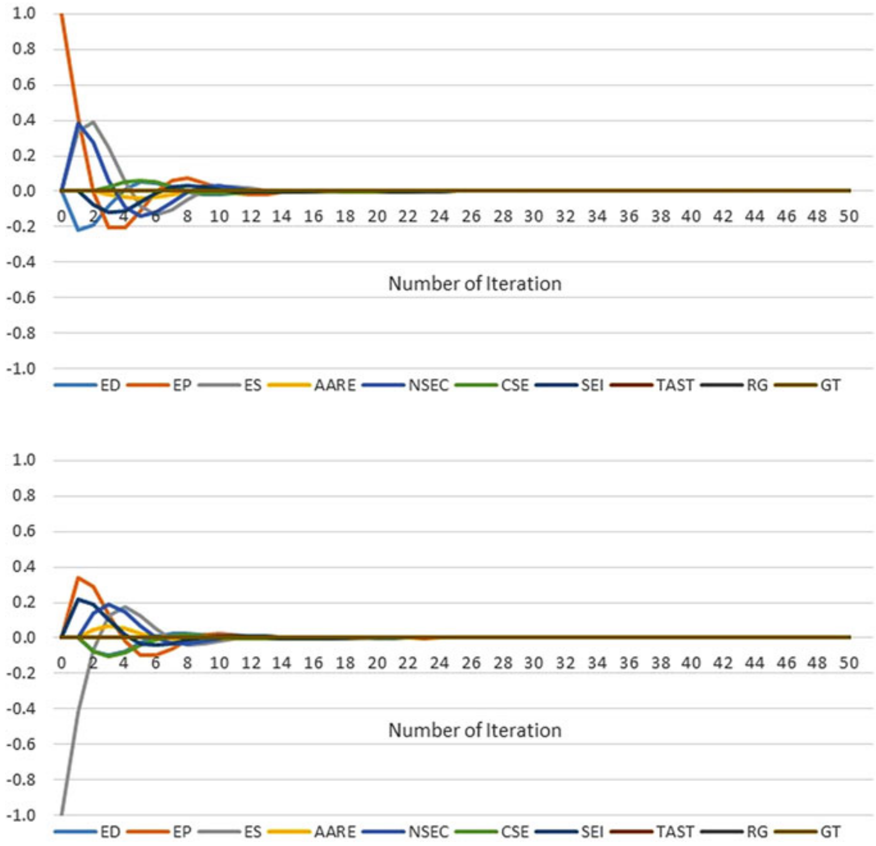
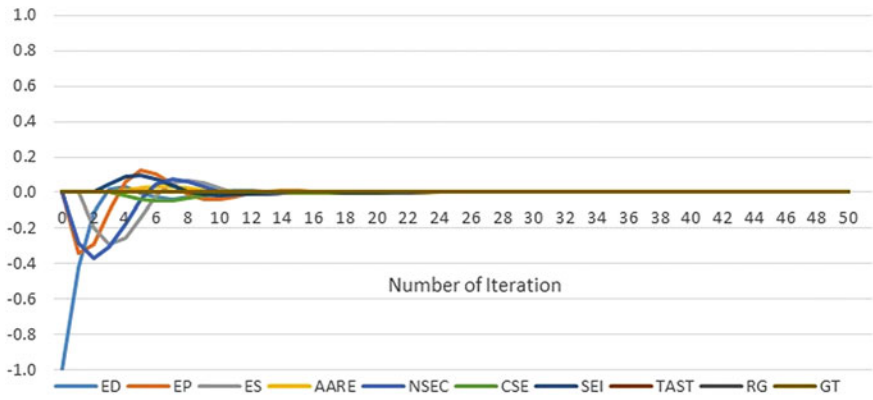


Fig. 8.5 Sample result of the FCM simulation process for increase of the energy price and decrease of the energy supply

Initial state is defined as $A^0 = [-1\,0\,0\,0\,0\,0\,0\,0\,0\,0]$ and reached the following results (Fig. 8.6):

(a) The first reaction of the system was decreasing the energy price that also affected the decrease of the new solar energy generations and energy supply.

(b) After the first reaction, energy demand was started to increase by decreasing of the energy price, but energy supply did not react suddenly and availability of alternative renewable energies and solar energy incentives were started to increase that it caused to decrease the cost of solar energy. In this period new solar energy generation capacity was continued to decrease that can be based on the reaction time, bureaucratic procedures or distrust to the sector.



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	-1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
1	-0.421899	-0.338591	0.000000	0.000000	-0.284434	0.000000	0.000000	0.000000	0.000000	0.000000
2	-0.113185	-0.292305	-0.199825	0.000000	-0.370092	0.000000	0.000000	0.000000	0.000000	0.000000
3	0.014835	-0.100655	-0.292420	0.000000	-0.307726	0.000000	0.044930	0.000000	0.000000	0.000000
4	0.029314	0.062930	-0.251562	0.010109	-0.173141	-0.015837	0.085802	0.000000	0.000000	0.000000
5	-0.000968	0.126644	-0.137824	0.023850	-0.037421	-0.037354	0.094926	0.000000	0.000000	0.000000
6	-0.028922	0.104845	-0.021345	0.032080	0.049257	-0.050228	0.073594	0.000000	0.000000	0.000000
7	-0.036589	0.044480	0.051099	0.030985	0.076362	-0.048506	0.037902	0.000000	0.000000	0.000000
8	-0.026467	-0.010893	0.069958	0.022467	0.061243	-0.035174	0.005559	0.000000	0.000000	0.000000
9	-0.009459	-0.038872	0.052079	0.011360	0.029643	-0.017786	-0.013238	0.000000	0.000000	0.000000
10	0.004490	-0.039165	0.021723	0.002134	0.002033	-0.003337	-0.017673	0.000000	0.000000	0.000000
11	0.010832	-0.023694	-0.002811	-0.003016	-0.012282	0.004728	-0.012840	0.000000	0.000000	0.000000
12	0.010205	-0.005853	-0.014091	-0.004246	-0.013869	0.006654	-0.005145	0.000000	0.000000	0.000000
13	0.005909	0.005931	-0.013702	-0.003069	-0.008321	0.004808	0.000855	0.000000	0.000000	0.000000
14	0.001325	0.009581	-0.007407	-0.001188	-0.001561	0.001862	0.003468	0.000000	0.000000	0.000000
15	-0.001560	0.007389	-0.000760	0.000245	0.002811	-0.000384	0.003227	0.000000	0.000000	0.000000

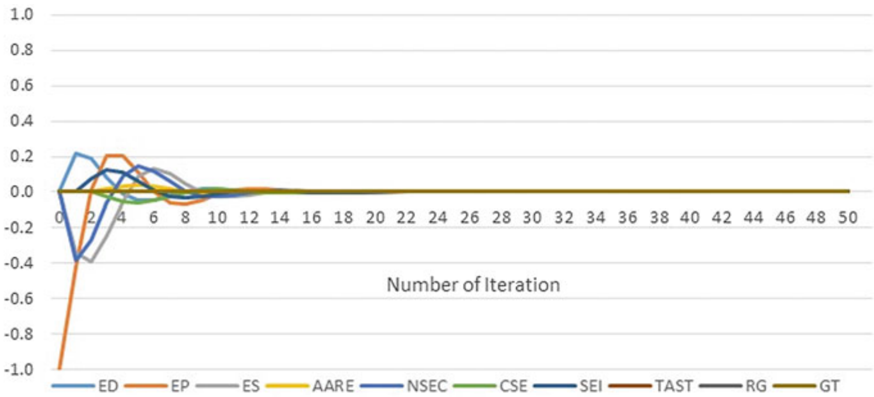
Fig. 8.6 The result of the FCM simulation process for the scenario 1.1 and a sample part of the iterations

(c) While solar energy incentives were increasing and cost of solar energy was decreasing, new solar energy generation capacity started to increase at the following iterations (i.e. time periods). At the same period, availability of alternative renewable energies, energy supply and energy demand increased while energy price was decreasing. When energy price was decreasing, market directed to the balancing strategies that include the decrease of the solar energy incentives that caused to increase of the cost of solar energy and decrease the new solar energy generation capacity, and also the decrease of the availability of alternative renewable energy caused to decrease of the energy supply and increase energy price that decreased the energy demand.

(d) System repeated the similar balancing policies in the short time periods and converged the steady state that all factors reached an equilibrium point "0". It means that energy demand will be reached an equilibrium for supplying energy in the long term and governments will not change their politics about solar energy incentives that do not depend any global treaties, regulations and technical applicability of solar technology.

(e) Technical applicability of solar technology, regulations, and global treaties did not reflect any changes that they stay ineffective during each iteration because of technical applicability of solar technology and global treaties are transmitter factors and the regulations are only affected by global treaties that stay on hold in the system.

ii. **Scenario 1.2**: Another worst scenario is that energy price was decreasing that can be based on the increasing energy supply, decreasing energy demand, falling cost of the energy technologies and energy sources and also many other different and latent effects. Initial state of this scenario was defined as $A^0 = [0 - 1\,0\,0\,0\,0\,0\,0\,0\,0]$ and reached the following results (Fig. 8.7):



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	0.000000	-1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
1	0.221278	-0.421899	-0.338591	0.000000	-0.384219	0.000000	0.000000	0.000000	0.000000	0.000000
2	0.192086	0.007499	-0.391414	0.000000	-0.272020	0.000000	0.076036	0.000000	0.000000	0.000000
3	0.084549	0.206065	-0.247792	0.017106	-0.063102	-0.026796	0.121679	0.000000	0.000000	0.000000
4	-0.008317	0.206851	-0.052274	0.035061	0.090396	-0.054895	0.110061	0.000000	0.000000	0.000000
5	-0.050242	0.108153	0.085876	0.040519	0.143260	-0.063414	0.061212	0.000000	0.000000	0.000000
6	-0.046909	0.000687	0.129787	0.031995	0.118694	-0.050072	0.008223	0.000000	0.000000	0.000000
7	-0.021260	-0.061897	0.102363	0.016247	0.060176	-0.025426	-0.025496	0.000000	0.000000	0.000000
8	0.004360	-0.071310	0.046565	0.001574	0.006090	-0.002454	-0.034491	0.000000	0.000000	0.000000
9	0.018005	-0.046932	-0.001941	-0.007052	-0.023867	0.011053	-0.025992	0.000000	0.000000	0.000000
10	0.018660	-0.014088	-0.026454	-0.009021	-0.028950	0.014135	-0.011259	0.000000	0.000000	0.000000
11	0.011566	0.009563	-0.027970	-0.006593	-0.018998	0.010329	0.000886	0.000000	0.000000	0.000000
12	0.003053	0.018238	-0.016699	-0.002768	-0.005476	0.004336	0.006692	0.000000	0.000000	0.000000
13	-0.002730	0.015168	-0.003497	0.000260	0.004059	-0.000408	0.006768	0.000000	0.000000	0.000000
14	-0.004641	0.007096	0.005036	0.001640	0.007336	-0.002569	0.003833	0.000000	0.000000	0.000000
15	-0.003685	-0.000218	0.007393	0.001600	0.005858	-0.002507	0.000591	0.000000	0.000000	0.000000

Fig. 8.7 The result of the FCM simulation process for the scenario 1.2 and a sample part of the iterations

(a) Firstly, decrease of the energy price affected the energy supply and new solar energy generation capacity as negatively and energy demand as positively. The other factors stayed as a neutral that protect their stable state. Similar to the previous case, technical applicability of solar technology, regulations, and global treaties did not reflect any changes that they stay ineffective during each iteration until reaching the convergence.

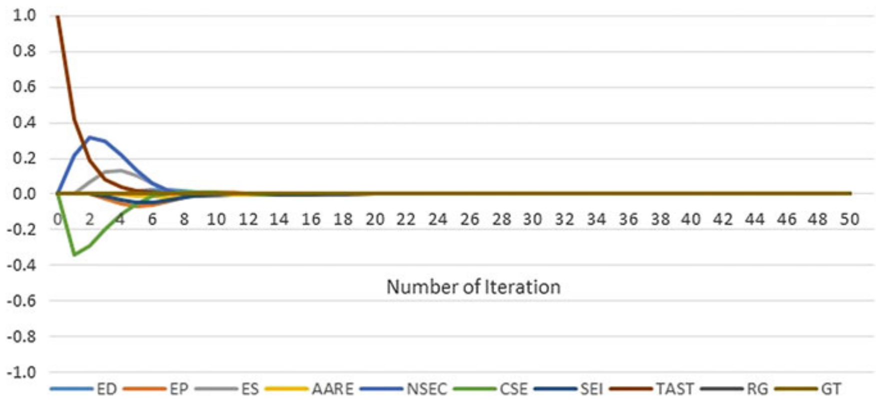
(b) Increasing energy demands and decreasing energy supply activated the increase of the energy prices that positively triggered the availability of alternative renewable energies and the solar energy incentives that caused to decrease the cost of solar energy, but new solar energy generation capacity did not give a reaction at the beginning.

(c) At the following iterations, availability of alternative energies decreased and increasing solar energy incentives caused to decrease the cost of solar energy and increase the new solar energy generation capacity. Increasing new energy generation capacities also increased the energy supply, but these increases did not directly affect the energy price that continued to increase while the energy demand was decreasing at the same period.

(d) System exhibited the balancing movements with floating steps based on the small changes. This balancing movements covered all concepts except technical applicability of solar technology, regulations and global treaties. At the steady state, the system converged to equilibrium zero point after the 50 iterations that it reflects no change in the concepts. If any policies that are related the regulations, technical applicability of solar technology, and global treaties are not developed by governments in the system, there will not be any change in the solar energy incentive, cost of solar energy and new solar energy generation capacity.

iii. **Scenario 1.3**: This scenario that is positive and looks at the bright side of the system was accepted the existence of the technical applicability of the solar technology in the systems. Technical applicability of solar technology reflects the locational state of the solar energy generation and changes from country to country. It is a transmitter concept that is not affected by another concept in the model. Its existence in the system was defined in the initial state as $A^0 = [0\,0\,0\,0\,0\,0\,0\,1\,0\,0]$ and reached the following results (Fig. 8.8):

(a) Existence of the technical applicability of the solar technology influenced the cost of the solar energy negatively and new solar energy generation capacity positively at the beginning of the iterations. At the same time, the technical applicability of the solar technology started to continuous decrease until to reach the zero point at the steady state. Its basic reasons can be the decreasing available lands for new solar energy generation and the increasing cost of the land usage. In spite of the "zero" technical applicability of solar technology, seeing small increase in the new solar energy generation capacity indicates its relationship with the cost of the land usage.



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000	0.000000	0.000000
1	0.000000	0.000000	0.000000	0.000000	0.221278	-0.338591	0.000000	0.421899	0.000000	0.000000
2	0.000000	0.000000	0.064634	0.000000	0.319986	-0.292305	0.000000	0.187606	0.000000	0.000000
3	0.000000	-0.022779	0.122069	0.000000	0.295506	-0.195134	-0.014542	0.084223	0.000000	0.000000
4	0.005125	-0.053230	0.132552	-0.003272	0.218168	-0.111902	-0.033996	0.037882	0.000000	0.000000
5	0.014282	-0.068763	0.103372	-0.009121	0.131200	-0.051680	-0.045092	0.017045	0.000000	0.000000
6	0.021895	-0.062267	0.057921	-0.014249	0.060062	-0.013369	-0.043522	0.007670	0.000000	0.000000
7	0.023858	-0.040697	0.017514	-0.016203	0.015353	0.006622	-0.032606	0.003452	0.000000	0.000000
8	0.019890	-0.016076	-0.006713	-0.014627	-0.004500	0.013256	-0.018611	0.001553	0.000000	0.000000
9	0.012567	0.002144	-0.014281	-0.010769	-0.007737	0.011978	-0.006864	0.000699	0.000000	0.000000
10	0.005173	0.010428	-0.011083	-0.006391	-0.003631	0.007563	0.000124	0.000315	0.000000	0.000000
11	-0.000019	0.010423	-0.004243	-0.002848	0.001110	0.003249	0.002550	0.000142	0.000000	0.000000
12	-0.002353	0.006179	0.001256	-0.000708	0.003431	0.000513	0.002102	0.000064	0.000000	0.000000
13	-0.002449	0.001508	0.003540	0.000154	0.003165	-0.000532	0.000663	0.000029	0.000000	0.000000
14	-0.001442	-0.001433	0.003096	0.000219	0.001541	-0.000483	-0.000498	0.000013	0.000000	0.000000
15	-0.000326	-0.002244	0.001403	-0.000014	-0.000110	-0.000047	-0.000921	0.000006	0.000000	0.000000

Fig. 8.8 The result of the FCM simulation process for the scenario 1.3 and a sample part of the iterations

(b) At the beginning of the iterations; solar energy incentive, availability of alternative renewable energy, energy supply, energy price and energy demand did not give any reaction immediately because of the indirect effects of the decreasing cost of the solar energy and increasing generation of the new solar energy whose influences took the time in the system. Regulations and global treaties stayed stable during the 50 iteration because of their transmitter properties.

(c) At the following iterations, solar energy incentives decreased but cost of solar energy decreased and new solar energy capacity increased through the support of the technical applicability on the solar energy. By using these advantages, solar energy substituted the alternative renewable energies and increased the energy supply, decreased energy price and increased the energy demand at the same period. Decreasing influence of the technical applicability of solar technology triggered the incentives on the solar energy that continued the similar effects on the system. When incentives were withdrawn and technical applicability continued to decrease, cost of solar energy started to increase and new solar energy generation capacities started to decrease whose place at the energy supply was partially filled by alternative renewable energies. But main balance between the energy supply and energy demand were provided by energy price whose increase decreased the energy demand in the model.

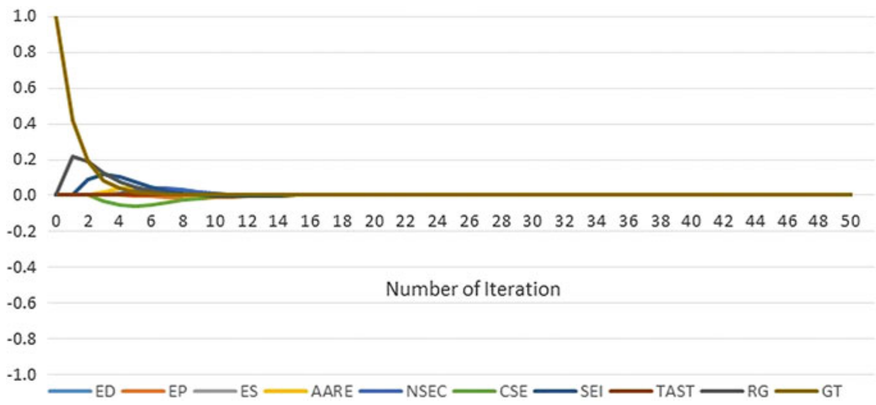
(d) At the last period, all concepts converged to the zero value that reflects the stability of the system. There will not be any change (increase or decrease) in the states of the concepts. For example, governments will not provide any regulations, incentives; while the cost of the solar energy and energy price are not changing, it is accepted that energy demand and energy supply will not change any time; while energy demand and energy supply are not changing, there will not be any requirements in order to generate the new solar energy and alternative renewable energies.

iv. **Scenario 1.4**: The other positive scenario is the existence of the global treaties in the solar energy generation model. Global treaties that include the binding rules accepted by all countries around the world have an important influence on the governments about their energy generation politics that are shown with regulations and legislations. For example, Kyoto protocol that is an international treaty and struggles with global warming by reducing greenhouse effects forces the governments to direct the renewable energies in order to decrease the global greenhouse gas emissions. If there is any global treaties related to energy generation, its existence in the system is defined in the initial state as $A^0 = [0\,0\,0\,0\,0\,0\,0\,0\,0\,1]$ and we reached the following results (Fig. 8.9):

(a) The effects of the global treaties on the other concepts were not observed in the short period such that technical applicability of solar technology that is transmitter concept stayed stable as zero. The first reaction was observed positively on the regulation that was designed by governments according the binding targets. The last reaction of the global treaties was observed on the energy demand because of the shortest path length (6) between these two concepts.

(b) Global treaties that forces the governments to direct the renewable energy increased the regulations about solar energy and solar energy incentives that they decreased the cost of solar energy and increased the new solar energy generation capacity and availability of alternative renewable energies. At this initial period, while the effect of the global treaties was decreasing, any changes were not observed in the energy supply, energy demand and energy price.

(c) At the balancing period, when the influences of the global treaties and regulations decreased that they caused to decrease the solar energy incentives and increase cost of solar energy, new solar energy generation capacity continued to increase with low rates and availability of alternative



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
1	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.221278	0.421899
2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.089379	0.000000	0.192086	0.187606
3	0.000000	0.000000	0.000000	0.020107	0.000000	-0.031496	0.117471	0.000000	0.127945	0.084223
4	0.000000	0.000000	0.005881	0.035464	0.012755	-0.055524	0.104299	0.000000	0.076376	0.037882
5	0.000000	-0.002073	0.016749	0.039406	0.028220	-0.061673	0.076394	0.000000	0.042867	0.017045
6	0.000466	-0.006837	0.026580	0.034907	0.036820	-0.054627	0.047933	0.000000	0.023121	0.007670
7	0.001748	-0.012281	0.030522	0.026487	0.036045	-0.041455	0.024948	0.000000	0.012130	0.003452
8	0.003550	-0.015668	0.027689	0.017531	0.028539	-0.027442	0.009271	0.000000	0.006235	0.001553
9	0.005123	-0.015558	0.020410	0.009975	0.018647	-0.015616	0.000467	0.000000	0.003155	0.000699
10	0.005806	-0.012389	0.012071	0.004594	0.009913	-0.007192	-0.003104	0.000000	0.001577	0.000315
11	0.005400	-0.007784	0.005308	0.001369	0.004054	-0.002142	-0.003474	0.000000	0.000780	0.000142
12	0.004181	-0.003470	0.001231	-0.000166	0.001119	0.000261	-0.002442	0.000000	0.000383	0.000064
13	0.002662	-0.000522	-0.000391	-0.000624	0.000216	0.000978	-0.001221	0.000000	0.000187	0.000029
14	0.001315	0.000841	-0.000479	-0.000555	0.000268	0.000870	-0.000386	0.000000	0.000090	0.000013
15	0.000403	0.001011	-0.000003	-0.000337	0.000494	0.000528	-0.000029	0.000000	0.000044	0.000006

Fig. 8.9 The result of the FCM simulation process for the scenario 1.2 and a sample part of the iterations

solar energies decreased low rates. Energy generation with solar and alternative renewable energies increased the energy supply that caused to decrease the energy price and increase energy demand.

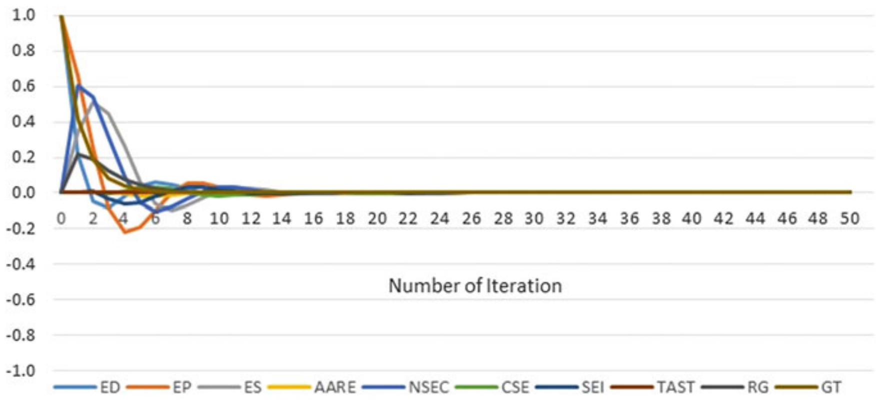
(d) The long term period showed that all concepts converged to the zero values at the steady state that means system reached to the balance and there will not be any change in the system. Disappear of the global treaties reflects that all binding target in the treaties that were executed through the regulations or legislations were carried out by governments. It is clear that treaties and regulations have an important influence on the renewable energy generations through incentives and cost.

Case 2. Combination of the concepts

In this case, some specific factors whose combinations were accepted as an important contribution to the new solar energy generation capacity were defined as positive and negative that represent the increase and decrease of the concepts in the system respectively. Concepts in the combinations were selected according to the real life problems that were defined by experts' knowledge and experiences. Scenarios that were described according to frequently encountered problems in the real life included the inverse combinations like the increase and decrease of the concepts at the same time. The number of concepts in each combination were not limited and the three most important ones among combinations that were defined in each scenario by experts were specially selected in order to evaluate the new solar energy generation capacity in long term. In this context, the behaviors of the concepts in three different scenarios were iterated 50 times and their steady state values were evaluated according to their initial state values.

i. **Scenario 2.1**: Despite the scenario is seen as a positive, it includes the worst and best state in same time. It is accepted that while energy demand and energy price were increasing, global treaties such as Kyoto Protocol, Vienna Convention for the Protection of the Ozone Layer, and U.S.-Canada Air Quality Agreement were increased all around the world at the same time. This scenario includes the encounter between global environmental sensitivity and energy tendency and its initial state is defined as $A^0 = [1\,1\,0\,0\,0\,0\,0\,0\,0\,1]$ and reached the following results (Fig. 8.10):

   (a) The model tended to decrease the impact of the existence concepts in the system. The highest reduction occurred in energy demand (78 %) and lowest reduction was observed in energy price (34 %) such that reduction of the global treaties (58 %) stayed in the medium levels. Availability of alternative renewable energies, solar energy incentives, technical applicability of solar energy and cost of solar energy did not give any reaction, while regulations, new solar energy generation capacity and energy supply increased in the first iteration. New solar energy generation capacity was the highest increasing concept that is highly affected by regulations and affected the energy supply by generated solar energy.
   (b) Increasing global treaties and regulations started to show their effects on the energy cost and energy price through increases of the availability of alternative renewable energies and new solar energy generation capacities in the medium period. Results showed that increase in the new solar energy generation capacity did not directly affected by solar energy incentives that indicated the decreasing trend and cost of solar energy that indicated the increasing trend in the same period. Increased energy supply by generating the alternative renewable energies and solar energy decreased energy price and increased energy demand. Technical applicability of solar energy that is transmitter concept also stay stable at zero value in the middle term and protect its position during 50 iterations.
   (c) Global treaties and regulations protected their positive effects until reaching a convergence at a steady state. However, other factors different from technical applicability of solar energy changed their position from

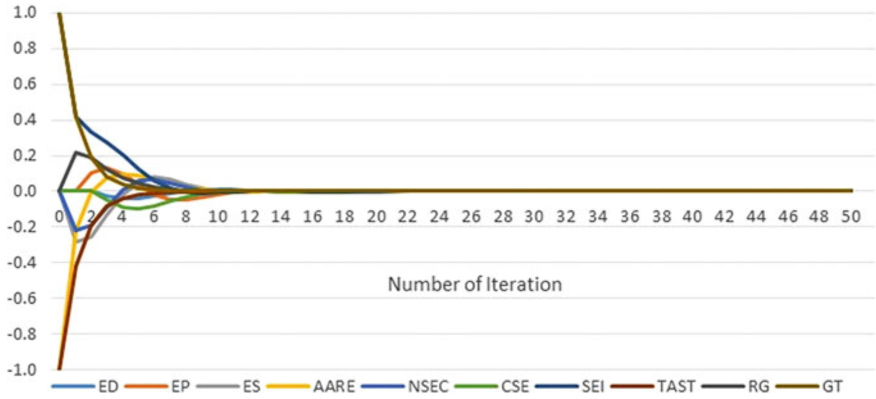


Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	1.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
1	0.221278	0.665432	0.338591	0.000000	0.602779	0.000000	0.000000	0.000000	0.221278	0.421899
2	-0.050105	0.252510	0.510380	0.000000	0.540933	0.000000	0.013434	0.000000	0.192086	0.187606
3	-0.079196	-0.083745	0.443761	0.003023	0.319447	-0.004735	-0.030985	0.000000	0.127945	0.084223
4	-0.016794	-0.218449	0.258495	-0.005611	0.088356	0.008791	-0.061893	0.000000	0.076376	0.037882
5	0.041570	-0.192894	0.063437	-0.016449	-0.057122	0.025767	-0.055025	0.000000	0.042867	0.017045
6	0.062028	-0.094230	-0.060893	-0.019780	-0.101750	0.030982	-0.021670	0.000000	0.023121	0.007670
7	0.049075	0.000926	-0.095870	-0.013776	-0.078195	0.021577	0.013313	0.000000	0.012130	0.003452
8	0.021872	0.051464	-0.069604	-0.003204	-0.029189	0.005017	0.032463	0.000000	0.006235	0.001553
9	-0.001737	0.055348	-0.022652	0.005862	0.012073	-0.009185	0.032782	0.000000	0.003155	0.000699
10	-0.013234	0.032268	0.014562	0.010014	0.031051	-0.015688	0.021123	0.000000	0.001577	0.000315
11	-0.013215	0.004722	0.029930	0.009259	0.029515	-0.014505	0.006868	0.000000	0.000780	0.000142
12	-0.007009	-0.013083	0.026468	0.005712	0.017202	-0.008948	-0.003328	0.000000	0.000383	0.000064
13	-0.000210	-0.017686	0.014000	0.001822	0.004016	-0.002853	-0.007297	0.000000	0.000187	0.000029
14	0.003885	-0.012967	0.001773	-0.000822	-0.004262	0.001288	-0.006358	0.000000	0.000090	0.000013
15	0.004666	-0.005091	-0.005260	-0.001801	-0.006555	0.002821	-0.003224	0.000000	0.000044	0.000006

Fig. 8.10 The result of the FCM simulation process for the scenario 2.1 and a sample part of the iterations

positive to negative or vice versa in order to balance the system in the long term. These concepts did not reflect the direct and parallel reactions with other concepts at the same time. For example, while solar energy incentives were increasing in some periods, cost of solar energy increased or decreased in same periods. At the long term with 50 iterations, concepts reached their steady stable value "zero" at the convergence state that represents the occurrence of no changes as increase or decrease in the model.

ii. **Scenario 2.2**: Scenario was designed based on the increasing and decreasing of some specific concepts in the system. Similar to the scenario 2.1, experts defined the supportive and preventive factors of the new energy generation within converse conditions. Increasing of the solar energy incentives and global treaties were accepted as the supportive factors that were used to develop the new renewable energy capacities, and on the other hand



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	0.000000	0.000000	0.000000	-1.000000	0.000000	0.000000	1.000000	-1.000000	0.000000	1.000000
1	0.000000	0.000000	-0.284434	-0.221278	-0.221278	0.000000	0.421899	-0.421899	0.221278	0.421899
2	0.000000	0.099928	-0.251903	-0.004648	-0.192086	0.000000	0.330572	-0.187606	0.192086	0.187606
3	-0.022480	0.132971	-0.134850	0.072161	-0.087951	-0.050353	0.275892	-0.084223	0.127945	0.084223
4	-0.040013	0.099121	-0.018426	0.094268	0.009142	-0.089978	0.203432	-0.037882	0.076376	0.037882
5	-0.040286	0.036978	0.056834	0.087965	0.060398	-0.098526	0.125951	-0.017045	0.042867	0.017045
6	-0.026443	-0.017593	0.081823	0.067819	0.066342	-0.082538	0.061174	-0.007670	0.023121	0.007670
7	-0.007941	-0.046048	0.069747	0.044254	0.046662	-0.055944	0.018480	-0.003452	0.012130	0.003452
8	0.006787	-0.048070	0.041723	0.024068	0.021903	-0.030463	-0.002465	-0.001553	0.006235	0.001553
9	0.013869	-0.033933	0.015276	0.010276	0.004361	-0.012291	-0.007971	-0.000699	0.003155	0.000699
10	0.013875	-0.015765	-0.000806	0.002830	-0.002903	-0.002475	-0.005746	-0.000315	0.001577	0.000315
11	0.009791	-0.001919	-0.005941	-0.000019	-0.002701	0.001023	-0.001766	-0.000142	0.000780	0.000142
12	0.004837	0.004682	-0.004145	-0.000406	0.000425	0.001133	0.000858	-0.000064	0.000383	0.000064
13	0.001123	0.005273	-0.000210	0.000010	0.003029	0.000230	0.001474	-0.000029	0.000187	0.000029
14	-0.000681	0.002843	0.002654	0.000336	0.003728	-0.000406	0.000786	-0.000013	0.000090	0.000013
15	-0.000946	0.000104	0.003385	0.000328	0.002791	-0.000455	-0.000207	-0.000006	0.000044	0.000006

Fig. 8.11 The result of the FCM simulation process for the scenario 2.2 and a sample part of the iterations

decreasing of the availability of alternative energies and technical applicability of solar energy were accepted as the preventive factors that were used to represent the nonexistence of availabilities of the new renewable energy generation in the system. Initial state of the scenario is defined as $A^0 = [0\,0\,0 - 1\,0\,0\,1 - 1\,0\,1]$ and the following results were obtained (Fig. 8.11):

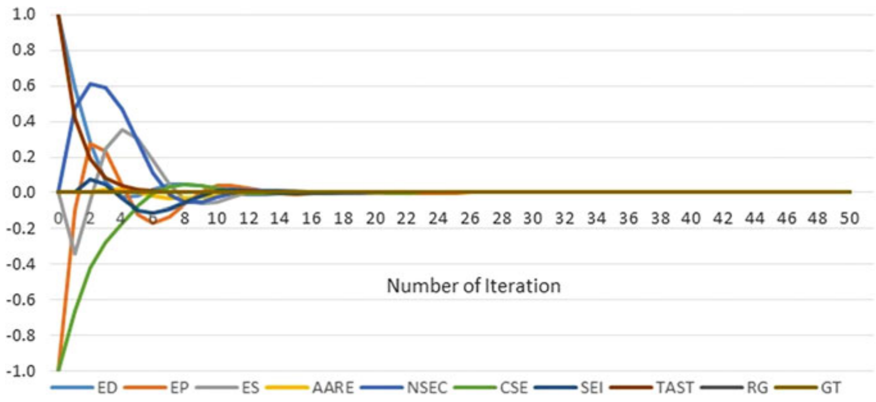
(a) Selected factors protected their sign but lose their influence in the short term. The highest decrease was observed on the availability of alternative renewable energies factor that can be based on the increasing number and effects of the related factors in the system. In this period, cost of solar energy and energy demand protected their situations as staying stable, while regulations and energy price increased and new solar energy generation capacity decreased in spite of solar energy incentives were increasing with low rate.

(b) The sign of the availability of alternative renewable energies factor changed from negative to positive that means that availabilities for generating new renewable energies started to rise in the medium term. Other initial factors protected their signs but lost their influence slowly in this period. Increasing solar energy incentives started to show its effects on the cost of solar energy that decreased in time and also increased the new solar energy generation capacity. Increase of the new solar and alternative energy generation by provided positive conditions increased the energy supply. Increasing energy supply did not decrease the energy price in the first step, but following steps energy demand decreased and they reflected their common influences on the energy price as decrease.

(c) In the long term, firstly technical applicability of solar technology and global treaties lost their influences, while solar energy incentives that is supported by energy supply and regulations protected its influence on the other factors until convergence. Factors exhibited the converse properties during 50 iterations such as energy price increased or decreased in some period while energy demand and energy supply were decreasing at the same time. This property reflect the complexity and dynamism of the system that is also indicate the real life model. The model reached an equilibrium point at "zero" that represents the stability of the factors after the 50 iterations.

iii. **Scenario 2.3**: In this scenario, we focused only in-degree factors of the new solar energy generation capacity that are energy price, technical applicability of solar technology, energy demand and cost of solar energy. Initial state vector was designed to support the increase of the new solar energy generation capacity in the long term. Therefore, it was accepted that energy demand and technical applicability of solar technology were increasing, and energy price and cost of solar energy were decreasing in the system. Initial state of the scenario was defined as $A^0 = [1 - 1\,0\,0\,0 - 1\,0\,1\,0\,0]$ and we reached the following results (Fig. 8.12):

(a) At the first period of the iterations, existence factors in initial state protected their positions within their signs but they decreased their influence whose the highest decrease was observed in energy price (91 %). Global treaties, regulations, solar energy incentives and availability of alternative renewable energies were stayed stable at the same time. Also, global treaties and regulations that are transmitter factors did not change their stable position during 50 iterations. As it is expected that new solar energy generation capacity started to increase and reflected the highest increase among the factors in the system. At the following iterations of the first period, increasing solar energy incentives and technical applicability of solar technology increased the availability of alternative renewable energies and decreased the solar energy cost, and increasing energy demand



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	1.000000	-1.000000	0.000000	0.000000	0.000000	-1.000000	0.000000	1.000000	0.000000	0.000000
1	0.588259	-0.097192	-0.338591	0.000000	0.475768	-0.665432	0.000000	0.421899	0.000000	0.000000
2	0.278989	0.275659	-0.047428	0.000000	0.611445	-0.420389	0.076036	0.187606	0.000000	0.000000
3	0.063436	0.234654	0.249308	0.017106	0.592081	-0.274855	0.044857	0.084223	0.000000	0.000000
4	-0.024246	0.040053	0.356693	0.017789	0.470173	-0.167590	-0.035893	0.037882	0.000000	0.000000
5	-0.019920	-0.115736	0.307117	-0.000071	0.288661	-0.075970	-0.096110	0.017045	0.000000	0.000000
6	0.017075	-0.165817	0.179841	-0.021653	0.111337	-0.006316	-0.111881	0.007670	0.000000	0.000000
7	0.044962	-0.131231	0.048672	-0.034903	-0.007776	0.033879	-0.090562	0.003452	0.000000	0.000000
8	0.049719	-0.060289	-0.036823	-0.036067	-0.056381	0.045920	-0.051658	0.001553	0.000000	0.000000
9	0.035923	0.003376	-0.064772	-0.027846	-0.053442	0.038307	-0.014960	0.000699	0.000000	0.000000
10	0.015404	0.036998	-0.051688	-0.015895	-0.027524	0.022261	0.007842	0.000315	0.000000	0.000000
11	-0.001392	0.040277	-0.022914	-0.005388	-0.001841	0.007142	0.015157	0.000142	0.000000	0.000000
12	-0.009689	0.025706	0.001772	0.000986	0.012215	-0.002179	0.011976	0.000064	0.000000	0.000000
13	-0.010143	0.007528	0.013719	0.003138	0.013969	-0.005224	0.004991	0.000029	0.000000	0.000000
14	-0.006258	-0.005024	0.013830	0.002535	0.008490	-0.004120	-0.000841	0.000013	0.000000	0.000000
15	-0.001686	-0.009342	0.007677	0.000952	0.001627	-0.001562	-0.003490	0.000006	0.000000	0.000000

Fig. 8.12 The result of the FCM simulation process for the scenario 2.3 and a sample part of the iterations

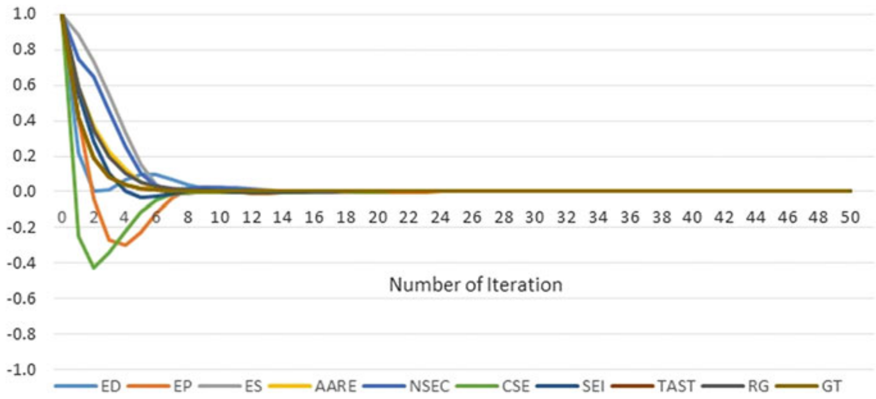
did not meet by energy supply with new energy generations that it caused to increase the energy price.

(b) Technical applicability of solar technology, new solar energy generation capacity and energy supply continued to have positive effects, when cost of solar energy and solar energy incentives continued to have a negative effect at the medium term. Solar energy incentives and energy demand changed their position from positive (increasing) to negative (decreasing) according to their first period positions. While energy price had a high influence on the other factors in the system; energy demand, cost of solar energy and technical applicability of solar technology continued to lost their influences. Availability of alternative renewable energies started this period with rising (positive) influence on the system, but at the following iterations, its influence changed from positive to negative in time.

(c) In the long term, technical applicability of the solar technology was firstly and energy price lastly reached an equilibrium point. Activation levels of the concepts fluctuated around the equilibrium value "zero" in order to balance the system, and at the end they reached their steady state values "zero" with decreasing rates. Zero equilibrium value of the model represents the stability of the system that there is not any factor that can activate the system. New solar energy generation capacity also reached to zero value that represents the sufficiency of the existent solar energy capacity and needlessness of the new solar energy generation in the system.

Case 3. Existence of all factors

This case represents the positively existence (i.e. increase) of all concepts in the systems whose initial state was defined as $A^0 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1]$. Although it included some opposite factors such as an increase of the energy demand and energy price at the same time, it was accepted that extreme conditions could be possible in any systems. We expected that the system would reach an equilibrium zero point that represents the stable balancing state of the concepts in the long term. Reached results during the 50 iterations as follow (Fig. 8.13):



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
1	0.221278	0.421899	0.882620	0.588259	0.747604	-0.249613	0.558052	0.421899	0.588259	0.421899
2	0.004648	-0.043241	0.733674	0.371600	0.645786	-0.428256	0.282852	0.187606	0.344900	0.187606
3	0.011820	-0.269607	0.545882	0.226846	0.454300	-0.343937	0.101540	0.084223	0.194891	0.084223
4	0.065885	-0.300055	0.336238	0.124281	0.251437	-0.216759	0.001801	0.037882	0.106249	0.037882
5	0.096856	-0.226336	0.154196	0.056272	0.106798	-0.111070	-0.031802	0.017045	0.056276	0.017045
6	0.094230	-0.121461	0.037285	0.018165	0.033529	-0.044750	-0.026207	0.007670	0.029151	0.007670
7	0.069620	-0.034570	-0.010915	0.002278	0.013308	-0.013602	-0.008376	0.003452	0.014843	0.003452
8	0.039087	0.012831	-0.012539	-0.000860	0.018634	-0.004385	0.004698	0.001553	0.007456	0.001553
9	0.014701	0.023968	0.004080	0.000670	0.027134	-0.004177	0.007955	0.000699	0.003705	0.000699
10	0.001223	0.014528	0.018415	0.002091	0.028059	-0.004930	0.004162	0.000315	0.001824	0.000315
11	-0.002719	0.000478	0.022223	0.001878	0.020932	-0.003796	-0.001532	0.000142	0.000892	0.000142
12	-0.001331	-0.008577	0.016839	0.000500	0.010387	-0.001218	-0.005328	0.000064	0.000433	0.000064
13	0.001331	-0.010264	0.007739	-0.000974	0.001319	0.001308	-0.006011	0.000029	0.000209	0.000029
14	0.002908	-0.006877	-0.000035	-0.001791	-0.003697	0.002697	-0.004361	0.000013	0.000101	0.000013
15	0.002856	-0.002057	-0.004045	-0.001787	-0.004688	0.002747	-0.001914	0.000006	0.000048	0.000006

Fig. 8.13 The result of the FCM simulation process for the scenario 3 and a sample part of the iterations

(a) At the first iteration, increase ratas of the concepts were decreased but stay positive, except at the cost of solar energy whose increase turn to negative state that represents the decrease of the cost in the solar energy generation. The cost of solar energy was directly affected by solar energy incentive and technical applicability and also increasing regulations and energy supply had an indirect impact on the cost of solar energy. Increasing incentives and availabilities for new renewable energies and solar energy caused to heavy increase in new energy generations and energy supply against the energy demand that also negatively affected the energy prices. At the same period, we observed the rapid decline of the global treaties and technical applicability of solar technology at same rate and also they reached to the steady state in a short time due to their transmitter properties.

(b) The system reacted against the decreasing energy price and turn to natural regulations in itself. In this way, regulations and solar energy incentives were diminished in time that it caused to increase of the cost of solar energy and decrease of the availability of alternative energies and new solar energy generation capacities. Decreasing in the new energy generation also decreased the total energy supply that increased the energy price and decreased the energy demand. In this period, the system tended to the new cycle that transformed the system towards the balancing period.

(c) The concepts in the system converged to unique zero values for 50 iterations. Steady state of the model represents the stability at zero values that means that concepts in the system neither will increase nor decrease in the long term. The latest converged concept was energy price that was followed respectively by energy supply, energy demand, and new solar energy generation capacity whose directly affecting factors that are solar energy incentives and cost of solar energy were also included in the latest converged concepts.

8.6 Conclusion

Energy that is the capacity for doing work can be obtained by converting other energy forms. Most of the world's convertible energy is obtained by fossil fuels that are burned and transformed to the new usable energy forms (EIA 2016). Fossil fuels (coil, petroleum, natural gas, etc.) are conventional energy source that is non-renewable, finite and becoming expensive in time. They also cause significant health, economic and environmental damages through air, water and land pollution and global warming. Global awareness about the dangers of fossil fuels has increased the tendency to the renewable energy usage. Renewable energies that are generated from renewable energy sources such as solar, wind, hydro, biomass, geothermal, wave and tidal actions are very important alternative energies against the fossil fuels. In this study, we focused on the solar energy and defined the factors around the generation of solar energy as global treaties, incentives, regulations, energy cost, energy demand, energy supply, energy price, technical applicability of solar energy and availability of alternative renewable energies. The new solar energy generation system reflects the complex and uncertain real-life properties and its imprecise relationships among its factors cannot be expressed by crisp values. Therefore system is represented by FCM and linguistic statements are used to define the imprecise causal relationships among factors. Linguistic values are transformed into crisp values by using Center of Gravity defuzzification method and FCM is simulated under the eight cases that are differentiated by applying the different initial state vectors. Steady states of the factors observed at the convergence are evaluated by experts in order to support the investors and governments for making decision about the new solar energy generation in the long term.

In the literature, there are various extensions of fuzzy sets such as hesitant, Type-2 and intuitionistic fuzzy sets. For the future research, FCMs can be improved with the extensions of fuzzy sets. Fuzziness inherent in the solar energy generation models can be better represented with these extensions.

References

Adaramola, M. (2015). Solar energy: application, economics, and Public Perception Apple Academic Press, Oakville, Canada.

Agency IE. (2009). World energy outlook 2009. http://www.worldenergyoutlook.org/media/weowebsite/2009/WEO2009.pdf. Accessed April 11, 2016.

Ameta, S. C., Ameta, R. (2016). Solar energy conversion and storage: photochemical modes. Electrochemical energy storage and conversion. Boca Raton: CRC Press.

Axelrod, R. M. (1976). Structure of decision: The cognitive maps of political elites. USA: Princeton University Press. doi:citeulike-article-id:10721833

Bogetoft, P. O., & Ballebye, Henrik. (2007). *Cooperatives and payment schemes: Lessons from theory and examples from Danish agriculture*. Frederiksberg: Copenhagen Business School Press.

BP: BP Statistical Review of World Energy. (2015). http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html. Accessed 2016.

Bueno, S., Salmeron, J. L. (2009) Benchmarking main activation functions in fuzzy cognitive maps. Expert Syst Appl*,* *36*(3, Part 1):5221–5229. doi:10.1016/j.eswa.2008.06.072

Commision, E. (2003). World energy, technology and climate policy outlook 2030. https://ec.europa.eu/research/energy/pdf/weto_final_report.pdf. Accessed April 11, 2016.

Dickerson, J. A., & Kosko, B. (1994). Virtual worlds as fuzzy cognitive maps. *Presence: Teleoperators & Virtual Environments, 3*(2), 173–189.

Diffenbach, J. (1982). Influence diagrams for complex strategic issues. *Strategic Management Journal, 3*(2), 133–146.

EIA . (2016). USEIA: Glossary. http://www.eia.gov/tools/glossary/. Accessed April 11, 2016.

Haykin, (1998) S. Neural networks: A comprehensive foundation. USA: Prentice Hall PTR.

Kahraman, C., Kaya, İ., & Cebi, S. (2009). A comparative analysis for multiattribute selection among renewable energy alternatives using fuzzy axiomatic design and fuzzy analytic hierarchy process. *Energy, 34*(10), 1603–1616. doi:10.1016/j.energy.2009.07.008

Kalogirou, S. A. (2014a). Chapter 12—Solar economic analysis. In: Solar energy engineering (Second Edition). Boston: Academic Press, pp. 701–734. doi:10.1016/B978-0-12-397270-5.00012-1

Kalogirou, S. A. (2014b). Solar energy engineering (Second Edition).

Kosko, B. (1986): Fuzzy cognitive maps. *International Journal of Man-Machine Studies, 24*(1):65–75. doi:citeulike-article-id:6695197

Kosko, B. (1997). Fuzzy engineering. Upper Saddle River, N.J.; London: Prentice Hall International.

Lee, C. C. (1990) Fuzzy logic in control systems: fuzzy logic controller. II. Systems, Man and Cybernetics, IEEE Transactions on 20 (2):419–435.

Mackay, M. E. (2015). Solar energy: An introduction. USA: Oxford University Press.

Özesmi, U., & Özesmi, S. L. (2004). Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. *Ecological Modelling, 176*(1–2), 43–64. doi:10.1016/j.ecolmodel.2003.10.027

REN21. (2015). REPNftsC: Renewables 2015 global status report. http://www.ren21.net/Portals/0/documents/e-paper/GSR2015KF/index.html#/8. Accessed 10 April 2016.

Silvi, C. (2008). History and future of renewable solar energy. *Development, 51*(3), 409–414. doi:10.1057/dev.2008.45

Sugeno, M. (1985). An introductory survey of fuzzy control. Information Sciences, *36*(1):59–83. doi:10.1016/0020-0255(85)90026-X

Tsadiras, A. K. (2008). Comparing the inference capabilities of binary, trivalent and sigmoid fuzzy cognitive maps. *Information Sciences, 178*(20), 3880–3894. doi:10.1016/j.ins.2008.05.015

Tsadiras, A. K., & Margaritis, K. G. (1997). Cognitive mapping and certainty neuron fuzzy cognitive maps. *Information Sciences, 101*(1–2), 109–130. doi:10.1016/S0020-0255(97)00001-7

United States Environmental Protection Agency (USEPA). (2016). Climate change. https://www3.epa.gov/climatechange/. Accessed April 7, 2016.

Xirogiannis, G., Glykas, M., & Staikouras, C. (2010) Fuzzy cognitive maps in banking business process performance measurement. In: M. Glykas (Ed) *Fuzzy cognitive maps: Advances in theory, methodologies, tools and applications* (pp. 161–200). Berlin: Springer. doi:10.1007/978-3-642-03220-2_7

Zhang, W. R., Chen, S. S., Bezdek, J. C. (1989). Pool2: A generic system for cognitive map development and decision analysis. IEEE Transactions on Systems, Man, and Cybernetics, *19*(1):31–39. doi:10.1109/21.24529

Zhang, M., Zhou, D., & Zhou, P. (2014). A real option model for renewable energy policy evaluation with application to solar PV power generation in China. *Renewable and Sustainable Energy Reviews, 40*, 944–955. doi:10.1016/j.rser.2014.08.021

Chapter 9
Planning of Efficient Natural Gas Consumption in a Combined Cycle Gas Turbine Power Plant Using Evolutionary Algorithms

H. Kutay Tinç and İrem Uçal Sarı

Abstract Energy generation industry is growing rapidly to meet the increasing energy demand. One of the most usable raw materials for energy production is natural gas. Combined cycle gas turbine power plants have a big portion among the power plants using natural gas for energy production. Therefore, in this chapter combine cycle gas turbine power plants have been analyzed with respect to the effects of market price changes to the amount of natural gas which a combined cycle gas turbine power plant would need for production throughout a year. The proposed model takes the costs of natural gas, ignition and maintenance of the turbine into account. It utilizes an evolutionary algorithm to minimize the power plant's risk and helps managers to find the optimal amount of natural gas consumption to achieve maximum profit. Also the proposed model is applied on a medium scale natural gas power plant for validation and the results are given.

9.1 Introduction

The increased life standards by the developing high technology, make human beings addicted to energy, especially in the form of electricity. Governments have focused on energy policies which plan sustainability of energy resources while meeting the current energy consumption demand. Most of the countries outsource

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the energy transformation and production processes to the private energy companies. In these countries, usually energy providers need to follow the price limitations which are determined by governments.

In the energy generation sector, one of the most important issues about raw materials is the alterations of their prices and their supply amounts due to the changes in the political and economic environments. The prices are directly affected with new (sometimes unexpected) national and international agreements between governments or suppliers and government as it is same for the supply amounts. Companies have to rapidly take into account this variability of the raw material prices and available supply amounts, and change their production schedules quickly to abandon from a possible bankrupt. This situation is as important in a reverse scenario where a change in price limitations or price spikes effect the amount of raw materials a power plant would need. Therefore, the efficient usage of the raw material is one of the most important aspects of the energy production process. It is important to make the best production scheduling and pricing of the product with respect to the available raw material and its cost.

Main sources of world electricity production and their percentages are defined as coal (40.3 %), natural gas (22.4 %), hydropower (16.1 %), nuclear power (10.8 %), renewable sources (4.7 %) and oil (4.1 %) in 2012 according to the world development indicators report. It is also seen that the percentage of the electricity production by natural gas is increasing whereas the rate of coal is decreasing in the world (World Bank Group 2015). Therefore, in this chapter we will focus on increasing the efficiency of energy production by natural gas.

As it is mentioned before, because of the price and available amount alterations of raw materials, there is high uncertainty on the parameters which are used to schedule the production and determine the product prices. Artificial intelligence techniques have been used to handle the uncertainty for a long time. They are especially important for having quick response to the changing circumstances. Evolutionary algorithms are one of the most used artificial intelligence techniques. They use mechanisms inspired by biological evolution. It is effective especially when the problem is huge and complex and when the exact methods cannot be used to find a solution. In this study, in order to deal with the uncertain environment, evolutionary algorithms are used in solving the proposed optimization model.

The main purpose of this chapter is to plan efficiently natural gas consumption in a combined cycle gas turbine power plant using evolutionary algorithms. Combined cycle gas turbine power plants are selected due to their high efficiency rates which make them preferred more in energy generation by natural gas.

This chapter is organized as follows: In Sect. 9.2 a detailed literature review on energy production is given. In Sect. 9.3 basic information about evolutionary algorithms is given. In Sect. 9.3 the formulation of algorithm is determined. In Sect. 9.4 the proposed methodology is applied to a real electricity generation company for validation. And finally the chapter is concluded with conclusion and discussions.

9.2 Literature Review

In this chapter, SCOPUS database is used for the literature review. The search of energy production (or generation) results in more than 30,000 articles. 1071 of them used Artificial Intelligent techniques. Figure 9.1 shows number of the documents published in each year.

There are lots of articles which used evolutionary algorithms in energy production. Ferreira et al. (2015) presented a multi-objective optimization of a micro gas turbine operating in cogeneration mode to provide electric and thermal power to fulfill the energy demands for a reference case. Barukcic et al. (2014) applied a multiobjective evolutionary approach to optimize power production based on renewable sources and loads in the distribution networks. Fazlollahi and Maréchal (2013) used multi-objective evolutionary algorithms and mixed integer linear programming to minimize costs and carbon dioxide emission in the simultaneous production of electricity and heat with biomass.

There are several articles focusing on power generation from natural gas. Sevik (2015) compared the use of NG in electricity generation in Turkey and the world, and analyzed the supply-demand projections and future prospects in the field of energy. Azmy and Mohamed (2005) extracted the required training database by performing the optimization offline at different load demands as well as different natural gas and electricity tariffs using a Genetic Algorithm (GA) to demonstrate the online optimal management of PEM fuel cells for onsite energy production to

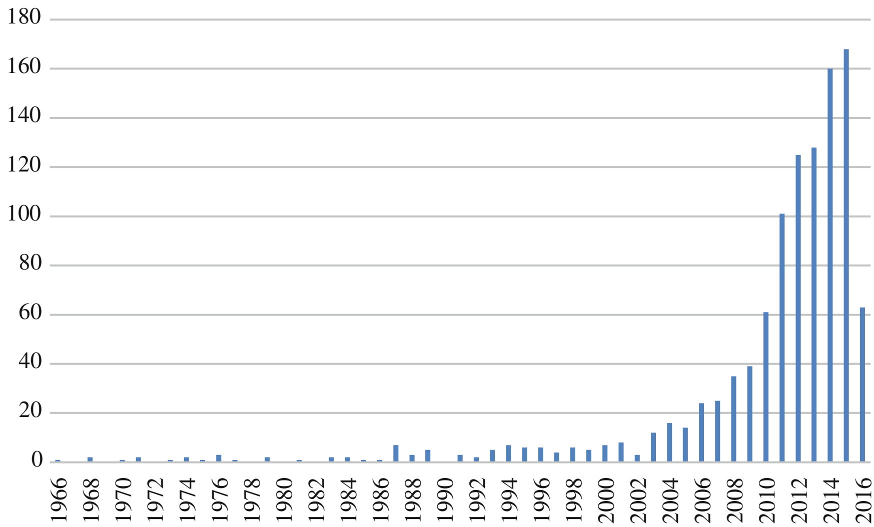

Fig. 9.1 Yearly published articles on energy production using artificial intelligent techniques

supply residential loads. Kantardzic and Gant (2007) analyzed the data streams and created 159 local models for prediction of natural gas-fired power generation from the data. Aguiar et al. (2007) presented a daily simulation model for technical and economical analysis of natural gas microturbine application for residential complex. Gassner and Maréchal (2012) used an evolutionary multi objective algorithm to optimize thermo-economic process of the polygeneration of synthetic natural gas, power and heat. Cetin et al. (2014) presented a thermoeconomic analysis methodology to calculate unit energy (electricity and heat) production cost for a combined cycle system with steam extraction (cogeneration system). Rovira et al. (2011) showed a methodology to achieve thermoeconomic optimisations of combined cycle gas turbine power plants taking into account the frequent off-design operation of the plant to improve the thermoeconomic design of the power plant. San Jose et al. (2008) examined the air quality impact of natural gas combined cycle electric power plants in Spain. Tsoutsanis et al. (2015) proposed component map fitting methods simultaneously determine the best set of equations for matching the compressor and the turbine map data for improving the accuracy and fidelity of the engine performance prediction and diagnosis. Bhavani et al. (2014) designed an indigenous condition monitoring system to identify the flame temperature and common faults in a gas turbine by processing the information from the flame images.

9.3 Evolutionary Algorithms

Fraser (1957) and Box (1957) build the foundations of evolutionary algorithms. Evolution is an optimization process where the aim is to improve the ability of an organism or a system to survive in dynamically changing and competitive environments. Evolutionary compotation refers to computer-based problem solving systems that use computational models of evolutionary processes, such as natural selection, survival of the fittest and reproduction, as the fundamental components of such computational systems (Engelbrecht 2007).

The evolutionary algorithm is a robust search and optimization methodology that is able to cope with ill-behaved problem domains, exhibiting attributes such as multimodality, discontinuity, time-variance, randomness, and noise. It permits a remarkable level of flexibility with regard to performance assessment and design specification. However, the evolutionary algorithm is not without its own challenges. Much care must be taken to produce an effective search algorithm and the methodology suffers from the image of computational inefficiency (Fleming and Purshouse 2002).

The most general properties of evolutionary algorithms are summarized as follows (Back 2000):

1. Evolutionary algorithms utilize the collective learning process of a population of individuals.
2. Descendants of individuals are generated by randomized processes intended to model mutation and recombination.
3. By means of evaluating individuals in their environment, a measure of quality or fitness value can be assigned to individuals.

There are three main paradigms within evolutionary algorithms, whose motivations and origins were independent from each other: evolution strategies, evolutionary programming and genetic algorithms (Coello 2005). Also genetic programming, gene expression programming, differential evolution, neuro-evolution and learning classifier system are some of the specific types of evolutionary algorithms.

9.4 Natural Gas Power Plant Systems

Natural gas can be used to generate electricity in a variety of ways. These include (1) conventional steam generation, similar to coal fired power plants in which heating is used to generate steam, which turns runs turbines with an efficiency of 30–35 %; (2) centralized gas turbines, in which hot gases from natural gas combustion used to turn the turbines and (3) combined cycle units, in which both steam and hot combustion gases are used to turn the turbines with an efficiency of 50–60 % (Demirbas 2009).

The most efficient method of generating electricity from natural gas is a combined cycle unit. In combined cycle natural gas power plants, gas turbines are directly driven by burning natural gas, and exhaust heat is utilized to produce steam for (conventional) steam turbines. Such combined cycle technology can increase the thermal efficiency from about 40 % to about 50–60 % (Weissenbacher 2009). In a combined cycle power plant, exhaust gases from the gas turbine pass through a heat recovery steam generator before being allowed to vent to the atmosphere. The heat recovery steam generator boils water, creating high temperature, high-pressure steam that expands in the steam turbine. The rest of the steam cycle is the normal one: A partial vacuum is created in the condenser, drawing steam from the turbine, and the resulting condensate is pumped back through the heat recovery steam generator to complete the cycle (Masters 2013).

In this study, a combined cycle gas turbine is considered for modeling natural gas consumption due to their high efficiency rates.

9.5 Modelling Natural Gas Consumption

Natural gas power plants use natural gas to create heat that turns turbines to generate electricity. They schedule their production daily and according to the market price by submitting demand bids on electricity prices a day before actual production date. These demand bids—with bids from other power plants and supply bids from the sellers—effect the market price where supply and demand totals meet.

Making wrong decisions about electricity production schedules might lead to more natural gas consumption to produce the same amount of total electricity for natural gas power plants. This reduces their efficiency and raises both their costs and their carbon footprints due to excessive emission of carbon dioxide. To prevent this, price forecasts are used to schedule production for a calendar year (12 months) at least 1 month before that year starts.

As forecasts are slightly erroneous at best (and horrifically off target at worst), changes to the long term forecast that was defined at first occur all the time. These changes can cause schedules of power plants to change and as most natural gas power plants do not have depots to store natural gas, they have to react accordingly.

9.5.1 Day Ahead Market Price

In Turkish Energy Market, electricity pricing is done by balancing the supply and the demand forecasts of market players for the next day's 24 h. As supply prices are different for different types of power plants and natural gas power plants, which have higher costs than other types of power plants, produce most of the energy in Turkey, which is about 44.5 % of total production, they are the price cutters almost all of the time.

Day Ahead Market Price, which is named PTF in Turkish Energy Market, is sensitive to availability rates of different types of power plants. Thermic power plants like coal power plants, natural gas power plants, fuel-oil power plants, biogas power plants and geothermal power plants, which make up 76.5 % of total electricity production of Turkey, tend to have an average of 70 % availability, whereas hydroelectricity power plants, which produce about 20 % of daily electricity usage, have an average of 45 % availability. Wind power plants are both low on capacity with only 3.5 % of production, and have a long and unpredictable availability range starting from 10 % and leading up to 70 %.[1] Figure 9.2 shows the percentages of the plant types for daily production of Turkish energy market.

Availability of thermic power plants depends on maintenance schedules and major breakdowns. Thus they are either known beforehand or are very rare. Also many natural gas power plants have close costs and are working interchangeably

[1] http://www.teias.gov.tr/yukdagitim/YukTevziRaporlari.htm

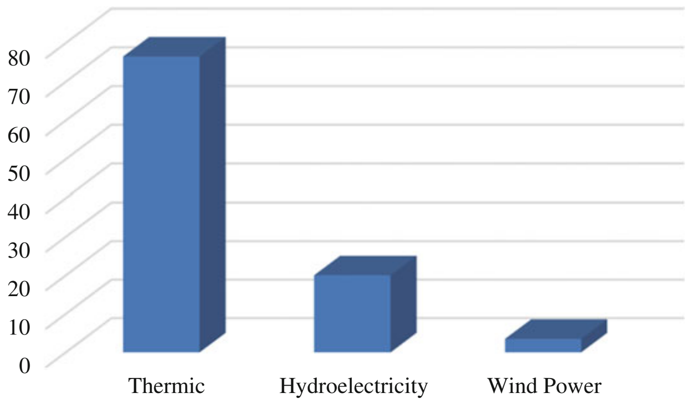

Fig. 9.2 Average production percentage for daily Turkish energy market

Table 9.1 Power plant availabilities (see Footnote 1)

Power plant type	Availability
Thermic	High—70 %
Hydroelectricity	Medium—45 %
Wind power	Highly irregular—10–70 %

every day. Hence only huge drops in thermic power availability can cause serious price fluctuations.

Hydroelectricity power plants' availability, apart from maintenance and breakdowns, is somewhat dependent on climate change. If a hydroelectricity power plant is built on a dam, it can only be affected on long term climate changes, on the other hand run off river type hydroelectric plants tend to get affected from climate change just like wind power plants and are another cause of price fluctuations (Table 9.1).

Monthly average PTF values from December 2011 to November 2015 and average daily PTF values of February 2014 can be found in Tables 9.2 and 9.3 respectively.

From these tables, both monthly and daily price fluctuations can be clearly observed. These jumps in price can occur because of two different scenarios:

1. Every seller that has a marginal cost equal to or close to the price-cutter has increased or decreased their prices due to an expectation (higher government reinforcements, gas crisis, raise in foreign currency, etc.)
2. Price-Cutter range has changed, either due to changes in production (breakdowns, high wind power generation, etc.) or due to abnormal demand behavior.

Table 9.2 Monthly PTF averages December 2011–November 2016 (https://rapor.epias.com.tr/rapor/)

Month\year	2011	2012	2013	2014	2015
1	–	148	155	163	173
2	–	196	135	172	140
3	–	122	128	139	124
4	–	113	144	161	102
5	–	141	138	155	108
6	–	144	147	152	125
7	–	168	157	176	133
8	–	161	152	178	155
9	–	154	156	164	161
10	–	152	144	156	138
11	–	145	152	181	134
12	150	153	193	172	–

Table 9.3 Daily PTF averages (01.02.2014–28.02.2014) (https://rapor.epias.com.tr/rapor/)

Date	PTF	Date	PTF
01.02.2014	148	15.02.2014	170
02.02.2014	137	16.02.2014	147
03.02.2014	152	17.02.2014	157
04.02.2014	166	18.02.2014	161
05.02.2014	188	19.02.2014	156
06.02.2017	217	20.02.2014	151
07.02.2014	209	21.02.2014	155
08.02.2014	208	22.02.2014	163
09.02.2014	199	23.02.2014	139
10.02.2014	202	24.02.2014	151
11.02.2014	206	25.02.2014	151
12.02.2014	204	26.02.2014	155
13.02.2014	195	27.02.2014	165
14.02.2014	183	28.02.2014	168

9.5.2 *Natural Gas Power Plant Schedule Optimization*

Being the price cutter means that your production schedule is not stable and subject to serious fluctuations, which makes forecasting your total production time and the amount of natural gas that must be bought for the next year a crucial part of power efficiency for a natural gas power plant. Most natural gas power plants cannot store natural gas and excessive buying leads to waste due to take or pay type of contracts whereas excessive consumption leads to penalties in the gas price.

The forecast of production time and the amount of natural gas consumed depends on the market price forecast for that year, which is very volatile and changes almost monthly. Using this forecast a Natural Gas Power Plant forms its initial production run scenario and decides on the amount of natural gas to be bought for the following year. The procedure is shown as a nonlinear optimization model below:

$$N_{pi} = g_p^{b_i} P_i \tag{9.5.1}$$

where N_{pi} is natural gas consumption rate at hour i, depends on the production rate at the same hour (m^3), P_i is production rate at hour i (MWh), g_p is natural gas consumption parameter which depends on the type of turbine/motor used (m^3/MWh) and b_i is natural gas consumption rate which equals to 1 at ignition and goes gradually lower with each consecutive production hour.

Before the start of a calendar year (i.e. 2016) a combined cycle gas turbine power plant has to buy its projected Natural Gas Consumption with a "Take or Pay" type agreement. This agreement states that you have to pay what you agree on whether you consume it or not. There is a 10 % error margin allowed but if you consume more than you have stated then the gas price goes up 50 %. And you have to pay for the full price even if you consume less than full. The margin states that you can go as low as 90 % of your projection without paying the full price or you can consume up to 110 % without incurring the 50 % penalty. This margin may be subject to changes depending on the type of contract.

The gas consumption of a single run can be optimized by means of this formula:

$$\text{Max}\left(\sum_{i=n}^{m} M_i \;*\; P - N_{pi} \;*\; c - O_i\right) - S_n \tag{9.5.2}$$

where M_i is estimated price of market at hour i $(1 \le i \le 8760)$, S_i is fixed start cost for turbine ignition at hour i $(TL) = S$ or 0, O_i is maintenance and other fixed costs per hour of production $(TL) = R$ or 0 and c is natural gas price (TL/m^3).

The formula must be greater than 0 for each unique production run between hours n and m, so that the operation yields a profit. The total maximization problem is actually modeled as following:

$$\text{Max}\, z = \sum\nolimits_i (M_i * P_i - N_{pi} * c - O_i - S_i) \tag{9.5.3}$$

$$\text{St} \quad P_i = 0, P_{i+1} > 0 \Rightarrow S_{i+1} = S, \quad otherwise\, S_{i+1} = 0 \tag{9.5.4}$$

$$P_i = 0 \Rightarrow O_i = 0, \quad otherwise\, O_i = R \tag{9.5.5}$$

The total amount of gas (m^3) to be bought before the year can be calculated as $G_T = \sum_i N_{pi}$.

The market price expectations might change before or during the calendar year. This might cause the combined cycle gas turbine power plant to change its production schedules drastically. The previous expectation of natural gas consumption becomes a constraint for the same problem in the second scenario. Hence a single run's profit can be formulated as:

$$\text{Max}\, z = \sum\nolimits_i (M_i * P_i - N_{pi} * c - O_i - S_i) \quad (9.5.6)$$

$$\text{St}\, P_i = 0, P_{i+1} > 0 \Rightarrow S_{i+1} = S, \quad \textit{otherwise}\, S_{i+1} = 0 \quad (9.5.7)$$

$$P_i = 0 \Rightarrow O_i = 0, \quad \textit{otherwise}\, O_i = R \quad (9.5.8)$$

$$0.9G_T \leq \sum N_{pi} \leq 1.1G_T \quad (9.5.9)$$

However, if the profit to be made from overconsumption is greater than the penalty incurred from paying the 50 % markup the right hand side of the constraint becomes obsolete. Moreover, if the maintenance and other fixed costs per hour of production is greater than the market price, which given the history of PTF might only happen if the power plant was initially planning to work about 90 % of the time, stopping the power plant and paying the excessive buying cost gives a better result.

Then, we can formulate the cost of excessive buying (too much natural gas) or excessive expenditure (not enough natural gas) scenarios as follows:

$$\text{If } \sum \mathrm{N_{pi}} < 0.9\mathrm{G_T} \quad \text{then}\, \mathrm{T} = (\mathrm{G_T} - \sum \mathrm{N_{pi}}) * \mathrm{c} \quad (9.5.10)$$

or

$$\text{If } \sum \mathrm{N_{pi}} > 1.1\mathrm{G_T} \quad \text{then}\, \mathrm{T} = (\sum \mathrm{N_{pi}} - \mathrm{G_T}) \; * \; 1.5 \; * \; \mathrm{c} \quad (9.5.11)$$

$$\text{Otherwise, } T = 0. \quad (9.5.12)$$

These three statements replace the constraint $0.9G_T \leq \sum N_{pi} \leq 1.1G_T$. Hence the model becomes:

$$\text{Max} \quad w = \sum_i (M_i \; * \; P_i - N_{pi} \; * \; c - O_i - S_i) - T \quad (9.5.13)$$

$$\text{St}\, P_i = 0, P_{i+1} > 0 \Rightarrow S_{i+1} = S, \quad \textit{otherwise}\, S_{i+1} = 0. \quad (9.5.14)$$

$$P_i = 0 \Rightarrow O_i = 0, \quad \textit{otherwise}\, O_i = R. \quad (9.5.15)$$

$$\sum \mathrm{N_{pi}} < 0.9\mathrm{G_T} \Rightarrow \mathrm{T} = (\mathrm{G_T} - \sum \mathrm{N_{pi}}) * \mathrm{c} \quad (9.5.16)$$

$$\sum \mathrm{N_{pi}} > 1.1\mathrm{G_T} \Rightarrow \mathrm{T} = (\sum \mathrm{N_{pi}} - \mathrm{G_T}) * 1.5 * \mathrm{c} \quad (9.5.17)$$

$$\text{Otherwise}, T = 0. \quad (9.5.18)$$

9.5.3 Using the Model to Determine the Best Scenario

Although all price forecasts for yearly PTF comes in based on different expectations for the year, most consultancy firms work around about the same scenarios when publishing their forecasts for long term. This usually results in producing two dominant scenarios which include a high precipitation /low price and a drought scenario where prices are higher than normal.

Power plants have to choose which scenario they want to use to make their initial production schedule and choosing any of the two scenarios would have a negative impact if the other one came to be true.

Following this reasoning two runs that take one of each scenario as the initial one and the other as the second scenario we can calculate two different profit expectations. If we let market prices for both scenarios to be $M1_i \leq M2_i$ for all i, the initial optimal gas bought for both scenarios to be $G1_T$ and $G2_T$ and the profits for each scenario after the gas is bought to be w_1 and w_2 then the problem becomes:

$$\mathrm{Max}(\mathrm{w}_1(\mathrm{G2_T}), \mathrm{w}_2(\mathrm{G1_T})) \tag{5.19}$$

This problem can be modelled and solved as a nonlinear programming model.

9.6 Application of the Proposed Model on a Medium Scale Natural Gas Power Plant for 2016 Market Clearing Price Forecasts

The power plant selected for the application has the following values for its parameters:

$$P_{max} = 100 \text{ MWh}$$
$$S_i = 500 \text{ TL}$$

(Each ignition of turbine costs 500 TLs as liquid fuel is used for ignition)

$$N_{pi} = 20.000 \text{ m}^3 \text{ at } 100 \text{ MWh production}$$
$$R = 20 \text{ TL}$$
$$c = 0.825 \text{ TL/m}^3$$

From these values, the hourly cost of producing 100 MWs is 18.500 TL, hence the cost of production is 185 TL/MWh.

We have 2 scenarios with annual averages of 149 TL/MWh and 150 TL/MWh. Although the yearly averages are close, monthly averages differ due to different

Table 9.4 Two forecast scenarios for 2016 PTFs

Month	DAM price 1	DAM price 2
1	164	160
2	149	162
3	131	129
4	121	130
5	115	136
6	143	143
7	156	149
8	168	166
9	160	147
10	145	152
11	162	155
12	174	168

renewable energy capacity expectations and different maintenance scenarios for power plants in the country (Table 9.4).

The first price scenario contains 1495 h where price is equal to or greater than 185, which is the cost of production for the power plant, and the second scenario contains 1255 h where price is equal to or greater than 185. Note that although the yearly average of the second scenario is greater, the number of viable production hours is significantly less for it.

When both scenarios are optimized separately using evolutionary algorithm the first scenario yields a total of 1484 production hours whereas the second one yields a total of 1253 production hours. The monthly breakdown of the production plans can be seen in Tables 9.5. and 9.6.

Note that both scenarios' production hours are very close to their viable hours. They could even surpass the viable hours. This is due to gaps in productivity and the way these gaps are filled by the algorithm. For example, if in a given time frame

Table 9.5 Scenario 1 production plan

Month	DAM price 1	Production hours 1
1	164	262
2	149	19
3	131	0
4	121	0
5	115	0
6	143	8
7	156	97
8	168	311
9	160	196
10	145	44
11	162	184
12	174	374

Table 9.6 Scenario 2 production plan

Month	DAM price 2	Production hours 2
1	160	199
2	162	171
3	129	0
4	130	0
5	136	0
6	143	0
7	149	135
8	166	236
9	147	178
10	152	60
11	155	38
12	168	236

2 production runs follow each other closely, because of the ignition cost, leaving a gap between them might be more costly than producing at a loss at those hours. Hence the algorithm decides to produce at those hours at a loss to avoid paying another ignition cost.

These production schedules would have the following gas costs (Table 9.7).

And if the price scenario changes somewhere after the start of 3rd month and before 6th month, the plant would either have a lack of or an excess of gas worth about 5.5 M TL—about 331 h of production.

For the first scenario, the expected profit is about 4.46 M TL if the price forecast is correct. Although if after two months of production the price forecast reverts to the second one, the plant has an excess of gas. As the take or pay agreement dictates, the plant has to work at least 300 more hours of pay for the gas not used during the year.

Table 9.7 Gas cost comparison

Month	Gas cost 1	Gas cost 2
1	4,323,000	3,283,500
2	313,500	2,821,500
3	0	0
4	0	0
5	0	0
6	132,000	0
7	1,600,500	2,227,500
8	5,131,500	3,894,000
9	3,234,000	2,937,000
10	726,000	990,000
11	3,036,000	627,000
12	6,171,000	3,894,000
Total	24,667,500	20,674,500

The average of PTF for the duration that the plant has to work for is 184.1 TL/MWh and the plant loses about 42,000 TL due to selling cheaper than its production cost and maintenance costs.

For the second scenario, the expected profit is about 3.95 M TL if the price forecast is correct. Although if after two months of production the price forecast reverts to the first one, the plant has a lack of gas. As the take or pay agreement dictates, the plant may buy extra gas for a 1.5 times the normal cost if it uses more than 10 % of the agreed total. This brings the total cost of 1 MW to 267.5 TL, where in normal circumstances a power plant cannot work.

The average of PTF for the duration that the plant can't work due to high gas price is 187 TL/MWh and the plant loses about 61.000 TL due to the opportunity cost.

When comparing the two scenarios, it is obvious that the first scenario is preferable for the given price forecasts. This may change if price forecasts change and each scenario should be analyzed separately.

9.7 Conclusion

Energy generation by using natural gas is a popular subject on energy management. Combined cycle gas turbine power plants have a big portion among the power plants using natural gas for energy production. In this chapter, we have analyzed the effects of market price changes to the amount of natural gas which a combined cycle gas turbine power plant would need for production throughout a year. The proposed model helps to minimize the power plant's risk and buy the optimal amount of natural gas to achieve maximum profit.

As energy demand must be met to avoid blackouts, energy will be generated either way. Any amount not generated by the CCGT analyzed in this chapter would be generated by a less efficient power plant with a higher carbon footprint. Also any extra production the CCGT would make mean that a power plant with a lesser carbon footprint be shut down for that period of time. Hence, optimizing the CCGT's production planning helps reduce the carbon footprint of the system as a whole as well as the plant's costs.

The proposed model takes the cost of natural gas, cost of ignition and maintenance cost of the turbine into account. A more complex model might include the ramp up and ramp down functions instead of a gas consumption rate function, but the results would be similar in regards to production hours and scenarios to be selected.

For further researches it is suggested to build a more complex model which includes the ramp up and ramp down functions and compare its results with ones obtained from the proposed model.

References

Aguiar, A. B. M., Pinto, J. O. P., Andrea, C. Q., & Nogueira, L. (2007). Modeling and simulation of natural gas microturbine application for residential complex aiming technical and economical viability analysis. In *Electrical Power Conference (EPC 2007)* (pp. 376–381). Canada: IEEE.

Azmy, A. M., & Mohamed, M. R. (2005). Decision tree-based approach for online management of fuel cells supplying residential loads. In *Power Tech* (pp. 1–7). Russia: IEEE.

Back, T. (2000) Introduction to evolutionary algorithms, In: T. Baeck, D. B Fogel, Z. Michalewicz (Eds), *Evolutionary computation 1: Basic algorithms and operators* (pp. 59–63). London: Taylor and Francis Group.

Barukcic, M., Hederic, Z., & Miklosevic, K. (2014). Multi objective optimization of energy production of distributed generation in distribution feeder. In *Energy Conference (ENERGYCON)* (pp. 1325–1333), IEEE International.

Bhavani, N. P. G., Sujatha, K., Kumaresan, M., Pongamal, R. S., & Reddy, S. B. (2014). Soft sensor for temperature measurement in gas turbine power plant. *International Journal of Applied Engineering Research, 9*(23), 21305–21316.

Box, G. E. P. (1957). Evolutionary operation: A method of increasing industrial productivity. *Applied Statistics, 6*, 81–101.

Cetin, B., Erdem, H. H., & Sevilgen, S. H. (2014) Energy based thermoeconomic analysis of a combined cycle system with steam extraction (cogeneration system). *Advances in Mechanical Engineering*, 794561.

Coello, C. A. C. (2005). An introduction to evolutionary algorithms and their applications. In F. F. Ramos, V. L. Rosillo, & H. Unger (Eds.), *Advanced distributed systems* (pp. 425–442). Berlin: Springer.

Demirbas, A. (2009). *Biofuels: Securing the planet's future energy needs*. London: Springer.

Engelbrecht, A. P. (2007) *Computational intelligence*—An introduction (2nd ed.). New York: Wiley.

Fazlollahi, S., & Maréchal, F. (2013). Multi-objective, multi-period optimization of biomass conversion technologies using evolutionary algorithms and mixed integer linear programming (MILP). *Applied Thermal Engineering, 50*(2), 1504–1513.

Ferreira, A. C., Vaz, A. I. F., Teixeira, S. F., & Teixeira, J. C. (2015) Thermal-economic design of a micro-gas turbine CHP system using a multi-objective optimization approach. In *PANACM 2015—1st Pan-American Congress on Computational Mechanics, in Conjunction with the 11th Argentine Congress on Computational Mechanics (MECOM 2015)* (pp. 1203–1214).

Fleming, P. J., & Purshouse, R. C. (2002). Evolutionary algorithms in control systems engineering: A survey. *Control Engineering Practice, 10*(11), 1223–1241.

Fraser, A. S. (1957). Simulation of genetic systems by automatic digital computers. *Australian Journal of Biological Science, 10*, 484–491.

Gassner, M., & Maréchal, F. (2012). Thermo-economic optimisation of the polygeneration of synthetic natural gas (SNG), power and heat from lignocellulosic biomass by gasification and methanation. *Energy & Environmental Science, 5*(2), 5768–5789.

Kantardzic, M., & Gant, J. (2007) Mining sequences in distributed sensors data for energy production. In *Proceedings of the Twentieth International Florida Artificial Intelligence Research Society Conference* (FLAIRS 2007) (pp. 484–489).

Masters, G. M. (2013). *Renewable and efficient electric power systems*. New York: Wiley.

Rovira, A., Sánchez, C., Munoz, M., Valdés, M., & Durán, M. D. (2011). Thermoeconomic optimisation of heat recovery steam generators of combined cycle gas turbine power plants considering off-design operation. *Energy Conversion and Management, 52*(4), 1840–1849.

San Jose, R., Pérez, J. L., Morant, J. L., Prieto, F., & González, R. M. (2008) The use of third generation air quality modeling systems for web operational realtime forecasting decision support systems: Spain case. In *Proceedings of iEMSs 4th Biennial Meeting—International Congress on Environmental Modelling and Software: Integrating Sciences and Information*

Technology for Environmental Assessment and Decision Making (iEMSs 2008) (Vol. 2, pp. 1154–1161).

Şevik, S. (2015). An analysis of the current and future use of natural gas-fired power plants in meeting electricity energy needs: The case of Turkey. *Renewable and Sustainable Energy Reviews, 52*, 572–586.

Tsoutsanis, E., Meskin, N., Benammar, M., & Khorasani, K. (2015). Transient gas turbine performance diagnostics through nonlinear adaptation of compressor and turbine maps. *Journal of Engineering for Gas Turbines and Power, 137*(9), 091201.

Weissenbacher, M. (2009), Sources of power: How energy forges human history. In *ABC-CLIO*.

World Bank Group (Ed.). (2015). *World development indicators 2012*. New York: World Bank Publications.

Part IV
Water Resources Management

Chapter 10
Water Resources Management Decision-Making Under Stochastic Uncertainty Using a Firefly Algorithm-Driven Simulation-Optimization Approach for Generating Alternatives

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Abstract In solving complex water resources management (WRM) problems, it can prove preferable to create numerous quantifiably good alternatives that provide multiple, disparate perspectives. This is because WRM normally involves complex problems that are riddled with irreconcilable performance objectives and possess contradictory design requirements which are very difficult to quantify and capture when supporting decisions must be constructed. By producing a set of options that are maximally different from each other in terms of their decision variable structures, it is hoped that some of these dissimilar solutions may convey very different perspectives that may serve to address these unmodelled objectives. In environmental planning, this maximally different option production procedure is referred to as modelling-to-generate-alternatives (MGA). Furthermore, many WRM decision-making problems contain considerable elements of stochastic uncertainty. This chapter provides a firefly algorithm-driven simulation-optimization approach for MGA that can be used to efficiently create multiple solution alternatives to problems containing significant stochastic uncertainties that satisfy required system performance criteria and yet are maximally different in their decision spaces. This algorithmic approach is both computationally efficient and simultaneously produces a prescribed number of maximally different solution alternatives in a single computational run of the procedure. The effectiveness of this stochastic MGA approach for creating alternatives in "real world", environmental policy formulation is demonstrated using a WRM case study.

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10.1 Introduction

Water allocation problems have challenged water managers for many decades (Huang and Loucks 2000; Maqsood et al. 2005). Implementing water resources management (WRM) has proven to be both controversial and laden with conflict as the competition between multiple municipal, industrial and agricultural water-users has intensified. Increased population shifts and shrinking water supplies have further exacerbated the user competition. This competition will be further aggravated if natural conditions become more unpredictable due to changing climatic conditions and as concern for water quantity and quality grows. Poorly-planned systems for effectively allocating water can become serious problems under disadvantageous river-flow and climatic conditions. In the past, increasing demand for water was met by the development of new water sources. However, significant economic and environmental costs associated with developing new water sources have rendered this approach unsustainable. The unlimited expansion of water sources is no longer the primary objective in WRM. Instead, for optimum water resource allocation, it is desired to improve the existing water allocation and management in a more efficient, equitable, and environmentally-benign manner by developing innovative environmental policy formulation techniques for water allocation under various complexities. Such environmental policy formulation can prove to be extremely complicated, since many components of water systems generally contain considerable degrees of uncertainty (Wang and Huang 2015a, b). The abundance of stochastic uncertainty renders most common decision approaches relatively unsuitable for practical implementation (Liu et al. 2014; Wang and Huang 2015a; Zhou et al. 2013).

Since WRM systems generally possess all of the characteristics associated with environmental planning, problems of WRM management have provided an ideal setting for testing a wide variety of modelling techniques used in support of environmental decision-making (Imanirad et al. 2017; Linton et al. 2002; Yeomans and Yang 2014). WRM decision-making frequently involves complex problems that possess design requirements which are very difficult to incorporate into any supporting modelling formulations and tend to be plagued by numerous unquantifiable components (Brugnach et al. 2007; Castelletti et al. 2012; De Kok and Wind 2003; Hipel and Walker 2011; Lund 2012; Janssen et al. 2010; Mowrer 2000; Walker et al. 2003; Wang and Huang 2015a, b). Numerous objectives and system requirements readily exist that can never be explicitly captured during the problem formulation stage (Fuerst et al. 2010; Wang et al. 2007). This commonly occurs in "real world" situations where final decisions must be constructed based not only upon clearly articulated specifications, but also upon environmental, political and socio-economic objectives that are either fundamentally subjective or not articulated (Baugh et al. 1997; Brill et al. 1982; Zechman and Ranjithan 2007).

Moreover, in public policy formulation, it may never be possible to explicitly convey many of the subjective considerations because there are numerous competing, adversarial stakeholder groups holding diametrically opposed perspectives.

Therefore many of the subjective aspects remain unknown, unquantified and unmodelled in the construction of any corresponding decision models. WRM policy formulation can prove even more complicated when the various system components also contain considerable stochastic uncertainties (Kasprzyk et al. 2012; Yeomans 2008). Consequently, WRM policy determination proves to be an extremely challenging and complicated undertaking (Janssen et al. 2010; Loughlin et al. 2001; van Delden et al. 2012; Zhou et al. 2013) requiring the employment of intelligent environmental management techniques.

Numerous ancillary mathematical modelling approaches have been introduced to support environmental policy formulation (see, for example, Castelletti et al. 2012; Fuerst et al. 2010; Linton et al. 2002; Lund 2012; Lund et al. 1994; Rubenstein-Montano and Zandi 1999; Rubenstein-Montano et al. 2000). However, while mathematically optimal solutions may provide the best answers to these modelled formulations, they generally do not supply the best solutions to the underlying real problems as there are invariably unmodelled aspects not apparent during the model construction phase (Brugnach et al. 2007; Hamalainen et al. 2013; Janssen et al. 2010; Loughlin et al. 2001; Lund 2012; Martinez et al. 2011; Reed and Kasprzyk 2009; Trutnevyte et al. 2012). Furthermore, although deterministic optimization-based techniques are designed to create single best solutions, the presence of the unmodelled issues coupled with the system uncertainties and opposition from powerful stakeholders can actually lead to the outright exclusion of any single (even an optimal) solution from further consideration (Caicedo and Zarate 2011; De Kok and Wind 2003; He et al. 2009; Hipel and Walker 2011; Kasprzyk et al. 2012; Kassab et al. 2011; Matthies et al. 2007; Yeomans 2008; Wang et al. 2007; Zechman and Ranjithan 2007). Under conflicting circumstances where no universally optimal solution exists, it has been stated that "there are no ideal solutions, only trade-offs" (Sowell 1987) and some behavioural aspects taken by decision-makers when faced with such difficulties are described in Hamalainen et al. (2013).

Within the WRM decision-making realm, there are habitually numerous stakeholder groups holding completely incongruent standpoints, essentially dictating that policy-makers must establish decision frameworks that somehow consider numerous irreconcilable points of view simultaneously (De Kok and Wind 2003; Fuerst et al. 2010; Hipel and Walker 2011; Matthies et al. 2007; McIntosh et al. 2011; Yeomans 2002, 2008). Hence, it is generally considered desirable to generate a reasonable number of very different alternatives that provide multiple, contrasting perspectives to the specified problem (Gunalay et al. 2012; Mathies et al. 2007; Walker et al. 2012; Yeomans 2011; Yeomans and Gunalay 2011). These alternatives should preferably all possess near-optimal objective measures with respect to all of the modelled objective(s) that are known to exist, but be as fundamentally different from each as possible in terms of the system structures characterized by their decision variables. By generating such a diverse set of solutions, it is hoped that at least some of the dissimilar alternatives can be used to address the requirements of the unknown or unmodelled criteria to varying degrees of stakeholder acceptability. Several approaches collectively referred to as modelling-to-generate-alternatives (MGA) have been developed in response to this multi-solution creation requirement (Brill et al. 1982; Caicedo and Yun 2011; DeCarolis 2011; Loughlin et al. 2001; Rubenstein-Montano and Zandi 1999; Rubenstein-Montano et al. 2000; Trutnevyte et al. 2012; Ursem and Justesen 2012; Yeomans 2011; Yeomans and Gunalay 2011; Zarate and Caicedo 2008; Zechman and Ranjithan 2007) and these approaches can be used to support intelligent environmental decision-making.

MGA approaches implement a systematic examination of a solution space in order to generate a set of alternatives that are good within the modelled objective space while being maximally different from each other in the decision space. The resulting alternatives provide a set of diverse approaches that all perform similarly with respect to the known modelled objectives, yet very differently with respect to any unmodelled issues (Walker et al. 2003, 2012). Subsequently the policy-makers must conduct comprehensive evaluations of these alternatives to determine which options more closely satisfy their particular circumstances. Thus, a good MGA process should enable a thorough exploration of the decision space for good solutions while simultaneously allowing for unmodelled objectives to be considered when making final decisions. Consequently, unlike the more customary practice of explicit solution determination inherent in most "hard" optimization methods of Operations Research, MGA approaches must necessarily be considered as decision support processes.

Deterministic MGA methods must be considered unsuitable for most WRM policy formulation, since the components of most WRM systems possess considerable stochastic uncertainty (Caicedo and Zarate 2011; Fuerst et al. 2010; He et al. 2009; Kasprzyk et al. 2012; Liu et al. 2014; Lund 2012; McIntosh et al. 2011; Reed and Kasprzyk 2009; Sun and Huang 2010; Tchobanoglous et al. 1993; Thekdi and Lambert 2012; Wang and Huang 2015; Zhou et al. 2013). Yeomans et al. (2003) incorporated stochastic uncertainty directly into planning using an approach referred to as simulation-optimization (SO). SO is a family of optimization techniques that incorporates inherent stochastic uncertainties expressed as probability distributions directly into its computational procedure (Fu 2002; Kelly 2002; Zou et al. 2010). To address the deficiencies in deterministic MGA methods, Yeomans (2002) demonstrated that SO could be used to generate multiple alternatives which simultaneously integrated stochastic uncertainties directly into each generated option. Since computational aspects can negatively impact SO's optimization capabilities, these difficulties clearly also extend into its use as an MGA procedure (Castelletti et al. 2012; Yeomans, 2008). Linton et al. (2002) and Yeomans (2008) have shown that SO can be considered an effective, though very computationally intensive, MGA technique for policy formulation. Furthermore, none of these SO-based approaches could ensure that the created alternatives were sufficiently different in decision variable structure from one another to be considered an effective MGA procedure.

In this chapter, a stochastic MGA procedure is described that efficiently generates sets of maximally different solution alternatives by executing an amended version of the nature-inspired Firefly Algorithm (FA) (Yang 2009, 2010; Yeomans and Yang 2014) combined with a co-evolutionary MGA approach (Imanirad et al. 2012a, b, 2013a, b, 2016, 2017). Yang (2010) has demonstrated that the FA is a more computationally efficient procedure than such commonly-used metaheuristics as enhanced particle swarm optimization, genetic algorithms, and simulated annealing (Cagnina et al. 2008; Gandomi et al. 2011). The FA-driven stochastic MGA procedure advances the deterministic approaches in Imanirad et al. (2012a, b, 2013a, b, 2017) by extending FA into SO for stochastic optimization and by exploiting the concept of co-evolution within the FA's solution methods to concurrently generate the requisite number of solution alternatives (see, Imanirad et al. 2016, 2017). Remarkably, this innovative algorithm can simultaneously generate the overall optimal solution together with n maximally different, locally optimal alternatives in a single computational run. Hence, the stochastic FA-driven procedure is computationally efficient for MGA purposes. Using the solution generation framework employed in Imanirad et al. 2016, the effectiveness of this method for WRM purposes is demonstrated using a case study taken from Huang and Loucks (2000) and Maqsood et al. (2005). More significantly, the practicality of this stochastic MGA FA-driven approach can quite easily be modified to many other stochastic planning systems and, therefore, can be readily adapted to address numerous other applications requiring intelligent environmental management.

10.2 Modelling to Generate Alternatives

Most optimization techniques appearing in the mathematical programming literature have almost exclusively focused on producing single optimal solutions to single-objective problems or, equivalently, generating noninferior solutions to multi-objective formulations (Brill et al. 1982; Janssen et al. 2010; Walker et al. 2003, 2012). While such algorithms may efficiently generate solutions to the derived complex mathematical models, whether these outputs actually establish "best" approaches to the underlying real problems has been called into question (Brill et al. 1982; Brugnach et al. 2007; Janssen et al. 2010; Loughlin et al. 2001). In most "real world" decision-making situations, there are numerous system objectives and requirements that are never explicitly included or apparent during the problem formulation (Brugnach et al. 2007; Walker et al. 2003). Furthermore, it may never be possible to explicitly express all of the subjective components because there are frequently numerous incompatible, competing, design requirements and, perhaps, adversarial stakeholder groups involved (Fuerst et al. 2010; Gunalay et al. 2012; Hipel and Walker 2011). Therefore most subjective aspects of a problem remain unquantified and unmodelled in the resultant decision models. This is a common occurrence in situations where final decisions are constructed based not only upon clearly stated and modelled objectives, but also upon more fundamentally subjective socio-political-economic goals and stakeholder preferences (Gunalay et al. 2012; Yeomans 2011; Yeomans and Gunalay 2011).

Several “real world” examples highlighting these types of incongruent modelling dualities in environmental decision-making are described in Brill et al. (1982), Loughlin et al. (2001) and Zechman and Ranjithan (2007).

When unmodelled objectives and unquantified issues exist, unorthodox approaches are needed that not only explore the decision space for noninferior sets of solutions, but also examine the decision space for discernibly inferior alternatives to the modelled problem. In particular, any search for good alternatives to problems known or suspected to contain unmodelled objectives must focus not only on the non-inferior solution set, but also necessarily on an explicit exploration of the formulation’s entire inferior feasible region.

To illustrate the implications of an unmodelled objective on a decision search, assume that the optimal solution for a quantified, single-objective, maximization decision problem is X^* with corresponding objective value Z_1^*. Now suppose that there exists a second, unmodelled, maximization objective Z_2 that subjectively reflects some unquantifiable component such as “political acceptability”. Let the solution X^c, belonging to the noninferior, 2-objective set, represent a potential best compromise solution if both objectives could somehow have been simultaneously evaluated by the decision-maker. While X^c might be viewed as the best compromise solution to the real problem, it would appear inferior to the solution X^* in the quantified mathematical model, since it must be the case that $Z_1^c \leq Z_1^*$. Consequently, when unmodelled objectives are factored into the decision making process, mathematically inferior solutions for the modelled problem can prove optimal to the underlying real problem (Imanirad et al. 2016; Yeomans 2011).

Therefore, when unquantified issues and unmodelled objectives could exist, unconventional methods are employed to not only search the decision space for noninferior sets of solutions, but also to simultaneously explore the decision space for inferior alternative solutions to the modelled problem. Population-based search techniques such as the FA permit concurrent examinations throughout a decision space and prove to be particularly proficient methods for searching throughout the problem’s feasible region.

The principal objective underlying MGA is to produce a manageably small set of alternatives that are quantifiably good with respect to the known modelled objective (s) yet are as different as possible from each other within the decision space. In doing this, the resulting solution set is likely to provide truly different alternatives that all perform somewhat similarly with respect to the modelled objective(s) yet very differently with respect to any unknown unmodelled issues. By generating a set of good-but-different solutions, the decision-makers can explore desirable qualities within the alternatives that may prove to satisfactorily address the various unmodelled objectives to varying degrees of stakeholder acceptability.

To properly motivate an MGA procedure, it is necessary to apply a more mathematically formal definition to the goals of the MGA process (Gunalay et al. 2012; Loughlin et al. 2001; Yeomans and Gunalay 2011). Suppose the optimal solution to an original mathematical model is X^* with objective value $Z^* = F(X^*)$. The following maximal difference model, subsequently referred to in the chapter as problem [P1], can then be solved to generate an alternative solution that is maximally different from X^*:

$$\text{Maximize } \Delta = \sum_i \left| X_i - X_i^* \right|$$
$$\text{Subject to}: \quad X \in D$$
$$|F(X) - Z^*| \leq T$$

where Δ represents some difference function (for clarity, shown as an absolute difference in this instance), D is the original mathematical model's feasible domain and T is a targeted tolerance value specified relative to the problem's original optimal objective Z^*. T is a user-supplied value that determines how much of the inferior region is to be explored in the search for acceptable alternative solutions.

10.3 Firefly Algorithm for Function Optimization

While this section supplies only a relatively brief synopsis of the FA procedure, more detailed explanations can be accessed in Gandomi et al. (2011), Imanirad et al. (2012a, b, 2013a, b, 2017) and Yang (2009, 2010). The FA is a nature-inspired, population-based metaheuristic. Each firefly in the population represents one potential solution to a problem and the population of fireflies should initially be distributed uniformly and randomly throughout the solution space. The solution approach employs three idealized rules. (i) The brightness of a firefly is determined by the overall landscape of the objective function. Namely, for a maximization problem, the brightness is simply considered to be proportional to the value of the objective function. (ii) The relative attractiveness between any two fireflies is directly proportional to their respective brightness. This implies that for any two flashing fireflies, the less bright firefly will always be inclined to move towards the brighter one. However, attractiveness and brightness both decrease as the relative distance between the fireflies increases. If there is no brighter firefly within its visible neighborhood, then the particular firefly will move about randomly. (iii) All fireflies within the population are considered unisex, so that any one firefly could potentially be attracted to any other firefly irrespective of their sex. Based upon these three rules, the basic operational steps of the FA can be summarized within the pseudo-code of Fig. 10.1 (Yang 2010).

In the FA, there are two important issues to resolve: the formulation of attractiveness and the variation of light intensity. For simplicity, it can always be assumed that the attractiveness of a firefly is determined by its brightness which in turn is associated with its encoded objective function value. In the simplest case, the brightness of a firefly at a particular location X would be its calculated objective value $F(X)$. However, the attractiveness, β, between fireflies is relative and will vary with the distance r_{ij} between firefly i and firefly j. In addition, light intensity decreases with the distance from its source, and light is also absorbed in the media,

Objective Function $F(\boldsymbol{X})$, $\boldsymbol{X} = (x_1, x_2, \ldots x_d)$
Generate the initial population of n fireflies, $\boldsymbol{X}_i$, $i = 1, 2, \ldots, n$
Light intensity I_i at $\boldsymbol{X}_i$ is determined by $F(\boldsymbol{X}_i)$
Define the light absorption coefficient γ
while (t < MaxGeneration)
for $i = 1{:}\ n$, all n fireflies
for $j = 1{:}\ n$,all n fireflies (inner loop)
if $(I_i < I_j)$, Move firefly i towards j; **end if**
Vary attractiveness with distance r via $e^{-\gamma r}$
end for j
end for i
Rank the fireflies and find the current global best solution $\boldsymbol{G}^*$
end while
Postprocess the results

Fig. 10.1 Pseudo code of the firefly algorithm

so the attractiveness needs to vary with the degree of absorption. Consequently, the overall attractiveness of a firefly can be defined as

$$\beta = \beta_0 \exp\left(-\gamma r^2\right)$$

where β_0 is the attractiveness at distance $r = 0$ and γ is the fixed light absorption coefficient for the specific medium. If the distance r_{ij} between any two fireflies i and j located at X_i and X_j, respectively, is calculated using the Euclidean norm, then the movement of a firefly i that is attracted to another more attractive (i.e. brighter) firefly j is determined by

$$X_i = X_i + \beta_0 \exp\left(-\gamma\left(r_{ij}\right)^2\right)\left(X_i - X_j\right) + \alpha\varepsilon_i.$$

In this expression of movement, the second term is due to the relative attraction and the third term is a randomization component. Yang (2010) indicates that α is a randomization parameter normally selected within the range [0,1] and ε_i is a vector of random numbers drawn from either a Gaussian or uniform (generally [−0.5,0.5] distribution). It should be explicitly noted that this expression represents a random walk biased toward brighter fireflies and if $\beta_0 = 0$, it becomes a simple random walk. The parameter γ characterizes the variation of the attractiveness and its value determines the speed of the algorithm's convergence. For most applications, γ is typically set between 0.1 and 10 (Gandomi et al. 2011; Yang 2010).

In any given optimization problem, for a very large number of fireflies $n \gg k$, where k is the number of local optima, the initial locations of the n fireflies should be distributed relatively uniformly throughout the entire search space. As the FA proceeds, the fireflies begin to converge into all of the local optima (including the global ones). Hence, by comparing the best solutions among all these optima, the global optima can easily be determined. Yang (2010) proves that the FA will approach the global optima when $n \to \infty$ and the number of iterations t, is set so that $t \gg 1$. In reality, the FA has been found to converge extremely quickly with n set in the range 20–50 (Gandomi et al. 2011; Yang 2009).

Two important limiting or asymptotic cases occur when $\gamma \to 0$ and when $\gamma \to \infty$. For $\gamma \to 0$, the attractiveness is constant $\beta = \beta_0$, which is equivalent to having a light intensity that does not decrease. Thus, a firefly would be visible to every other firefly anywhere within the solution domain. Hence, a single (usually global) optima can easily be reached. If the inner loop for j in Fig. 10.1 is removed and X_j is replaced by the current global best G^*, then this implies that the FA reverts to a special case of the accelerated particle swarm optimization (PSO) algorithm. Subsequently, the computational efficiency of this special FA case is equivalent to that of enhanced PSO. Conversely, when $\gamma \to \infty$, the attractiveness is essentially zero along the sightline of all other fireflies. This is equivalent to the case where the fireflies randomly roam throughout a very thick foggy region with no other fireflies visible and each firefly roams in a completely random fashion. This case corresponds to a completely random search method. As the FA operates between these two asymptotic extremes, it is possible to adjust the parameters α and γ so that the FA can outperform both a random search and the enhanced PSO algorithms (Gandomi et al. 2011).

The computational efficiencies of the FA will be exploited in the subsequent MGA solution approach. As noted, between the two asymptotic extremes, the population in the FA can determine both the global optima as well as the local optima concurrently. The concurrency of population-based solution procedures holds huge computational and efficiency advantages for MGA (Yeomans 2011; Yeomans and Gunalay 2011). An additional advantage of the FA for MGA implementation is that the different fireflies essentially work independently of each other, implying that FA procedures are better than genetic algorithms and PSO for MGA because the fireflies will tend to aggregate more closely around each local optimum (Gandomi et al. 2011; Yang 2010). Consequently, with a judicious selection of parameter settings, the FA can be made to simultaneously converge extremely quickly into both local and global optima (Gandomi et al. 2011; Yang 2009, 2010).

10.4 A Simulation-Optimization Approach for Stochastic Optimization

The optimization of large stochastic problems proves to be very complicated when numerous system uncertainties have to be incorporated directly into the solution procedures (Fu 2002; Imanirad et al. 2016; Kelly 2002; Zou et al. 2010). SO is a broadly defined family of stochastic solution approaches that combines simulation with an underlying optimization component for optimization (Fu 2002). In SO, all unknown objective functions, constraints, and parameters are replaced by discrete event simulation models in which the decision variables provide the settings under which the simulation is performed. While SO holds considerable potential for solving a wide range of difficult stochastic problems, it cannot be considered a "magic bullet" because of its accompanying processing time requirements (Fu 2002; Kelly 2002).

The general process of SO can be summarized in the following way (Imanirad et al. 2016; Kelly 2002). Suppose the mathematical representation of the optimization problem possesses n decision variables, X_i, expressed in vector format as $X = [X_1, X_2, \ldots, X_n]$. If the problem's objective function is designated by F and its feasible region is represented by D, then the related mathematical programming problem is to optimize $F(X)$ subject to $X \in D$ When stochastic conditions exist, values for the constraints and objective are determined by simulation. Thus, any direct solution evaluation between two distinct solutions X_1 and X_2 requires the comparison of some statistic of F modelled with X_1 to the same statistic modelled with X_2 (Fu 2002; Yeomans 2008). These statistics are calculated by a simulation performed on the solutions, in which each candidate solution provides the decision variable settings in the simulation. While simulation presents a mechanism for comparing results, it does not provide the means for determining optimal solutions to problems. Hence, simulation, by itself, cannot be used as a stochastic optimization procedure.

Since all measures of system performance in SO are stochastic, every potential solution, X, must be determined through simulation. Because simulation is computationally intensive, an optimization algorithm is employed to guide the search for solutions through the problem's feasible domain in as few simulation runs as possible (Yeomans 2008, 2012; Zou et al. 2010). As stochastic system problems frequently contain numerous potential solutions, the quality of the final solution could be highly variable unless an extensive search has been performed throughout the problem's entire feasible region. Population-based metaheuristic such as the FA are conducive to these extensive searches because the complete set of candidate solutions maintained in their populations permit searches to be undertaken throughout multiple sections of the feasible region, concurrently.

An FA-directed SO approach contains two alternating computational phases; (i) an "evolutionary phase" directed by the FA module and (ii) a simulation module (Yeomans and Yang 2014). As described earlier, the FA maintains a population of candidate solutions throughout its execution. The evolutionary phase evaluates the entire current population of solutions during each generation of the search and evolves from the current population to a subsequent one. Because of the system's stochastic components, all performance measures are necessarily statistics calculated from the responses generated in the simulation module. The quality of each solution in the population is found by having its performance criterion, F, evaluated in the simulation module. After simulating each candidate solution, their respective objective values are returned to the evolutionary FA module to be utilized in the creation of the ensuing population of candidate solutions.

A primary characteristic of FA procedures is that better solutions in a current population possess a greater likelihood for survival and progression into the subsequent population. Thus, the FA module advances the system toward improved solutions in subsequent generations and ensures that the solution search does not become trapped in some local optima. After generating a new candidate population in the FA module, the new solution set is returned to the simulation module for comparative evaluation. This alternating, two-phase search process terminates when an appropriately stable system state (i.e. an optimal solution) has been attained. The optimal solution produced by the procedure is the single best solution found over the course of the entire search (Yeomans and Yang 2014).

10.5 FA-Driven SO Algorithm for Stochastic MGA

Linton et al. (2002) and Yeomans (2008) have shown that SO can be used as a computationally intensive, stochastic MGA technique and these approaches have been applied to WRM problems (Yeomans 2010; Yeomans and Gunalay 2008a, b, 2009). Because of the very long computational runs, Yeomans (2012) subsequently examined several approaches to accelerate the search times and solution quality of SO. This section parallels the framework of Imanirad et al. (2016) in describing an FA-driven MGA method (see Yeomans and Yang 2014) that incorporates stochastic uncertainty using SO to much more efficiently generate sets of maximally different solution alternatives.

The FA-driven stochastic MGA approach is designed to generate a pre-determined small number of close-to-optimal, but maximally different alternatives, by essentially adjusting the value of T in [P1] and using the FA to solve each corresponding, maximal difference problem instance. This algorithm provides a stochastic extension to the deterministic approaches of Imanirad et al. (2013a, b, 2017). By exploiting the co-evolutionary solution structure within the population of the FA, stratified subpopulations within the algorithm's overall population are established as the Fireflies collectively evolve toward different local optima within the solution space. In this process, each desired solution alternative undergoes the common search procedure driven by the FA. However, the survival of solutions depends not only upon how well the solutions perform with respect to the modelled objective(s), but also by how far away they are from all of the other alternatives generated in the decision space.

A direct process for generating these alternatives with the FA would be to iteratively solve the maximum difference model [P1] by incrementally updating the target T whenever a new alternative needs to be produced and then re-running the algorithm. Such an iterative approach would parallel the seminal Hop, Skip, and Jump (HSJ) MGA algorithm of Brill et al. (1982) in which, once an initial problem formulation has been optimized, supplementary alternatives are created one-by-one through a systematic, incremental adjustment of the target constraint to force the sequential generation of the suboptimal solutions. While this direct approach is straightforward, it is relatively computationally expensive as it requires a repeated execution of the specific optimization algorithm employed (Gunalay et al. 2012; Imanirad et al. 2012a, b; Yeomans 2011; Yeomans and Gunalay 2011).

In contrast, the concurrent FA-driven MGA approach is designed to generate the pre-determined number of maximally different alternatives within the entire population in a single run of the FA procedure (i.e. the same number of runs as if FA were used solely for function optimization purposes) and its efficiency is based upon the concept of co-evolution (Imanirad et al. 2012a, b, 2013a, b). In this FA-driven co-evolutionary approach, pre-specified stratified subpopulation ranges within the FA's overall population are established that collectively evolve the search toward the creation of the stipulated number of maximally different alternatives. Each desired solution alternative is represented by each respective subpopulation and each subpopulation undergoes the common processing operations of the FA.

The FA-driven approach can be structured upon any standard FA solution procedure containing the appropriate encodings and operators that best correspond to the problem. The survival of solutions in each subpopulation depends simultaneously upon how well the solutions perform with respect to the modelled objective (s) and by how far away they are from all of the other alternatives. Consequently, the evolution of solutions in each subpopulation toward local optima is directly influenced by those solutions currently existing in all of the other subpopulations, which necessarily forces the concurrent co-evolution of each subpopulation towards good but maximally distant regions of the decision space. This co-evolutionary concept enables the simultaneous search for, and production of, the set of quantifiably good solutions that are maximally different from each other according to [P1] (Yeomans and Gunalay 2011).

By employing this co-evolutionary concept, it becomes possible to implement an FA-driven MGA procedure that concurrently produces alternatives which possess objective function bounds that are analogous, but inherently superior, to those created by a sequential HSJ-styled solution generation approach. While each alternative produced by an HSJ procedure is maximally different only from the single, overall optimal solution together with a bound on the objective value which is at least x % different from the best objective (i.e. x = 1, 2 %, etc.), the concurrent co-evolutionary FA procedure is able to generate alternatives that are no more than x % different from the overall optimal solution but with each one of these solutions being as maximally different as possible from every other generated alternative that is produced. Co-evolution is also much more efficient than a sequential HSJ-styled approach in that it exploits the inherent population-based searches of FA procedures to concurrently generate the entire set of maximally different solutions using only a single population. Specifically, while an HSJ-styled approach would need to run n different times in order to generate n different alternatives, the concurrent algorithm need run only once to produce its entire set of maximally different alternatives irrespective of the value of n. Hence, it is a much more computationally efficient solution generation process.

The steps involved in the stochastic FA-driven co-evolutionary MGA algorithm are as follows (see Imanirad et al. 2016):

1. Create the initial population stratified into P equally-sized subpopulations. P represents the desired number of maximally different alternative solutions within a prescribed target deviation from the optimal to be generated and must be set a priori by the decision-maker. S_p represents the pth subpopulation set of

solutions, $p = 1,\ldots,P$ and there are K solutions contained within each S_p. Note that the target for each S_p could be a common deviation value (e.g. all P alternatives need to be within 10 % of optimal) or the targets for each S_p could represent different selected increments (e.g. one alternative would need to be within 1 % of optimal, another alternative would need to be within 2 %, etc.).

2. Evaluate each solutions in S_1 using the simulation module and identify the best solution with respect to the modelled objective. S_1 is the subpopulation dedicated to the search for the overall optimal solution to the modelled problem. The best solution residing in S_1 is employed in establishing the benchmarks for the relaxation constraints used to create the maximally different solutions as in P1.
3. Evaluate all solutions in S_p, $p = 2,\ldots,P$, with respect to the modelled objective using the simulation module. Solutions meeting the target constraint and all other problem constraints are designated as *feasible*, while all other solutions are designated as *infeasible*.
4. Apply an appropriate elitism operator to each S_p to preserve the best individual in each subpopulation. In S_1, this is the best solution evaluated with respect to the modelled objective. In S_p, $p = 2,\ldots,P$, the best solution is the feasible solution most distant in decision space from all of the other subpopulations (the distance measure is defined in Step 7). Note: Because the best solution to date is always placed into each subpopulation, at least one solution in S_p will always be feasible. This step simultaneously selects a set of alternatives that respectively satisfy different values of the target T while being as far apart as possible (i.e. maximally different in the sense of [P1] from the solutions generated in each of the other subpopulations. By the co-evolutionary nature of this algorithm, the alternatives are simultaneously generated in one pass of the procedure rather than the P implementations suggested by the necessary HSJ-styled increments to T in problem [P1].
5. Stop the algorithm if the termination criteria (such as maximum number of iterations or some measure of solution convergence) are met. Otherwise, proceed to Step 6.
6. Identify the decision space centroid, C_{ip}, for each of the $K' \leq K$ feasible solutions within $k = 1, \ldots, K$ of S_p, for each of the N decision variables X_{ikp}, $i = 1,\ldots,N$. Each centroid represents the N-dimensional centre of mass for the solutions in each of the respective subpopulations, p. As an illustrative example for determining a centroid, calculate $C_{ip} = (1/K') \times \sum_k X_{ikp}$. In this calculation, each dimension of each centroid is computed as the straightforward average value of that decision variable over all of the values for that variable within the feasible solutions of the respective subpopulation. Alternatively, a centroid could be calculated as some fitness-weighted average or by some other appropriately defined measure.
7. For each solution $k = 1, \ldots, K$, in each S_q, calculate D_{kq}, a distance measure between that solution and all other subpopulations. As an illustrative example for determining a distance measure, calculate $D_{kq} = Min\{\sum_i |X_{ikp} - C_{ip}|;\ p = 1,\ldots,P, p \neq q\}$. This distance represents the minimum distance between

solution k in subpopulation q and the centroids of all other subpopulations. Alternatively, the distance measure could be calculated by some other appropriately defined function.

8. Rank the solutions within each S_p according to the distance measure D_{kq} objective—appropriately adjusted to incorporate any constraint violation penalties. The goal of maximal difference is to force solutions from one subpopulation to be as far apart as possible in the decision space from the solutions of each of the other subpopulations. This step orders the specific solutions in each subpopulation by those solutions which are most distant from the solutions in all of the other subpopulations.
9. In each S_p, apply the appropriate FA "change operations" to the solutions and return to Step 2.

10.6 Case Study of Water Resources Management Under Uncertainty

As indicated throughout the previous sections, decision-makers faced with situations containing numerous uncertainties generally prefer to be able to select from a set of "near best" alternatives that differ significantly from each other in terms of the system structures characterized by their decision variables. The effectiveness of the FA-driven SO MGA procedure will be illustrated using the water resources management case taken from Huang and Loucks (2000) and Maqsood et al. (2005). While this section briefly outlines the case, more extensive details, data, and descriptions can be found in (Huang and Loucks 2000; Maqsood et al. 2005; Yeomans 2010; Yeomans and Gunalay 2008a, b; Yeomans and Gunalay 2009).

Huang and Loucks (2000) and Maqsood et al. (2005) examined a water resources management case study for allocating water in a dry season from an unregulated reservoir to three categories of users: (i) a municipality, (ii) an industrial concern, and (iii) an agricultural sector. The industrial concern and agricultural sector were undergoing significant expansion and needed to know the quantities of water they could reasonably expect. If insufficient water were available, these entities would be forced to curtail their expansion plans. If the promised water was delivered, it would contribute positive net benefits to the local economy per unit of water allocated. However, if the water was not delivered, the results would reduce the net benefits to the users.

The major problems in these circumstances involved (i) how to effectively allocate water to the three user groups in order to achieve maximum net benefits under the uncertain conditions and (ii) how to incorporate the water policies in terms of allowable amounts within this planning problem with the least risk of system disruption. Included within these decisions is a determination of which one of the multiple possible pathways that the water would flow through in reaching the users. It is further possible to subdivide the various water streams with each resulting substream sent to a different user. Since cost differences from operating the facilities at different capacity levels produce economies of scale, decisions have to be made to determine how much water should be sent along each flow pathway to each user type. Therefore, any single policy option can be composed of a combination of many decisions regarding which facilities received water and what quantities of water would be sent to each user type. All of these decisions were compounded by overriding system uncertainties regarding the seasonal water flows and their likelihoods.

Thus, the WRM case considers how to effectively allocate the water to the three user groups in order to derive maximum net benefits under the elements of uncertainty present and how to incorporate water policies in terms of allowable amounts within this planning problem with the least risk for causing system disruption. Since the uncertainties could be expressed collectively as interval estimates, probability distributions and uncertainty membership functions, the approach of Maqsood et al. (2005) was used to show how to improve upon the earlier efforts of Huang and Loucks (2000) by providing a solution for the WRM problem with a net benefit of $2.02 million.

10.6.1 Mathematical Model for the WRM Planning Case

This section briefly describes the stochastic programming method that Maqsood et al. (2005) formulated to solve the WRM planning case. In the formulation, penalties are imposed when policies that have been expressed as targets are violated. Also within the model, any uncertain parameter A is represented by $A^{\pm}$ and its corresponding values are generated via probability distributions. More extensive details and descriptions of the model, and all of the underlying data for the parameter values, can be found in Huang and Loucks (2000) and Maqsood et al. (2005).

In the region studied, the municipal, industrial, and agricultural water demands have been increasing due to population and economic growth. Because of this, it is necessary to ensure that the different water users know where they stand by providing information that is needed to make decisions for various activities and investments. For example, farmers who know there is only a small chance of receiving sufficient water in a dry season are not likely to make major investment in irrigation infrastructure. Similarly, industries are not likely to promote developments of projects that are water intensive knowing that they will have to limit their water consumption. If the promised water cannot be delivered due to insufficiency, the users will have to either obtain water from more expensive alternate sources or curtail their development plans. For example, municipal residents may have to curtail watering of lawns, industries may have to reduce production levels or increase water recycling rates, and farmers may not be able to conduct irrigation as planned. These impacts will result in increased costs or decreased benefits in relation to the regional development. It is thus desired that the available water be effectively allocated to minimize any associated penalties. Thus, the problem can be formulated as maximizing the expected value of the net system benefits. Based upon the local water management policies, a quantity of water can be pre-defined for each user. If this quantity is delivered, it will result in net benefits; however, if not delivered, the system will then be subject to penalties.

The WRM authority is responsible for allocating water to each of the municipality, the industrial concerns, and the agricultural sector. As the quantity of stream flows from the reservoir are uncertain, the problem is formulated as a stochastic programming problem. This stochastic programming model can account for the uncertainties in water availability. However, uncertainties may also exist in other parameters such as benefits, costs and water-allocation targets. To reflect all of these uncertainties, the following stochastic programming model was constructed by Maqsood et al. (2005):

$$\text{Max}\, f^{\pm} = \sum_{i=1}^{m} B_i^{\pm} W_i^{\pm} - \sum_{i=1}^{m} \sum_{j=1}^{n} p_j C_i^{\pm} S_{ij}^{\pm}$$

$$\sum_{i=1}^{m} \left(W_i^{\pm} - S_{ij}^{\pm} \right) \leq q_j^{\pm}, \ \forall j$$

$$S_{ij}^{\pm} \leq W_i^{\pm} \leq W_{i\max}^{\pm}, \ \forall i$$

$$S_{ij}^{\pm} \geq 0, \ \forall i, j$$

In this formulation $f^{\pm}$ represents the net system benefit ($/m^3) and $B_i^{\pm}$ represents the net benefit to user i per m^3 of water allocated ($). $W_i^{\pm}$ is the fixed allocation amount (m^3) for water that is promised to user i, while $W_{i\max}^{\pm}$ is the maximum allowable amount (m^3) that can be allocated to user i. The loss to user i per m^3 of water not delivered is given by $C_i^{\pm}$, where $C_i > B_i(\$)$. $S_{ij}^{\pm}$ corresponds to the shortage of water, which is the amount (m^3) by which W_i is not met when the seasonal flow is q_j. $q_j^{\pm}$ is the amount (m^3) of seasonal flow with p_j probability of occurrence under j flow level, where p_j provides the probability (%) of occurrence of flow level j. The variable i, $i = 1, 2, 3$, designates the water user, where $i = 1$ for municipal, 2 for industrial, and 3 for agricultural. The value of j, $j = 1, 2, 3$, is used to delineate the flow level, where $j = 1$ represents low flows, 2 represents medium flows, and 3 represents high flows. Finally, m is the total number of water users and n is the total number of flow levels.

The developed formulation can provide results that are expressed as stable solutions with different risk levels within pre-established criteria (Maqsood et al. 2005). This stochastic programming model holds two significant advantages in comparison to other optimization techniques that deal with uncertainties. Firstly, it enables the ability to reflect uncertainties expressed not only as probability distributions but also as possibility distributions. Secondly, it enables a linkage to be made with previously-existing or pre-defined policies that have to be respected whenever a modeling effort is undertaken. In this formulation, penalties are imposed when these policies, that are expressed as targets, are violated.

10.6.2 Using the Co-evolutionary MGA Method for the WRM Planning Case

As outlined earlier, when public policy planners are faced with difficult and controversial choices, they generally prefer to be able to select from a set of near-optimal alternatives that differ significantly from each other in terms of their system structures. In order to create these alternative planning options for the WRM system, it would be possible to place extra target constraints into the original model which would force the generation of solutions that were different from their respective, initial optimal solutions. Suppose for example that five additional planning alternative options were created through the inclusion of a technical constraint on the objective function that decreased the total system benefits of the original model from 2 % up to 10 % in increments of 2 %. By adding these incremental target constraints to the original SO model and sequentially resolving the problem 5 times, it would be possible to create a specific number of alternative policies for WRM planning.

However, to improve upon the process of running five separate additional instances of the computationally intensive SO algorithm to generate these solutions, the FA-driven MGA procedure described in the previous section was run only once, thereby producing the 5 additional alternatives shown in Table 10.1. The table shows the overall system benefits for the 5 maximally different options generated. Given the performance bounds established for the objective in each problem instance, the decision-makers can feel reassured by the stated performance for each of these options while also being aware that the perspectives provided by the set of dissimilar decision variable structures are as different from each other as is feasibly possible. Hence, if there are stakeholders with incompatible standpoints holding diametrically opposing viewpoints, the policy-makers can perform an assessment of these different options without being myopically constrained by a single overriding perspective based solely upon the objective value.

Table 10.1 System benefits ($ millions) for 6 maximally different alternatives

Maximally different solutions	WRM system benefits ($ millions)
Best solution overall	2.021
Best solution within 2 %	1.987
Best solution within 4 %	1.946
Best solution within 6 %	1.915
Best solution within 8 %	1.872
Best solution within 10 %	1.840

Furthermore, it should also be explicitly noted that the objective values for the alternatives created do not differ from the highest benefit solution by *at least* the stated 2, 4, …, 10 %, respectively, but, in general, actually differ by less than these pre-specified upper deviation limits. This is because each of the best alternatives produced in S_2, S_3, S_4, S_5, S_6 have solutions whose structural variables differ maximally from those of all of the other alternatives generated while simultaneously guaranteeing that their objective values deviate from the overall best objective by *no more* than 2, 4, …, 10 %, respectively. Thus, the goal of the alternatives generated in this MGA procedure are very different from those produced in the more straightforward HSJ-style, single-alternative-generation approach, while simultaneously establishing much more robust guarantees on the solution quality.

Although a mathematically optimal solution may not provide the best approach to the real problem, it can be demonstrated that the co-evolutionary procedure does indeed produce very good solution values to the originally modelled problem, itself. Table 10.1 clearly highlights how the alternative generated in S_1 by the MGA procedure is "good" with respect to the optimal solution found in Maqsood et al. (2005). In fact, it should be explicitly noted that the overall best solution produced by the MGA procedure (i.e. the solution in S_1) is actually identical to the one found by the function optimization approach of Maqsood et al. (2005). This is not mere coincidence because an expansion in the population size of the SO procedure to include the subpopulations S_2, S_3, ..., S_6 does not detract from its evolutionary capabilities to find the best, function optimization solution in subpopulation S_1. Hence, in addition to its alternative generating capabilities, the MGA procedure simultaneously performs exceedingly well with respect to function optimization.

In summary, the computational example highlights several important features with respect to the FA-driven simulation-optimization MGA technique: (i) An FA can be effectively employed as the underlying optimization search routine for SO routines; (ii) Because of the evolving nature of its population-based solution searches, the co-evolutionary capabilities within the FA can be exploited to simultaneously generate more good alternatives than planners would be able to create using other MGA approaches; (iii) By the design of the MGA algorithm, the alternatives generated are good for planning purposes since all of their structures are guaranteed to be as mutually and maximally different from each other as possible (i.e. these differences are not just simply different from the overall optimal solution as in an HSJ-style approach to MGA); (iv) The approach is very computationally efficient since it need only be run once to generate its entire set of multiple, good solution alternatives (i.e. to generate n maximally different solution alternatives, the MGA algorithm would need to be run exactly the same number of times that the FA would need to be run for function optimization purposes alone—namely once—irrespective of the value of n); and, (v) The best overall solutions produced by the MGA procedure will be identical to the best overall solutions that would be produced by the FA for function optimization purposes alone.

10.7 Conclusions

WRM decision-making problems contain multifaceted performance requirements which inevitably include complicated, incongruent performance objectives and unquantifiable modelling features. These problems often possess incompatible design specifications which are difficult—if not impossible—to capture when the supporting decision models are formulated. Consequently, there are unmodelled problem components, generally not apparent during model construction, that can significantly influence the acceptability of any model's solutions. These competing and ambiguous components force WRM decision-makers to incorporate many conflicting requirements into their decision process prior to settling upon a final solution.

Because of this, supplementary modelling techniques that support decision formulation must inherently capture the essence of these aspects while retaining sufficient flexibility to simultaneously consider the impacts from the planning and stochastic uncertainties. Rather than constructing exactly one, mathematically optimal solution, in these situations, it is more desirable to be able to generate a set of provably good options that provide distinctive perspectives to any potentially unmodelled issues. The distinctive structures captured by these dissimilar alternatives reflect very different system features, thereby addressing some of the unmodelled issues during the policy formulation stage.

This chapter has provided a stochastic FA-driven MGA approach that demonstrated how the co-evolutionary features of the FA could be employed to direct a stochastic SO search process to concurrently generate a set of maximally different, near-optimal alternatives. This stochastic MGA method creates several solutions containing the requisite problem features, with each alternative generated providing a very different perspective to the problem considered. The practicality of this FA-driven stochastic MGA approach can clearly be extended into numerous disparate intelligent environmental management applications and can be readily modified to many other "real world" planning situations. Such extensions for waste management planning, energy risk analysis and agricultural planning will be examined in forthcoming research initiatives.

References

Baugh, J. W., Caldwell, S. C., & Brill, E. D. (1997). A mathematical programming approach for generating alternatives in discrete structural optimization. *Engineering Optimization, 28*(1), 1–31.

Brill, E. D., Chang, S. Y., & Hopkins, L. D. (1982). Modelling to generate alternatives: The HSJ approach and an illustration using a problem in land use planning. *Management Science, 28*(3), 221–235.

Brugnach, M., Tagg, A., Keil, F., & De Lange, W. J. (2007). Uncertainty matters: Computer models at the science-policy interface. *Water Resources Management, 21*, 1075–1090.

Cagnina, L. C., Esquivel, C. A., & Coello, C. A. (2008). Solving engineering optimization problems with the simple constrained particle swarm optimizer. *Informatica, 32*, 319–326.

Caicedo, J. M., & Yun, G. J. (2011). A novel evolutionary algorithm for identifying multiple alternative solutions in model updating. *Structural Health Monitoring—An International Journal, 10*(5), 491–501.

Caicedo, J. M., & Zarate, B. A. (2011). Reducing epistemic uncertainty using a model updating cognitive system. *Advances in Structural Engineering, 14*(1), 55–65.

Castelletti, A., Galelli, S., Restelli, M., & Soncini-Sessa, R. (2012). Data-driven dynamic emulation modelling for the optimal management of environmental systems. *Environmental Modelling and Software, 34*(3), 30–43.

De Kok, J. L., & Wind, H. G. (2003). Design and application of decision support systems for integrated water management; lessons to be learnt. *Physics and Chemistry of the Earth, 28*(14–15), 571–578.

DeCaroli, J. F. (2011). Using modeling to generate alternatives (MGA) to expand our thinking on energy futures. *Energy Economics, 33*(2), 145–152.

Fu, M. C. (2002). Optimization for simulation: Theory vs. practice. *INFORMS Journal on Computing, 14*(3), 192–215.

Fuerst, C., Volk, M., & Makeschin, F. (2010). Squaring the circle? Combining models, indicators, experts and end-users in integrated land-use management support tools. *Environmental Management, 46*(6), 829–833.

Gandomi, A. H., Yang, X. S., & Alavi, A. H. (2011). Mixed variable structural optimization using firefly algorithm. *Computers & Structures, 89*(23–24), 2325–2336.

Gunalay, Y., Yeomans, J. S., & Huang, G. H. (2012). Modelling to generate alternative policies in highly uncertain environments: An application to municipal solid waste management planning. *Journal of Environmental Informatics, 19*(2), 58–69.

Hamalainen, R. P., Luoma, J., & Saarinen, E. (2013). On the importance of behavioral operational research: The case of understanding and communicating about dynamic systems. *European Journal of Operational Research, 228*(3), 623–634.

He, L., Huang, G. H., & Zeng, G.-M. (2009). Identifying optimal regional solid waste management strategies through an inexact integer programming model containing infinite objectives and constraints. *Waste Management, 29*(1), 21–31.

Hipel, K. W., & Walker, S. G. B. (2011). Conflict analysis in environmental management. *Environmetrics, 22*(3), 279–293.

Huang, G. H., & Loucks, D. P. (2000). An inexact two-stage stochastic programming model for water resources management under uncertainty. *Civil Engineering and Environmental Systems, 17*(1), 95–118.

Imanirad, R., Yang, X. S., & Yeomans, J. S. (2012a). A computationally efficient, biologically-inspired modelling-to-generate-alternatives method. *Journal on Computing, 2*(2), 43–47.

Imanirad, R., Yang, X. S., & Yeomans, J. S. (2012b). A co-evolutionary, nature-inspired algorithm for the concurrent generation of alternatives. *Journal on Computing, 2*(3), 101–106.

Imanirad, R., Yang, X. S., & Yeomans, J. S. (2013a). A biologically-inspired metaheuristic procedure for modelling-to-generate-alternatives. *International Journal of Engineering Research and Applications, 3*(2), 1677–1686.

Imanirad, R., Yang, X. S., & Yeomans, J. S. (2013b). Modelling-to-generate-alternatives via the firefly algorithm. *Journal of Applied Operational Research, 5*(1), 14–21.

Imanirad, R., Yang, X. S., & Yeomans, J. S. (2016). Stochastic decision-making in waste management using a firefly algorithm-driven simulation-optimization approach for generating alternatives. In S. Koziel, L. Leifsson, & X. S. Yang (Eds.), *Recent advances in simulation-driven modeling and optimization* (pp. 299–323). Heidelberg: Springer.

Imanirad, R., Yang, X. S., & Yeomans, J. S. (2017). Environmental decision-making under uncertainty using a biologically-inspired simulation-optimization algorithm for generating alternative perspectives. *International Journal of Business Innovation and Research, 11*(1), 38–59.

Janssen, J. A. E. B., Krol, M. S., Schielen, R. M. J., & Hoekstra, A. Y. (2010). The effect of modelling quantified expert knowledge and uncertainty information on model based decision making. *Environmental Science & Policy, 13*(3), 229–238.

Kasprzyk, J. R., Reed, P. M., & Characklis, G. W. (2012). Many-objective De Novo water supply Portfolio planning under deep uncertainty. *Environmental Modelling and Software, 34*, 87–104.

Kassab, M., Hipel, K. W., & Hegazy, T. (2011). Multi-criteria decision analysis for infrastructure privatisation using conflict resolution. *Structure And Infrastructure Engineering, 7*(9), 661–671.

Kelly, P. (2002). Simulation optimization is evolving. *INFORMS Journal on Computing, 14*(3), 223–225.

Linton, J. D., Yeomans, J. S., & Yoogalingam, R. (2002). Policy planning using genetic algorithms combined with simulation: The case of municipal solid waste. *Environment and Planning B: Planning and Design, 29*(5), 757–778.

Liu, J. D., Li, Y. P., Huang, G. H., & Zeng, H. T. (2014). A dual-interval fixed-mix stochastic programming method for water resources management under uncertainty. *Resources, Conservation and Recycling, 88*(1), 50–66.

Loughlin, D. H., Ranjithan, S. R., Brill, E. D., & Baugh, J. W. (2001). Genetic algorithm approaches for addressing unmodeled objectives in optimization problems. *Engineering Optimization, 33*(5), 549–569.

Lund, J. (2012). Provoking more productive discussion of wicked problems. *Journal of Water Resources Planning and Management, 138*(3), 193–195.

Lund, J. R., Tchobanoglous, G., Anex, R. P., & Lawver, R. A. (1994). Linear programming for analysis of material recovery facilities. *ASCE Journal of Environmental Engineering, 120*, 1082–1094.

Maqsood, I. M., Huang, G. H., & Yeomans, J. S. (2005). Water resources management under uncertainty: An interval-parameter fuzzy two-stage stochastic programming approach. *European Journal of Operational Research, 167*(1), 208–225.

Martinez, L. J., Joshi, N. N., & Lambert, J. H. (2011). Diagramming qualitative goals for multiobjective project selection in large-scale systems. *Systems Engineering, 14*(1), 73–86.

Matthies, M., Giupponi, C., & Ostendorf, B. (2007). Environmental decision support systems: Current issues, methods and tools. *Environmental Modelling and Software, 22*(2), 123–127.

McIntosh, B. S., Ascough, J. C., & Twery, M. (2011). Environmental decision support systems (EDSS) development—Challenges and best practices. *Environmental Modelling and Software, 26*(12), 1389–1402.

Mowrer, H. T. (2000). Uncertainty in natural resource decision support systems: Sources, interpretation and importance. *Computers and Electronics in Agriculture, 27*(1–3), 139–154.

Reed, P. M., & Kasprzyk, J. R. (2009). Water resources management: The myth, the wicked, and the future. *Journal of Water Resources Planning and Management, 135*(6), 411–413.

Rubenstein-Montano, B., & Zandi, I. (1999). Application of a genetic algorithm to policy planning: The case of solid waste. *Environment and Planning B: Planning and Design, 26*(6), 791–907.

Rubenstein-Montano, B., Anandalingam, G., & Zandi, I. (2000). A genetic algorithm approach to policy design for consequence minimization. *European Journal of Operational Research, 124*, 43–54.

Sowell, T. (1987). *A conflict of visions*. New York: William Morrow & Co.

Sun, W., & Huang, G. H. (2010). Inexact piecewise quadratic programming for waste flow allocation under uncertainty and nonlinearity. *Journal Of Environmental Informatics, 16*(2), 80–93.

Tchobanoglous, G., Thiesen, H., & Vigil, S. (1993). *Integrated solid waste management: Engineering principles and management issues*. New York: McGraw-Hill.

Thekdi, S. A., & Lambert, J. H. (2012). Decision analysis and risk models for land development affecting infrastructure systems. *Risk Analysis, 32*(7), 1253–1269.

Trutnevyte, E., Stauffacher, M., & Schlegel, M. (2012). Context-specific energy strategies: Coupling energy system visions with feasible implementation scenarios. *Environmental Science and Technology, 46*(17), 9240–9248.

Ursem, R. K., & Justesen, P. D. (2012). Multi-objective distinct candidates optimization: Locating a few highly different solutions in a circuit component sizing problem. *Applied Soft Computing, 12*(1), 255–265.

van Delden, H., Seppelt, R., White, R., & Jakeman, A. J. (2012). A methodology for the design and development of integrated models for policy support. *Environmental Modelling and Software, 26*(3), 266–279.

Walker, W. E., Harremoes, P., Rotmans, J., Van der Sluis, J. P., Van Asselt, M. B. A., Janssen, P., et al. (2003). Defining uncertaint—A conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment, 4*(1), 5–17.

Walker, S. G. B., Hipel, K. W., & Inohara, T. (2012). Attitudes and preferences: Approaches to representing decision maker desires. *Applied Mathematics and Computation, 218*(12), 6637–6647.

Wang, L., Fang, L., & Hipel, K. W. (2007). On achieving fairness in the allocation of scarce resources: Measurable principles and multiple objective optimization approaches. *IEEE Systems Journal, 1*(1), 17–28.

Wang, S., & Huang, G. H. (2015a). A multi-level Taguchi-factorial two-stage stochastic programming approach for characterization of parameter uncertainties and their interactions: An application to water resources management. *European Journal of Operational Research, 240*(2), 572–581.

Wang, S., & Huang, G. H. (2015b). An integrated approach for water resources decision making under interactive and compound uncertainties. *Omega, 44*(1), 32–40.

Yang, X. S. (2009). Firefly algorithms for multimodal optimization. *Lecture Notes in Computer Science, 5792*, 169–178.

Yang, X. S. (2010). *Nature-inspired metaheuristic algorithms* (2nd ed.). Frome, UK: Luniver Press.

Yeomans, J. S. (2002). Automatic generation of efficient policy alternatives via simulation-optimization. *Journal of the Operational Research Society, 53*(11), 1256–1267.

Yeomans, J. S. (2008). Applications of simulation-optimization methods in environmental policy planning under uncertainty. *Journal of Environmental Informatics, 12*(2), 174–186.

Yeomans, J. S. (2010). Applications of information technology techniques for water resources planning under uncertainty. *International Journal of Technology, Knowledge and Society, 6*(2), 57–66.

Yeomans, J. S. (2011). Efficient generation of alternative perspectives in public environmental policy formulation: Applying co-evolutionary simulation-optimization to municipal solid waste management. *Central European Journal of Operations Research, 19*(4), 391–413.

Yeomans, J. S. (2012). Waste management facility expansion planning using simulation-optimization with grey programming and penalty functions. *International Journal of Environmental and Waste Management, 10*(2/3), 269–283.

Yeomans, J. S., & Gunalay, Y. (2008a). Water resources policy formulation using simulation optimization combined with fuzzy interval programming. *Asian Journal of Information Technology, 7*(8), 374–380.

Yeomans, J. S., & Gunalay, Y. (2008b). Water resources planning under uncertainty using simulation optimization. *Lecture Notes in Management Science, 1*, 286–295.

Yeomans, J. S., & Gunalay, Y. (2009). Using simulation optimization techniques for water resources planning. *Journal of Applied Operational Research, 1*(1), 2–14.

Yeomans, J. S., & Gunalay, Y. (2011). Simulation-Optimization techniques for modelling to generate alternatives in waste management planning. *Journal of Applied Operational Research, 3*(1), 23–35.

Yeomans, J. S., & Yang, X. S. (2014). Municipal waste management optimization using a firefly algorithm-driven simulation-optimization approach. *International Journal of Process Management and Benchmarking, 4*(4), 363–375.

Yeomans, J. S., Huang, G. H., & Yoogalingam, R. (2003). Combining simulation with evolutionary algorithms for optimal planning under uncertainty: An application to municipal solid waste management planning in the Regional Municipality of Hamilton-Wentworth. *Journal of Environmental Informatics, 2*(1), 11–30.

Zarate, B. A., & Caicedo, J. M. (2008). Finite element model updating: Multiple alternatives. *Engineering Structures, 30*(12), 3724–3730.

Zechman, E. M., & Ranjithan, S. R. (2007). Generating alternatives using evolutionary algorithms for water resources and environmental management problems. *Journal of Water Resources Planning and Management, 133*(2), 156–165.

Zhou, Y., Huang, G. H., & Yang, B. (2013). Water resources management under multi-parameter interactions: A factorial multi-stage stochastic programming approach. *Omega, 41*(3), 559–573.

Zou, R., Liu, Y., Riverson, J., Parker, A., & Carter, S. (2010). A nonlinearity interval mapping scheme for efficient waste allocation simulation-optimization analysis. *Water Resources Research, 46*(8), 1–14.

Chapter 11
Fuzzy Neural Network (EFuNN) for Modelling Dissolved Oxygen Concentration (DO)

Salim Heddam

Abstract The aim of this research is to propose a new fuzzy neural network based model, called evolving fuzzy neural network (EFuNN) that extends existing artificial intelligence methods for modelling hourly dissolved oxygen concentration in river ecosystem. To demonstrate the capability and the usefulness of the EFuNN model, a one year period from 1 January 2014 to 31 December 2014, of hourly dissolved oxygen (DO) and Water quality variables data collected by the United States Geological Survey (USGS), were used for the development of the models. Two stations are chosen: the bottom (USGS station no: 420741121554001) and the top (USGS station no: 11509370), at Klamath River above Keno Dam nr Keno, Oregon, USA. For comparison purposes, *a* multiple linear regression (MLR) model that was frequently used for predicting water quality variables in previous studies is also built. The inputs variables used for the EFuNN and MLR models are water pH, temperature (TE), specific conductance (SC), and sensor depth (SD). In both models, 60 % of the data set was randomly assigned to the training set, 20 % to the validation set, and 20 % to the test set. The performances of the models are evaluated using root mean square errors (RMSE), mean absolute error (MAE) and correlation coefficient (CC) statistics. The lowest RMSE and highest CC values were obtained with the EFuNN model. The results obtained in the current study demonstrate the potential applicability of the proposed modeling approach in modelling dissolved oxygen concentration in river ecosystem.

11.1 Introduction

Dissolved oxygen (DO) is a vital component of the aquatic ecosystems, and its accurate estimation in river and stream is highly recommended by many researchers worldwide. DO can be defined as the quantity of molecular oxygen dissolved in

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water and is one of the most important parameters affecting the health of aquatic ecosystems, fish mortality, odors, and other aesthetic qualities of surface waters (Chin 2006). According to O'Driscoll et al. (2016) the principal sources of DO in stream are (i) diffusion from the atmosphere, (ii) mixing of the stream water at riffles, and (iii) photosynthesis from in-stream primary production. DO can be affected by forest management activities (O'Driscoll et al. 2016), ambient temperature, atmospheric pressure, and ion activity (USGS 2008). DO is used as a water quality index and mainly reported as an important indicator of water pollution in river (Sun et al. 2016; Mohan and Pavan Kumar 2016), and used for studying and estimates of lake metabolism variability (Rafael Cavalcanti et al. 2016), and for detection of possible pollution episodes (Sancho et al. 2016). DO play foundational roles in aquatic ecosystems by controlling many chemical and biological reactions (Inthasaro and Wu 2016). It is also reported that DO is an important factor influencing the dynamics of phytoplankton and zooplankton populations and a model has been recently proposed and tested describing the role of DO on the plankton dynamics (Dhar and Baghel 2016). Development of DO simulation model is a useful tool for assessing the variation of DO in rivers ecosystems. In the last few years, several researchers have investigated the capabilities and usefulness of the artificial intelligence techniques (AIT) for modelling DO. Generally, the models reported are based on simple and multiple linear regression based models (MLR), artificial neural networks (ANN), fuzzy logic, and Neurofuzzy system.

The ANN models have been utilized extensively (Schmid and Koskiaho 2006; Heddam 2014a; Ay and Kisi 2012; Ranković et al. 2010; Antanasijević et al. 2013; Antanasijević et al. 2014; Akkoyunlu et al. 2011; Kayombo et al. 2000). Schmid and Koskiaho (2006) investigated the adequacy of multi-layer perceptron artificial neural network (MLPNN) in modelling near-bottom DO in the Finnish free water surface wetland at Hovi in Finland country. Heddam (2014a) applied generalized regression neural network (GRNN) based model for modelling hourly DO, at Klamath River, Oregon, USA. Ay and Kisi (2012) compared the MLPNN and the radial basis function neural network (RBFNN), for modelling DO, in Colorado, USA. Ranković et al. (2010) developed MLPNN in the Gruźa Reservoir, Serbia. Antanasijević et al. (2013) compared three types of ANN namely, GRNN, MLPNN and Recurrent Neural Network (RNN), for prediction of DO in the Danube River, North Serbia. Antanasijević et al. (2014) applied GRNN with the Monte Carlo Simulation (MCS) technique for input selection, across multiple sites; located on the Danube River, North Serbia. Akkoyunlu et al. (2011) examined the depth-dependent estimation of a lake's DO using two ANN methods: (1) the RBFNN and the MLPNN, and (2) the multiple linear regression (MLR). The comparison results revealed that the ANN methods were noticeably superior to those of MLR in modelling the DO. Kayombo et al. (2000) developed DO sub-model in secondary facultative waste stabilization ponds. Basant et al. (2010) used the partial least squares (PLS2) regression and the MLPNN modeling methods to predict the DO and BOD in river. Kisi et al. (2013) investigated the accuracy of three artificial intelligence techniques, namely MLPNN, ANFIS and gene expression programming (GEP) in modeling daily DO in, Colorado, USA. Heddam (2014b) compared two ANFIS models for modeling hourly DO, at Klamath River, Oregon, USA. In another study, Heddam (2014c) applied dynamic evolving neural-fuzzy inference system (DENFIS), for modelling hourly DO in Klamath River, Oregon, USA. Najah et al. (2014) compared MLPNN and ANFIS for modelling monthly DO in the Johor River, Malaysia. Evrendilek and Karakaya (2014) investigated the effects of discrete wavelet transforms (DWT) with the orthogonal Symmlet and the semi orthogonal Chui-Wang B-spline on predictive power of multiple non-linear regression models (MNLR) models for diel, daytime (diurnal) and nighttime (nocturnal) DO dynamics. In another study, Evrendilek and Karakaya (2015) used median and linear regression models of saturated DO after denoising by using DWT with Chui-Wang B-spline and Coiflet wavelets decomposition. Recently, An et al. (2015) used the nonlinear grey Bernoulli model [NGBM (1, 1)] to simulate and forecasting DO in the Guanting reservoir (inlet and outlet), located at the upper reaches of the Yongding River in the northwest of Beijing, China. Bayram et al. (2015) investigated the applicability of teaching-learning based optimization (TLBO) algorithm in modeling stream DO in turkey. Leppi et al. (2016) developed a mixed-effect model for predicting DO from 20 lakes across northern Alaska.

In summary, having analyzed the literature review reported above, we would draw the following conclusions. First, few studies have paid attention to the modelling of DO at hourly time step, since the concentration of DO varies significantly over different time periods of day. Second, no study has been conducted to estimates DO at the top of the river using data from the bottom and vice versa. Third, limited study has, to our knowledge, been performed to predict DO in river ecosystem using only a few numbers of input variables. In this chapter we present a new and powerful tool for modeling hourly DO using water quality variables as input. We test this new model with data from the Klamath River above Keno Dam nr Keno, in Oregon, USA, to illustrate how the proposed model can predict DO very well using only few input variables. To the author's knowledge, DO modelling with EFuNN is the first study in the literature. Therefore, the present study investigates the use of EFuNN system in the development of robust model for DO modelling.

11.2 Study Area and Data Used

11.2.1 Data

The historical hourly DO and the four water quality variables data for 1 year (from 1 January 2014 to 31 December 2014, 8678 data) which were used in this study is available at the United States Geological Survey (USGS): http://or.water.usgs.gov/cgi-bin/grapher/table_setup.pl?site_id. Two stations are chosen: the bottom (USGS station no: 420741121554001) and the top (USGS station no: 11509370), at

Klamath River above Keno Dam nr Keno, Oregon, USA (Latitude 42° 07′ 41″, Longitude 121° 55′ 40″). Figure 11.1 shows the locations of the stations in study area. For the two stations the data set is divided into three sub-data sets: (i) a training set, (ii) a validation set and (iii) a test set. Among the 8678 data, 5208 input-output pairs (60 %), randomly chosen from the data sequence, were used in the training set, 1735 input-output pairs (20 %), were used in the validation set and the remaining 1735 data (20 %) of the available data set were reserved for testing the developed models. The statistical parameters of DO and water quality variables data such as the mean, maximum, minimum, standard deviation, and the coefficient of variation values (i.e., X_{mean}, X_{max}, X_{min}, S_x, and C_v respectively) are given in Table 11.1. Because the five variables described above had different dimensions, and there was major difference among values, it was considered to be necessary to standardize the primary data in order to enhance the training speed and the precision of the models. Input data were entered into the models after normalization. For this purpose, Eq. (11.1) was utilized (Heddam 2014c, d):

$$x_{ni,k} = \frac{x_{i,k} - m_k}{Sd_K} \tag{11.1}$$

$x_{ni,k}$: is the normalized value of the variable k (input or output) for each sample i (in our study we have 8678 samples, each sample formed with four inputs (water quality variables) and one output (DO). $x_{i,k}$ the original value of the variable k (input or output). m_k and S_{dk} are the mean value and standard deviation of the variable k (input or output). All the input and output variables were normalized to have zero mean and unit variance. Normalization increases significantly the performance of the models (Heddam et al. 2016; Heddam 2016).

The water quality variables are described briefly herein in order to highlight background water quality, concentration ranges, and notable differences between concentrations at the top and bottom of the water column. DO were generally higher at the top. It can be seen from Table 11.1, for the top station, DO ranged over three orders of magnitude, with minimum and maximum values of 0.1 and nearly 14 mg/L (13.50 mg/L). The mean of all observations was 7.37 mg/L. At the bottom station, DO ranged over three orders of magnitude, with minimum and maximum values of 0.0 and nearly 12 mg/L (11.60 mg/L). The mean of all observations was 6.50 mg/L. According to Table 11.1, temperature inversely related to the concentration of DO in water; as temperature increases, DO decrease. Conversely, a temperature decline causes the oxygen concentration to increase. It can be seen in Table 11.1, for the bottom station, the TE of water ranged over three orders of magnitude, with minimum and maximum values of 1.6 and nearly 24.10 °C. The mean of all observations was 12.14 °C. At the top station, TE ranged over three orders of magnitude, with minimum and maximum values of 1.4 and nearly 27 °C (26.50 °C). The mean of all observations was 12.47 °C. SC ranged from 120 to 305 μS/cm, with a mean value of 156.11 μS/cm (Table 11.1), at the top station. At the bottom station, the minimum value of SC 122 μS/cm, was slightly higher than the value at the top. The maximum for SC was slightly higher than 300 μS/cm,

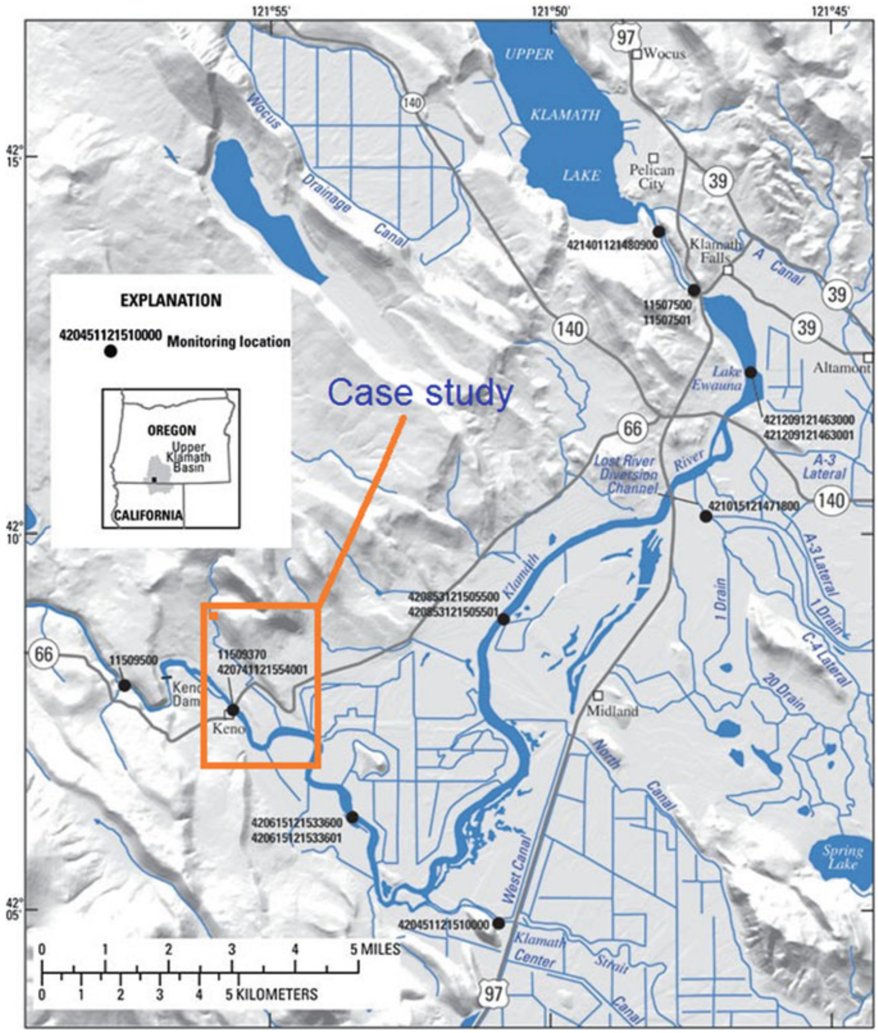

Fig. 11.1 Map showing the study area, Klamath River above Keno Dam nr Keno, Oregon, USA (adopted from Sullivan et al. 2012, 2013a, b)

and the mean of all observations was 156.25 μS/cm slightly higher than the value at the top. The pH of water ranged over three orders of magnitude, with minimum and maximum values of 7.00 and 9.8, with a mean value of 7.83 (Table 11.1), at the top station. At the bottom station, the minimum value of pH, 6.90, was slightly less than the value at the top. The maximum for pH was slightly less than 10.0, and the mean of all observations was 7.73 slightly less than the value at the top. Pearson correlation coefficients were calculated to identify the statistically significant correlation between the variables as shown in Table 11.2. It can be seen from

Table 11.1 Hourly statistical parameters of data set

Data	Unit	X_{mean}	X_{max}	X_{min}	S_x	C_v	CC
USGS 11509370 (top)							
TE	°C	12.48	26.50	1.40	7.08	0.57	−0.75
pH	/	7.83	9.80	7.00	0.56	0.07	−0.05
SC	μS/cm	156.11	305.00	120.00	24.32	0.16	0.52
SD	m	1.02	1.29	0.72	0.11	0.11	−0.08
DO	mg/l	7.37	13.50	0.10	2.91	0.39	1.00
USGS420741121554001 (bottom)							
TE	°C	12.14	24.10	1.60	6.77	0.55	−0.84
pH	/	7.73	9.60	6.90	0.53	0.06	−0.08
SC	μS/cm	156.25	304.00	122.00	24.52	0.15	0.56
SD	m	4.37	4.93	2.12	0.36	0.08	0.21
DO	mg/l	6.50	11.60	0.00	3.44	0.53	1.00

X_{mean} mean; X_{max} maximum; X_{min} minimum; S_x standard deviation; C_v coefficient of variation; *CC* coefficient de correlation with DO

Table 11.2, for the bottom station, the strong negative correlation coefficient between TE and DO is (CC = −0.85), implying that any model built using TE will certainly be able to compute the DO satisfactorily, this two parameters are highly interrelated with each other, the negative correlation coefficient indicates that as one variable increases, the other decreases, and vice versa (Heddam 2014b, c). At the top station, as seen from Table 11.2, the correlation coefficient between TE and DO is (CC = −0.75).

Table 11.2 Pearson correlation coefficients between and among physical water-quality parameters, and dissolved oxygen concentration

	TE (°C)	pH/	SC (μS/cm)	SD (m)	DO (mg/L)
USGS 11509370 (top)					
TE (°C)	1.00				
pH	0.50	1.00			
SC (μS/cm)	−0.63	−0.26	1.00		
SD (m)	0.24	0.11	−0.07	1.00	
DO (mg/L)	−0.75	−0.05	0.52	−0.08	1.00
USGS420741121554001 (bottom)					
TE (°C)	1.00				
pH	0.32	1.00			
SC (μS/cm)	−0.63	−0.14	1.00		
SD (m)	−0.38	−0.06	0.34	1.00	
DO (mg/L)	−0.85	−0.08	0.56	0.21	1.00

°C degree celsius; *μS/cm* microseimens per centimeter; *m* meter; *mg/L* milligrams per liter

11.2.2 Performance Indices

To assess the fitting and predictive accuracy of the models, the data sets were mathematically evaluated using both statistical and graphical model evaluation. A number of prediction accuracy measures have been adopted in the literature. Moriasi et al. (2007) recommended many types of criteria: error index (root mean squared error: RMSE and mean absolute error: MAE), and standard regression (coefficient of correlation: CC).

$$RMSE = \sqrt{\frac{1}{\mathrm{N}}\sum_{i=1}^{\mathrm{N}}(\mathrm{O}_i - \mathrm{P}_i)^2} \tag{11.2}$$

$$MAE = \frac{1}{\mathrm{N}}\sum_{i=1}^{\mathrm{N}}|\mathrm{O}_i - \mathrm{P}_i| \tag{11.3}$$

$$CC = \frac{\frac{1}{\mathrm{N}}\sum(\mathrm{O}_i - \mathrm{O}_m)(\mathrm{P}_i - \mathrm{P}_m)}{\sqrt{\frac{1}{\mathrm{N}}\sum_{i=1}^{n}(\mathrm{O}_i - \mathrm{O}_m)^2}\sqrt{\frac{1}{\mathrm{N}}\sum_{i=1}^{n}(\mathrm{P}_i - \mathrm{P}_m)^2}} \tag{11.4}$$

where N is the number of data points, O_i is some measured value and P_i is the corresponding model prediction. O_m and P_m are the average values of O_i and P_i.

11.3 Models

In this section, we present the fundamental basis of the proposed techniques used to model DO. The first proposed technique mainly adopts the EFuNN approach while the second is the so-called multiple linear regression (MLR) approaches.

11.3.1 Evolving Fuzzy Neural Network (EFuNN)

Evolving Fuzzy Neural Network (EFuNN) was originally proposed by Kasabov (2001). According to Kasabov (2001) EFuNN is a fuzzy neural network based on Evolving connectionist Systems (ECoS) theory that implement fuzzy rules and fuzzy inference, with all the artificial neural network (ANN) characteristics of training, recall, adaptation, and so on (Kasabov 2007). EFuNN was the first ECoS network described and is an application of the ECoS principles to the Fuzzy Neural Network (FuNN) (Kasabov 2007). Further, in the EFuNN model the evolving process is based on either of the two assumptions (Kasabov 2001): (i) no rule nodes exist prior to learning and all of them are created (generated) during the evolving process, or (ii) there is an initial set of rule nodes that are not connected to the input and output nodes and become connected through the learning (evolving) process. Using a hybrid learning mode, EFuNN consists of five layers to implement different node functions (Kasabov 2007). A summary of EFuNN layers (Kasabov 2001, 2007) is described as follows and the corresponding equivalent EFuNN structure is shown in Fig. 11.2. EFuNN has a five-layer structure (Fig. 11.2a). But here nodes and connections are created and connected as data examples are presented. An optional short-term memory layer can be used through a feedback connection from the rule node layer (Fig. 11.2b). The layer of feedback connections could be used if temporal relationships of input data are to be memorized structurally (Kasabov 2001, 2007, 2015).

1. The input layer represents input variables.
2. The second layer of nodes (fuzzy input neurons) represents fuzzy quantization of each input variable space. The second layer is also called the condition layer (Kasabov 2001). For example, a triangular MFs for a condition neuron c, is defined by (Kasabov 2001):

$$\mathrm{A_c} = \begin{cases} 1 - \frac{I_i - W_{i,c}}{W_{i,c+1} - W_{i,c}}, & W_{i,c} \langle I_i \langle W_{i,c+1} \\ 1 - \frac{W_{i,c} - I_i}{W_{i,c} - W_{i,c-1}}, & W_{i,c-1} \langle I_i \langle W_{i,c} \\ 1, & W_{i,c} = I_i \\ 0, & \text{Otherwise} \end{cases} \tag{11.5}$$

where A_c is the activation of the condition node c, $W_{i,c}$ is the connection weight defining the center of the MF attached to condition neuron c, $W_{i,c-1}$ is the connection weight defining the center of the MF to the left of c, $W_{i,c+1}$ is the connection

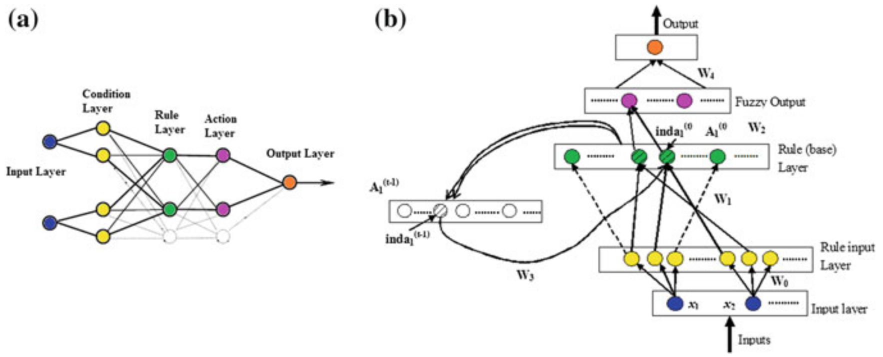

Fig. 11.2 EFuNN with a short term memory and a feedback connection (Kasabov 2001)

weight defining the center of the MF to the right of c, **I** is the input vector, and $W_{i,c}$ is the connection weight from input node i to condition node c (Kasabov 2001).

1. The third layer contains rule (case) nodes that evolve through supervised and/or unsupervised learning. Each rule node r is defined by two vectors of connection weights, $W_1(r)$ and $W_2(r)$. A linear activation function, or a Gaussian function, is used for the neurons of this layer (Kasabov 2001, 2007, 2015). The third layer is also called the evolving layer or the rule layer [37]. The distance measure used in this layer is described as:

$$D_{\mathrm{n}} = \frac{(1/2)\left(\sum_{i=1}^{c} \left|I_i - W_{i,n}\right|\right)}{\sum_{i=1}^{c} W_{i,n}} \tag{11.6}$$

where c is the number of condition neurons (fuzzy inputs), **I** is the fuzzified input vector, and **W** is the condition to rule layer weight matrix.

2. The fourth layer of neurons represents fuzzy quantization of the output variables, similar to the input fuzzy neuron representation (Watts 2009).
3. The fifth layer represents the values of the output variables. This value is calculated according to (Watts 2009):

$$A_0 = \frac{\sum_{a=i}^{m} W_{0,a}\,\mathrm{A_a}}{\sum A_a} \tag{11.7}$$

where $\mathrm{A_0}$ is the activation of the output node 0, $\mathrm{A_a}$ is the activation of action node a, m is the number of action neurons attached to 0, and $W_{0,a}$ is the value of the connection weight from action node a to output 0.

EFuNN has been used in many areas of scientific research. Abraham and Nath (2001) compared two AIT namely, EFuNN and MLPNN trained using scaled conjugate gradient algorithm (CGA), with the conventional statistical approach based on Box-Jenkins autoregressive integrated moving average (ARIMA) model, to predict electricity demand in the State of Victoria, Australia. Abraham et al. (2001) compared four soft computing models namely: (i) EFuNN, (ii) ANN using Scaled Conjugate Gradient Algorithm (ANNSCGA), (iii) Adaptive Basis Function Neural Network (ABFNN) and (iv) GRNN, with the Multivariate Adaptive Regression Splines (MARS) model for forecasting monthly rainfall in Kerala state, the southern part of the Indian peninsula. Abraham and Jain (2005) investigated the capabilities of EFuNN, decision trees (DT), support vector machines (SVM), linear genetic programming (LGP) and an ensemble method to model fast and efficient intrusion detection systems (IDS). The authors reported that using EFuNN they achieved a detection accuracy of 100 %. Kasabov (2006) investigated the capabilities of EFuNN in macroeconomics and Bioinformatics application. Woodford

(2008) applied and compared EFuNN and three standard classifiers namely, The K-means classifier, the MLPNN classifier and the SVM classifier for horticultural applications, specifically for classification and identification of pest damage on apple tree leaves. Gopalakrishnan (2011) compared two ECOS, namely DENFIS and EFuNN, with the MLPNN for rubblized pavement inverse analysis. Yurdakul et al. (2014) Employed three adaptive hybrid intelligence (AHI) namely, ANFIS, DENFIS, and EFuNN, for predicting Specific cutting energy (SE_{cut}) based on 40 different natural building stones in nineteen different stone processing plants.

11.3.2 Multiple Linear Regression

Multiple linear regression (MLR) is a method used to quantify the relationship between several independent or predictor variables and a dependent variable. A set of coefficients (β_i) defines the single linear combination of independent variables (water quality variables) and the DO. A multilinear model can be represented as:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \cdots + \beta_n x_n \tag{11.8}$$

where β_0 is a constant and $\beta_i, i = 1, \ldots, n$ are regression coefficients. Y is the dependent variable and X_i are the independent variables. In this study, the coefficients β_0, β_1, β_2 … β_n were determined using least squares method (LSM).

11.4 Results and Discussions

The objective of this study was to develop DO prediction models based on optimal set of inputs. The inputs variables used for the EFuNN and MLR models are water pH, TE, SC, and SD. Four different simulations were performed to evaluate the performance of EFuNN, they are, namely: (1) predicting DO for the bottom station; (2) predicting DO for the top station; (3) predicting DO for the top station using input data of Bottom station; and (4) predicting DO for the bottom station using input data of top station. In the all four simulation the results using MLR model are also presented. A comparison and discussion of the all results obtained are also provided. The present study examined various combinations of these parameters as inputs to the models investigated so as to evaluate the degree of effect of each of these variables on the DO. Six models were developed and compared. The six models are the four-factor input vector model (TE, pH, SC and SD), called M6; the three-factor input vector model(TE, pH and SC), called M5; the three-factor input vector model (TE, pH and SD), called M4; the two-factor input vector model (pH and SC), called M3; the two-factor input vector model (TE and SC), called M2 and the two-factor input vector model (TE and pH), called M1, respectively

Table 11.3 Combinations of input variables considered in developing models

Model	Input structure	Output
M1	TE and pH	DO
M2	TE and SC	DO
M3	SC and pH	DO
M4	TE, pH, and SD	DO
M5	TE, pH, and SC	DO
M6	TE, pH, SC and SD	DO

(Table 11.3). A comparison of the performance of the EFuNN model with that of the MLR model was carried out to study their efficacy in predicting DO.

As reported earlier the training, validation and testing periods of the EFuNN model were maintained same as the corresponding period of the MLR model. In this study The EFuNN model was performed using NeuCom© v0.919 software available from the Knowledge Engineering and Discovery Research Institute (KEDRI) Auckland University of Technology, New Zealand, (www.kedri.aut.ac.nz/areas-of-expertise/data-mining-and-decision-support-systems/neucom). There are several model parameters to be optimized for the EFuNN model: (i) sensitivity threshold; (ii) error threshold; (iii) number of membership functions used in the fuzzy inference system; (iv) learning rate for the weights of first layer(W_1); and (v) learning rate for the weights of second layer (W_2). In the present study we applied EFuNN using the following value of parameters:

- Sensitivity threshold: 0.9
- Error threshold: 0.1
- Number of membership functions: 3
- Learning rate for W_1: 0.1
- Learning rate for W_2: 0.1

11.4.1 Predicting DO for the Top Station (USGS 11509370)

The model evaluation statistics for each EFuNN and MLR models tested are presented in Table 11.4 in both the training, validation and testing phases, for the top station. In general, the EFuNN prediction models have higher accuracies compared to the counterpart MLR prediction models. A general remark is that both EFuNN perform significantly better than the MLR models as it is shown by the higher CC, and the lower MAE and RMSE values. The performance of EFuNN is very promising. Regression models equations for DO, using MLR are shown in Table 11.5. From Table 11.4, for the EFuNN model, it is observed that the MAE, RMSE and CC values vary in the range of 0.422–1.400, 0.642–1.937 and 0.749–0.976 mg/L respectively, in the training phase. In addition, in the validation phase, the values of MAE, RMSE and CC, ranged from 0.451 to 1.427 mg/L, 0.691 to 1.969 mg/L, and 0.741 to 0.972 mg/L, respectively. Finally, in the testing phase, the values of MAE, RMSE and CC, ranged from 0.485 to 1.357 mg/L, 0.777 to 1.895 mg/L, and 0.742 to 0.962 mg/L, respectively. It may be seen from Table 11.4, the CC values for all the six models are reasonably good, being smallest (0.741) for M3 model and greatest (0.976) for M6 model. The values of other model performances such as RMSE, and MAE indicate that the forecast performance of the EFuNN model is very good, except the model M3 that is relatively acceptable. As can be observed from Table 11.4, the EFuNN (M6) model performed better than the other models in the training, validation, and testing phases. During training, the EFuNN (M6) performs better than the others. Also, in the validation and testing phases, the EFuNN (M6) outperforms all others models in terms of various performance criteria.

As seen from Table 11.4, the six MLR models have shown significant variations based on the three performance criteria. The lowest value of the RMSE of forecasting models is 1.566 mg/L (in MLR M6) and the highest value of the CC is 0.845 (in MLR M6). In addition, the lowest value of MAE is 1.166 mg/L also (in MLR M6). From the results of training, validation, and testing all the six models

Table 11.4 Performances of the EFuNN and MLR models in different phases for USGS 11509370 station

Model	EFuNN			MLR		
	Training			Training		
	CC	RMSE	MAE	CC	RMSE	MAE
M1	0.934	1.042	0.612	0.832	1.619	1.198
M2	0.844	1.568	1.094	0.748	1.939	1.496
M3	0.749	1.937	1.400	0.520	2.497	2.002
M4	0.962	0.801	0.492	0.840	1.586	1.199
M5	0.951	0.901	0.498	0.833	1.617	1.194
M6	0.976	0.642	0.422	0.840	1.585	1.197
	Validation			Validation		
	CC	RMSE	MAE	CC	RMSE	MAE
M1	0.937	1.028	0.618	0.840	1.591	1.179
M2	0.857	1.511	1.063	0.762	1.900	1.479
M3	0.741	1.969	1.427	0.542	2.467	1.968
M4	0.962	0.804	0.509	0.845	1.567	1.195
M5	0.948	0.934	0.527	0.841	1.588	1.194
M6	0.972	0.691	0.451	0.845	1.566	1.177
	Testing			Testing		
	CC	RMSE	MAE	CC	RMSE	MAE
M1	0.931	1.030	0.604	0.832	1.569	1.174
M2	0.830	1.575	1.095	0.734	1.921	1.463
M3	0.742	1.895	1.357	0.530	2.401	1.915
M4	0.960	0.801	0.494	0.839	1.537	1.174
M5	0.943	0.939	0.508	0.833	1.565	1.170
M6	0.962	0.777	0.485	0.840	1.534	1.166

Table 11.5 Regression equations for the models developed for USGS 11509370 station

Model	Regression equations
M6	−8.55 − 0.40 TE + 2.23 pH + 0.003 SC + 2.91 SD
M5	−5.94 − 0.38 TE + 2.21 pH + 0.005 SC
M4	−8.14 − 0.40 TE + 2.24 PH + 2.97 SD
M3	−5.97 + 0.44 pH + 0.06 SC
M2	9.52 − 0.29 TE + 0.01 SC
M1	−5.18 − 0.39 TE + 2.23 pH

developed in this study are evaluated all together, and the M1, M4, M5, and M6 models are conspicuous. Among these, the M4 and M6 models have quite low MAE and high CC, and the M6 model is very successful on testing phase. All these four models were examined comparing their ability on predicting hourly DO. During training, the MLR (M6) performs slightly better than the others. Also, in the validation and testing phases, the MLR (M6) outperforms all other models in terms of various performance criteria. The statistical indicators in the Table 11.4 indicate that the calculated DO using EFuNN are more accurate compared to MLR models (relatively low values of MAE and RMSE, and high values of CC. In conclusion, the M6 model is the best developed model for modelling DO, and EFuNN performs better than MLR model. The scatterplots of the measured versus calculated values of DO of the EFuNN and MLR M6 model analyzed herein are shown in Figs. 11.3 and 11.4 for the training, validation, and testing phases, respectively.

11.4.2 *Predicting DO of Bottom Station (USGS 420741121554001)*

The accuracy and performance of EFuNN model for predicting DO in the bottom station are evaluated and compared using RMSE, MAE, and CC statistical criterion. Table 11.6 shows all these criteria in the training, validation and testing phases. The

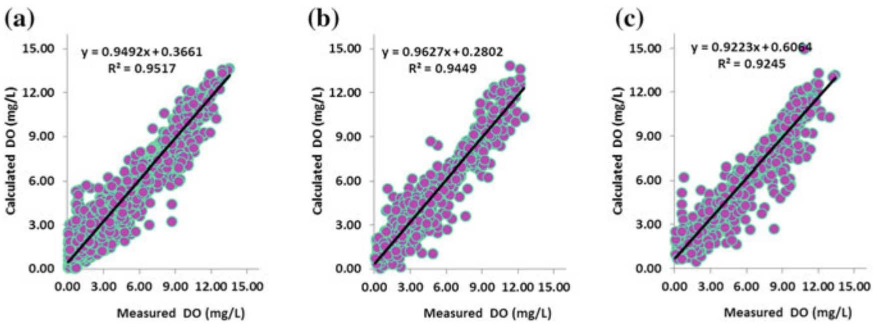

Fig. 11.3 Scatterplots of measured and calculated dissolved oxygen concentration (DO) with EFuNN M6 model for USGS 11509370 station (*top*) in the **a** training, **b** validation and **c** testing phase, respectively

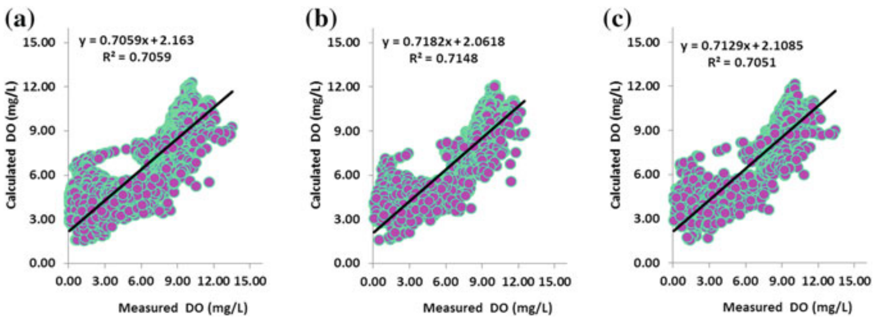

Fig. 11.4 Scatterplots of measured and calculated dissolved oxygen concentration (DO) with MLR M6 model for USGS 11509370 station (*top*) in the **a** training, **b** validation and **c** testing phase, respectively

Table 11.6 Performances of the EFuNN and MLR models in different phases for USGS 420741121554001 station

Model	EFuNN			MLR		
	Training			Training		
	CC	RMSE	MAE	CC	RMSE	MAE
M1	0.962	0.934	0.526	0.869	1.700	1.334
M2	0.928	1.277	0.889	0.846	1.828	1.453
M3	0.814	1.992	1.397	0.561	2.840	2.389
M4	0.990	0.492	0.348	0.879	1.637	1.311
M5	0.985	0.588	0.377	0.869	1.698	1.330
M6	0.992	0.428	0.298	0.880	1.630	1.304
	Validation			Validation		
	CC	RMSE	MAE	CC	RMSE	MAE
M1	0.964	0.931	0.517	0.870	1.731	1.352
M2	0.924	1.335	0.919	0.849	1.851	1.473
M3	0.830	1.953	1.393	0.575	2.866	2.413
M4	0.990	0.508	0.361	0.881	1.661	1.325
M5	0.984	0.627	0.393	0.871	1.725	1.344
M6	0.992	0.437	0.304	0.883	1.648	1.311
	Testing			Testing		
	CC	RMSE	MAE	CC	RMSE	MAE
M1	0.963	0.935	0.507	0.873	1.687	1.321
M2	0.929	1.275	0.890	0.852	1.811	1.439
M3	0.819	1.983	1.394	0.563	2.856	2.399
M4	0.989	0.512	0.361	0.884	1.616	1.288
M5	0.985	0.592	0.389	0.873	1.686	1.318
M6	0.992	0.451	0.303	0.885	1.610	1.286

table shows that, all models (M1–M6) have a small RMSE value, particularly M4, M5 and M6 models.

According to Table 11.6 for all three EFuNN models (M4, M5 and M6), the performance in the training phase was slightly better than the performance for the validation and testing phases, with only few improvements. Nevertheless, the M6 model must be considered as the best model developed. M3 model that used SC and pH as input, only performed much poorer than M1 and M2 in terms of RMSE, MAE, and CC. As seen from Table 11.6, the six EFuNN models have shown significant variations based on the three performance criteria. In the training phase, the lowest value of the RMSE of predictive models is 0.428 mg/L (in EFuNN M6) and the highest value of the CC is 0.992 (in EFuNN M6). In addition, the lowest value of MAE is 0.298 mg/L also (in EFuNN M6). Table 11.6 indicates that the EFuNN (M6) has the smallest MAE (0.304 mg/L), RMSE (0.437 mg/L), and the highest CC (0.992) in the validation phase; and in the testing phase the EFuNN (M6) has the smallest MAE (0.303 mg/L), RMSE (0.451 mg/L) and the highest CC (0.992). Table 11.6 presents the performance of different MLR models in estimating DO in terms of MAE, RMSE and CC statistics, respectively. As seen from Table 11.6, the six MLR models have shown significant variations based on the three performance criteria. The lowest value of the RMSE of forecasting models is 1.610 (mg/L) (in MLR M6) and the highest value of the CC is 0.885 (in MLR M6). In addition, the lowest value of MAE is 1.286 (mg/L) also (in MLR M6). From the results of training, validation, and testing all the six models developed in this study are evaluated all together, and the M1, M4, M5, and M6 models are conspicuous. Among these, the M4 and M6 models have quite low MAE and high CC, and the M6 model is very successful on testing phase. All these four models were examined comparing their ability on predicting hourly DO. During training, the MLR (M6) performs slightly better than the others. Also, in the validation and testing phases, the MLR (M6) outperforms all other models in terms of various performance criteria. In conclusion, the M6 model is the best developed model for modelling DO. Regression models equations for DO, using MLR are shown in Tables 11.7. The scatterplots of the measured versus calculated values of the DO of the EFuNN and MLR M6 model analyzed herein are shown in Figs. 11.5 and 11.6 for the training, validation, and testing phases, respectively.

Table 11.7 Regression equations for the models developed for USGS 420741121554001 station

Model	Regression equations
M6	6.40 − 0.47 TE + 1.40 pH + 0.008 SC – 1.41 SD
M5	0.84 − 0.45 TE + 1.35 pH + 0.004 SC
M4	7.42 − 0.49 TE + 1.42 pH – 1.35 SD
M3	−6.18 + 0.04 pH + 0.08 SC
M2	10.46 − 0.41 TE + 0.007 SC
M1	1.55 − 0.46 TE + 1.36 pH

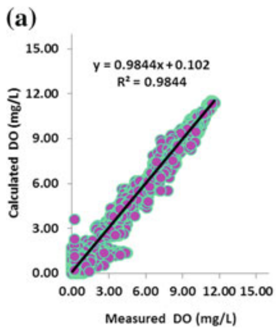

Fig. 11.5 Scatterplots of measured and calculated dissolved oxygen concentration (DO) with EFuNN M6 model for USGS 420741121554001 station (*bottom*) in the **a** training, **b** validation and **c** testing phase, respectively

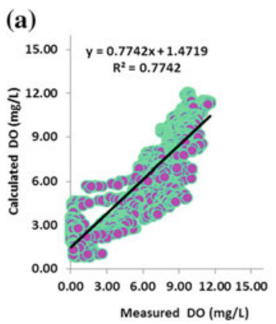

Fig. 11.6 Scatterplots of measured and calculated dissolved oxygen concentration (DO) with MLR M6 model for USGS 420741121554001 station (*bottom*) in the **a** training, **b** validation and **c** testing phase, respectively

11.4.3 Predicting DO of the Top Station Using Input Data of Bottom Station

Since the measure of the water quality variables at the top of the river is normally easily accomplished in comparison to the bottom of the river, and missing observations in time series data are very common especially at a higher depth, it is nevertheless sometimes useful to investigated the capabilities of the developed models for predicting DO for the top station using input from the bottom station and vice versa. In this section of the present study we reported the results of estimation DO at the top station using input from the bottom station and results are reported in Tables 11.8 for EFuNN and MLR models respectively. From Table 11.8, the EFuNN model developed herein was found to yield better agreement with experimental observations for the training, validation, and testing data set compared to data predicted by the MLR model. It may be seen from Table 11.8, in the training phase, the CC values for all the six models are reasonably good, being smallest (0.615) for M3 model and greatest (0.80) for the all remaining models. The values of other model performances such as RMSE and MAE indicate that the forecast performance of the EFuNN model is generally acceptable. In the validation phase, the models M1 and M2, performs slightly better than the others. Also, in the testing phase, the EFuNN M1 outperforms all other models in terms of various performance criteria. It may be seen from Table 11.8, the RMSE, MAE and CC, values for all models in the case of multiple linear regression (MLR) were found to be lower than those for the EFuNN models, there by establishing the superiority of the EFuNN models. The prediction accuracy for the regression models was lower when compared to EFuNN models for all the six models tested. As seen in Table 11.8, the six MLR models showed significant variations based on the four performances criteria. In the training phase, the lowest value of the RMSE of forecasting models is 1.95 mg/L (in MLR M6, M5, M2 and M1) and the highest value of the CC is 0.745 (in MLR M4 and M6). In addition, the lowest value of MAE is 1.514 mg/L (in MLR M1, M2 and M5). Table 11.8 indicates that the all MLR developed models are similar in the validation phase, except model M3 that is very lower. M3 has the low CC (0.516) and the highest RMSE and MAE (2.513 mg/L) and (2.060 mg/L) in the validation phase. In the testing phase, the MLR M3 has the low CC (0.476), MAE (2.011 mg/L) and RMSE (2.489 mg/L).

11.4.4 Predicting DO of the Bottom Station Using Input Data of the Top Station

The CC, RMSE and MAE of the EFuNN and MLR models in training, validation and testing phases are listed in Table 11.9. The all EFuNN models produced relatively better performance among these MLR models. The EFuNN M6 model yielded lower RMSE, MAE and high CC in training; whereas the EFuNN M5 gave better performance in MAE, RMSE and CC, in the validation phase. In the testing phase, RMSE and MAE for the EFuNN M4 were lower than those for the remaining models. Except M3 model, that provide low results models, the EFuNN models remain identical in their performance in all three phases. Thus, the EFuNN M6 model was considered superior to the all other models overall. The performance measures of RMSE, MAE and CC of the optimal EFuNN in testing are 1.495, 1.089 and 0.902 mg/L, respectively. On the whole, the EFuNN developed using the combination of different four inputs yielded acceptable prediction on DO. The CC values of all models (except for the DO models M3) were larger than 0.89 that is very promising.

Table 11.9 shows the results obtained using MLR models. In terms of statistical significance, the difference between the six models shown on Table 11.9 is not significant and the exception is for the model M3 that provide low results. As a general observation, we can say that the model M6 is superior to the all other

Table 11.8 Performances of the EFuNN and MLR models in different phases for USGS 11509370 station using input of USGS 420741121554001 station

Model	EFuNN			MLR		
	Training			Training		
	CC	RMSE	MAE	CC	RMSE	MAE
M1	0.806	1.731	1.294	0.744	1.952	1.514
M2	0.803	1.743	1.312	0.744	1.953	1.514
M3	0.615	2.304	1.791	0.500	2.531	2.050
M4	0.798	1.760	1.330	0.745	1.951	1.516
M5	0.802	1.747	1.307	0.744	1.952	1.514
M6	0.799	1.757	1.317	0.745	1.951	1.516
	Validation			Validation		
	CC	RMSE	MAE	CC	RMSE	MAE
M1	0.810	1.721	1.303	0.759	1.911	1.491
M2	0.812	1.712	1.295	0.759	1.911	1.490
M3	0.636	2.264	1.790	0.516	2.513	2.060
M4	0.806	1.736	1.324	0.759	1.911	1.490
M5	0.807	1.733	1.307	0.758	1.911	1.491
M6	0.804	1.744	1.322	0.759	1.911	1.490
	Testing			Testing		
	CC	RMSE	MAE	CC	RMSE	MAE
M1	0.791	1.729	1.293	0.726	1.946	1.499
M2	0.789	1.737	1.318	0.727	1.944	1.497
M3	0.607	2.246	1.759	0.476	2.489	2.011
M4	0.781	1.766	1.329	0.727	1.942	1.498
M5	0.781	1.766	1.325	0.726	1.946	1.499
M6	0.781	1.763	1.324	0.727	1.942	1.498

models. However, the performance of neural models was clearly good for the training data set and was reasonably good for validation and testing. The performance measures of RMSE, MAE and CC of the optimal MLR in testing are 1.781, 1.421 and 0.857 mg/L, respectively. Table 11.9 show that the EFuNN M6 performed better during training, validation, and testing, and it outperforms the MLR M6 in terms of the entire standard statistical measures. In the training phase, the EFuNN M6 improved the MLR M6 forecast of about 18.30 and 24.77 % reduction in RMSE and MAE values, respectively. In addition, improvements of the forecast results regarding the correlation coefficient (CC) value during the training phase were approximately 5.3 %. In addition, in the validation phase as seen in Table 11.9, the values with the EFuNN M6 prediction were able to produce a good forecast, as compared to those with MLR M6 prediction. In the validation phase, the EFuNN M6 improved the MLR M6 forecast of about 14.73 and 22.83 % reduction in RMSE and MAE values, respectively. In addition, improvements of the forecast results regarding the correlation coefficient (CC) value during the

Table 11.9 Performances of the EFuNN and MLR models in different phases for USGS 420741121554001 station using input of USGS 11509370 station

Model	EFuNN			MLR		
	Training			Training		
	CC	RMSE	MAE	CC	RMSE	MAE
M1	0.899	1.499	1.102	0.847	1.825	1.456
M2	0.897	1.515	1.131	0.847	1.825	1.457
M3	0.730	2.346	1.833	0.603	2.738	2.267
M4	0.900	1.494	1.107	0.850	1.809	1.436
M5	0.901	1.486	1.087	0.847	1.825	1.457
M6	0.903	1.477	1.081	0.850	1.808	1.437
	Validation			Validation		
	CC	RMSE	MAE	CC	RMSE	MAE
M1	0.892	1.581	1.161	0.845	1.870	1.501
M2	0.891	1.590	1.186	0.846	1.868	1.500
M3	0.707	2.477	1.951	0.593	2.821	2.313
M4	0.893	1.576	1.167	0.848	1.857	1.501
M5	0.894	1.572	1.151	0.846	1.868	1.500
M6	0.893	1.580	1.156	0.849	1.853	1.498
	Testing			Testing		
	CC	RMSE	MAE	CC	RMSE	MAE
M1	0.902	1.493	1.090	0.854	1.799	1.433
M2	0.900	1.508	1.112	0.854	1.798	1.435
M3	0.742	2.314	1.817	0.608	2.744	2.251
M4	0.903	1.487	1.085	0.857	1.781	1.418
M5	0.901	1.499	1.094	0.854	1.800	1.436
M6	0.902	1.495	1.089	0.857	1.781	1.421

validation phase were approximately 4.40 %. In the testing phase, the EFuNN M6 improved the MLR M6 forecast of about 16.05 and 23.36 % reduction in RMSE and MAE values, respectively. In addition, improvements of the forecast results regarding the correlation coefficient (CC) value during the testing phase were approximately 4.50 %.

11.5 Conclusions

In this study, an EFuNN model is developed to model the nonlinear relationships between hourly DO and water quality variables. The EFuNN is compared with the standard MLR model. From the results comparing the performance of the two models, it indicates that EFuNN perform well than MLR. We can conclude that EFuNN provides a promising alternative technique in modelling DO. The predictive capabilities of the models are evaluated in terms of CC, RMSE and MAE. The study indicated that modeling of DO is possible through the use of EFuNN models. The best EFuNN model among six combinations of the input variables, used TE, pH, SC, and SD as the inputs parameters. Also, it can be concluded according to the results and deductions obtained from this study that the temperature of water is the important parameter that affects the estimation of DO. The most promising results discovered in the present study are the possibilities of predicting DO very well with high precision, and also we demonstrated at the first time the capabilities and the usefulness of an AIT for predicting DO at the top of the river using only data from the bottom of the river and vice versa. Based on the preliminary findings and despite the research contribution of the present investigation, further and extended research could include: (i) first, the generalizability of the model must be demonstrated by analysis of the capabilities of the EFuNN under others conditions using others inputs water quality variables, so as to understand the response of the EFuNN model using different type of inputs, (ii) second, applying the EFuNN model at various time step (monthly, daily and hourly) needs to be studied and the results must be compared to see them, and tries to answer an interesting question: is it possible to obtain more efficient and more robust models by varying the time step? This question is very important as the data at hourly time step are not available in the majority of the stations worldwide, and generally in the majority of the stations the data are available at monthly and daily time step, (iii) third, in order to demonstrate the potential and usefulness of the applied model, it would certainly very convincing to applied the EFuNN using a large data set, rather than one year.

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References

Abraham, A., & Jain, L. (2005). Soft computing models for network intrusion detection systems. In S. Halgamuge, & L. Wang, (Eds.), *Classification and clustering for knowledge discovery, studies in computational intelligence* (pp. 191–207). Berlin, Germany: Springer-Verlag. doi:10.1007/11011620_13

Abraham, A., & Nath, B. (2001). A neuro-fuzzy approach for modelling electricity demands in Victoria. *Applied Soft Computing, 1*, 127–138. doi:10.1016/S1568-4946(01)00013-8

Abraham, A., Steinberg, D., & Philip, N. S. (2001). Rainfall forecasting using soft computing model and multivariate adaptive regression splines, In *IEEE Transaction on System, Man, Cybernetics Special Issue Fusion Software Computer Hard Computer Industrial Application* (vol. 1, pp. 1–6), Feb. 2001.

Akkoyunlu, A., Altun, H., & Cigizoglu, H. (2011). Depth-integrated estimation of dissolved oxygen in a Lake. *ASCE Journal of Environmental Engineering, 137*(10), 961–967. doi:10.1061/(ASCE)EE.1943-7870.0000376

An, Y., Zou, Z., & Zhao, Y. (2015). Forecasting of dissolved oxygen in the Guanting reservoir using an optimized NGBM (1, 1) model. *Journal of Environmental Sciences, 29*, 158–164. doi:10.1016/j.jes.2014.10.005

Antanasijević, D., Pocajt, V., Perić-Grujić, A., et al. (2014). Modelling of dissolved oxygen in the Danube River using artificial neural networks and Monte Carlo Simulation uncertainty analysis. *Journal of Hydrology, 519*, 1895–1907. doi:10.1016/j.jhydrol.2014.10.009

Antanasijević, D., Pocajt, V., Povrenović, D., et al. (2013). Modelling of dissolved oxygen content using artificial neural networks: Danube River, North Serbia, case study. *Environmental Science and Pollution Research, 20*(12), 9006–9013. doi:10.1007/s11356-013-1876-6

Ay, M., & Kisi, O. (2012). Modeling of dissolved oxygen concentration using different neural network techniques in Foundation Creek, El Paso County, Colorado. *ASCE Journal of Environmental Engineering, 138*(6), 654–662. doi:10.1061/(ASCE)EE.1943-7870.0000511

Basant, N., Gupta, S., Malik, A., et al. (2010). Linear and nonlinear modeling for simultaneous prediction of dissolved oxygen and biochemical oxygen demand of the surface water-a case study. *Chemometrics and Intelligent Laboratory Systems, 104*, 172–180. doi:10.1016/j.chemolab.2010.08.005

Bayram, A., Uzlu, E., Kankal, M., et al. (2015). Modeling stream dissolved oxygen concentration using teaching-learning based optimization algorithm. *Environmental Earth Science, 73*, 6565–6576. doi:10.1007/s12665-014-3876-3

Chin, D. A. (2006). Water-quality engineering in natural systems. Wiley. ISBN-13: 978-0-471-71830-7 (cloth), p. 628. doi:10.1002/0471784559

Dhar, J., & Baghel, R. S. (2016). Role of dissolved oxygen on the plankton dynamics in Spatio-temporal domain. *Modeling Earth Systems Environment, 2*, 6. doi:10.1007/s40808-015-0061-y

Evrendilek, F., & Karakaya, N. (2014). Regression model-based predictions of diel, diurnal and nocturnal dissolved oxygen dynamics after wavelet denoising of noisy time series. *Physica A, 404*, 8–15. doi:10.1016/j.physa.2014.02.062

Evrendilek, F., & Karakaya, N. (2015). Spatiotemporal modeling of saturated dissolved oxygen through regressions after wavelet denoising of remotely and proximally sensed data. *Earth Science Informatics, 8*, 247–254. doi:10.1007/s12145-014-0148-4

Gopalakrishnan, k. (2011). Knowledge-based evolving connectionist systems for condition evaluation of sustainable roadways: A feasibility study. *International Journal of Intelligent Engineering Informatics, 1*(2), 125–141. doi:10.1504/IJIEI.2011.040175

Heddam, S. (2014a). Generalized regression neural network (GRNN) based approach for modelling hourly dissolved oxygen concentration in the Upper Klamath River, Oregon, USA. *Environmental Technology, 35*(13), 1650–1657. doi:10.1080/09593330.2013.878396

Heddam, S. (2014b). Modelling hourly dissolved oxygen concentration (DO) using two different adaptive neuro-fuzzy inference systems (ANFIS): A comparative study. *Environmental Monitoring and Assessment, 186*, 597–619. doi:10.1007/s10661-013-3402-1

Heddam, S. (2014c). Modelling hourly dissolved oxygen concentration (DO) using dynamic evolving neural-fuzzy inference system (DENFIS) based approach: Case study of Klamath River at miller island boat ramp, Oregon, USA. *Environmental Science and Pollution Research, 21*, 9212–9227. doi:10.1007/s11356-014-2842-7

Heddam, S. (2014d). Generalized regression neural network (GRNN)-based approach for colored dissolved organic matter (CDOM) retrieval: Case study of Connecticut River at Middle Haddam Station, USA. *Environmental Monitoring and Assessment, 186*, 7837–7848. doi:10.1007/s10661-014-3971-7

Heddam, S. (2016). Secchi disk depth estimation from water quality parameters: Artificial neural network versus multiple linear regression models? *Environmental Process*. doi:10.1007/s40710-016-0144-4

Heddam, S., Lamda, H., & Filali, S. (2016). Predicting effluent biochemical oxygen demand in a wastewater treatment plant using generalized regression neural network based approach: A comparative study. *Environmental Process, 3*(1), 153–165. doi:10.1007/s40710-016-0129-3

Inthasaro, P., & Wu, W. (2016). One-dimensional model of water quality and aquatic ecosystem/ecotoxicology in river systems. In L. K. Wang, C. T. Yang, & M.-H. S. Wang (Eds.), *Advances in water resources management*, *handbook of environmental engineering*, Vol. 16. doi:10.1007/978-3-319-22924-9_3

Kasabov, N. (2001). Evolving fuzzy neural networks for online supervised/unsupervised, Knowledge-based learning. *IEEE Transactions on Systems, Man, and Cybernetics. Part B, Cybernetics, 31*(6), 902–918. doi:10.1109/3477.969494

Kasabov, N. (2006). Adaptation and interaction in dynamical systems: Modelling and rule discovery through evolving connectionist systems. *Applied Software Computing, 6*, 307–322. doi:10.1016/j.asoc.2005.01.006

Kasabov, N. (2007). *Evolving connectionist systems: The knowledge engineering approach* (p. 465). New York: Springer. ISBN 978-1-84628-345-1. doi:10.1007/978-1-84628-347-5

Kasabov, N. (2015). Evolving connectionist systems for adaptive learning and knowledge discovery: Trends and directions. *Knowledge-Based Systems, 80*, 24–33. doi:10.1016/j.knosys.2014.12.032

Kayombo, S., Mbwette, T. S. A., Mayo, A. W., et al. (2000). Modelling diurnal variation of dissolved oxygen in waste stabilization ponds. *Ecological Modelling, 127*, 21–31. doi:10.1016/S0304-3800(99)00196-9

Kisi, O., Akbari, N., Sanatipour, M., et al. (2013). Modeling of dissolved oxygen in river water using artificial intelligence techniques. *Journal of environmental informatics JEI, 22*(2), 92–101. doi:10.3808/jei.201300248

Leppi, J. C., Arp, C. D., & Whitman, M. S. (2016). Predicting late winter dissolved oxygen levels in arctic lakes using morphology and landscape metrics. *Environmental Management, 57*, 463–-473. doi:10.1007/s00267-015-0622-x

Mohan, S., & Pavan, Kumar K. (2016). Waste load allocation using machine scheduling: Model application. *Environmental Process, 3*(1), 139–151. doi:10.1007/s40710-016-0122-x

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., et al. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE & American Society of Agricultural and Biological Engineers, 50*(3), 885–900.

Najah, A., El-Shafie, A., Karim, O. A., et al. (2014). Performance of ANFIS versus MLP-NN dissolved oxygen prediction models in water quality monitoring. *Environmental Science and Pollution Research, 21*(3), 1658–1670. doi:10.1007/s11356-013-2048-4

O'Driscoll, C., O'Connor, M., Asam, Z. Z., et al. (2016). Forest clear felling effects on dissolved oxygen and metabolism in peatland streams. *Journal of Environmental Management, 166*, 250–259. doi:10.1016/j.jenvman.2015.10.031

Rafael Cavalcanti, J., Da Motta-Marques, D., & Fragoso, C. R. (2016). Process-based modeling of shallow lake metabolism: Spatio-temporal variability and relative importance of individual processes. *Ecological Modelling, 323*, 28–40. doi:10.1016/j.ecolmodel.2015.11.010

Ranković, V., Radulović, J., Radojević, I., et al. (2010). Neural network modeling of dissolved Oxygen in the Gruźa reservoir, Serbia. *Ecological Modelling, 221*, 1239–1244. doi:10.1016/j.ecolmodel.2009.12.023

Sancho, J., Iglesias, C., Piñeiro, J., et al. (2016). Study of water quality in a spanish river based on statistical process control and functional data analysis. *Mathematical Geosciences, 48*, 163–186. doi:10.1007/s11004-015-9605-y

Schmid, B., & Koskiaho, J. (2006). Artificial neural network modeling of dissolved oxygen in a wetland pond: The case of Hovi Finland. *ASCE Journal of Hydrology Engineering, 11*(2), 188–192. doi:10.1061/(ASCE)-0699(2006)11:2(188)

Sullivan, A. B., Rounds, S. A., Asbill-Case, J. R. et al. (2013). Macrophyte and pH buffering updates to the Klamath River water-quality model upstream of Keno Dam, Oregon: U.S. Geological Survey Scientific Investigations Report 2013-5016, p. 52. http://pubs.usgs.gov/sir/2013/5016/

Sullivan, A. B., Rounds, S. A., Deas, M. L. et al. (2012). Dissolved oxygen analysis, TMDL model comparison, and particulate matter shunting-Preliminary results from three model scenarios for the Klamath River upstream of Keno Dam, Oregon: U.S. Geological Survey Open-File Report 2012-1101, p. 30. http://pubs.usgs.gov/of/2012/1101/

Sullivan, A. B., Sogutlugil, I. E., Rounds, S. A. et al. (2013). Modeling the water-quality effects of changes to the Klamath River upstream of Keno Dam, Oregon: U.S. Geological Survey Scientific Investigations Report 2013-5135, p. 60. http://pubs.usgs.gov/sir/2013/5135

Sun, W., Xia, C., Xu, M., et al. (2016). Application of modified water quality indices as indicators to assess the spatial and temporal trends of water quality in the Dongjiang River. *Ecological Indicators, 66*, 306–312. doi:10.1016/j.ecolind.2016.01.054

U.S. Geological Survey. (2008). *National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, Chaps. A1–A9 variously dated*. Chapter A6, 6-2 dissolved oxygen, p 48. http://water.usgs.gov/owq/FieldManual/Chapter6/6.2_contents.html

Watts, M. (2009). A decade of Kasabov's evolving connectionist systems: A review. *IEEE Transaction on System Man Cybernetics, Part C: Applied Review, 39*(3), 253–269. doi:10.1109/TSMCC.2008.2012254

Woodford, B. J. (2008). Evolving Neuro computing systems for horticulture applications. *Applied Software Computing, 8*, 564–578. doi:10.1016/j.asoc.2006.05.006

Yurdakul, M., Gopalakrishnan, K., & Akdas, H. (2014). Prediction of specific cutting energy in natural stone cutting processes using the neuro-fuzzy methodology. *International Journal of Rock Mechanics and Mining Sciences, 67*, 127–135. doi:10.1016/j.ijrmms.2014.01.015

Part V
Sustainability

Chapter 12
Cumulative Belief Degrees Approach for Assessment of Sustainable Development

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Abstract Over the past decades, sustainable development has emerged as one of the most prominent issues at all levels of society, from the global to the local level. To achieve a better balance between the economic, social and environmental dimensions of sustainable development in all countries of the world, starting from underdeveloped countries to developed countries, the right implementation of the sustainable development principles has a strategic significance that shapes the future of the countries. In this respect, measurement of sustainable development performance of countries is necessary in order to apply right sustainable development strategies, track the process, investigate the interactions between sustainability aspects, etc. The main purpose of this chapter is to demonstrate a new approach for measuring sustainable development levels of the countries using a cumulative belief degree approach. The approach enables the use of an incomplete data that is one of the critical problems in measuring sustainability of countries. Twenty-seven indicators for measuring 20 themes are selected based on the recommendations of United Nations Economic Commission for Europe (UNECE) and data availability. Finally, the proposed approach is applied to rank 138 countries according to their sustainable development performances based on the most recent data available.

12.1 Introduction

The concept of sustainable development emerged as a response to a growing environmental challenges and social, economic and technical imbalances in global development (Waas et al. 2011). As a result of natural disasters, wars and climate changes, natural resources have been severely depleted day by day in the whole world. Economic, social and environmental changes appear as the greatest threats to under-or less-developed countries. The aim of sustainable development is to bal-

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DOI 10.1007/978-3-319-42993-9_12

ance economic, environmental and social needs of human being, allowing prosperity for now and future generations. In that case, the importance of sustainable development has emerged as an urgent action plan which consists of diverse aspects such as socioeconomic development, public health, natural resources, global partnership, climate change, biodiversity etc. Sustainable development policy provides great advantages in order to improve standard of living, promote social justice and economic progress. The main issue is being in harmony with present and future needs while fulfilling the economic, environmental and social factors which are the core dimensions of the sustainability, except for technical and institutional aspects (Harris 2000; Parris and Kates 2003; Soubbotina 2004; Munda 2005; Waas et al. 2011).

Advanced international organizations/institutions adopted sustainable development as a guide to support development models that focus on utilization of the resources efficiently, increasing job opportunities and living standards, providing transportation and educational conditions at international level. The significance of the issue will be remained as long as human being exist since it affects human life directly in terms of quality of life, social justice and well-being. Therefore, sustainability strategies have been carried out by a growing number of international institutions and/or organizations to assist communities in developing economic and social opportunities for all citizens. A wide range of these organizations aim to develop large-scale substantial projects in order to strengthen economic relations of the countries, increase technological investments and prioritize educational standards to raise welfare to provide fair living conditions. These institutions, and their components, can be listed as follows: The World Bank, International Organization for Sustainable Development (IOSD), International Institute for Sustainable Development (IISD), World Business Council for Sustainable Development (WBCSD), World Resources Institute (WRI), World Wide Fund for Nature (WWF), United Nations Development Programme Evaluation Resource Centre (UNDPERC), The United Nations Commission on Sustainable Development (CSD), United Nations (UN), Organization for Economic Co-operation and Development (OECD), European Union Open Data Portal (EuroStat), Global Footprint Network (GFN) (United Nations 2007; Boggia and Cortina 2010; Bolcárová and Kološta 2015; UNECE 2014).

In order to assess sustainable development, sustainability related indicators are issued to capture various thematic areas including human, environmental and energy. Indicators are used as metrics for determining progress the existing system or state to evaluate future nature of the complex system. Hence, decision making procedure can be realized easily due to the measurable risk level under uncertain conditions (Iddrisu and Bhattacharyya 2015). Instances of such indicators include the Ecological Footprint, the Environmental Sustainability Index (ESI), the Environmental Performance Index (EPI) and Human Development Index (HDI) which are the best known composite indicators (Blancard and Hoarau 2013). The Ecological Footprint, developed by Wackernagel and Rees (1996), a measure of biological productive land and water, is concerned as a measure of biological capacity. Both ESI and EPI have been developed by the Center for Environmental

Law and Policy at Yale University and the Center of International Earth Science Information Network (CIESIN) at Columbia University in collaboration with the World Economic Forum (WEF) (Hsu et al. 2016). HDI is introduced by the United Nations Programme for Development (UNDP) (Nationen 2015). Iddrisu and Bhattacharyya (Iddrisu and Bhattacharyya 2015) have analyzed the existing indicators on energy sustainability to developed a composite index, SEDI (Sustainable Energy Development Index) to eliminate weakness of the existing indicators. The proposed indicator incorporates intra and inter-generational needs for measuring sustainability level. SEDI has been compared with other indicators such as EDI, EPI and HDI in order to show success of the method.

In the literature, the earliest and most relevant publications related to sustainability are the Limits to Growth (Meadows and Club of Rome 1972), Our Common Future, commonly known as the Brundtland Report (World Commission on Environment and Development 1987) and Agenda 21 (1992). All these publications point to the significance of the subject and the necessity of the sustainable directions. Since then, the publications, policies and reports have been proceeded rapidly.

Parris and Kates (2003) have clarified sustainable development terminology in detailed according to goals, indicators, trends and polices since information abundance leads to the ambiguity and confusion for evaluating sustainable development. Due to the lack of a universal standard for data and methods of sustainable development measurement, they have proposed an analytical framework in order to recognize differences among goals, indicators, targets, trends by making comparisons and selections. Moreover, they analysed twelve selected efforts to characterize and measure sustainable development.

Assessment of sustainable development can be conducted for different size of territories. For instance; Munda (2005) has discussed the measuring of sustainability of cities using a multi-criteria framework with an illustrative example. Amsterdam, New York, Budapest and Moscow are selected as cities to determine urban sustainability. The author has discussed the robustness of the proposed method by using different criteria weights and has achieved different rankings owing to importance of coefficients and/or criteria weights. On the other hand, Boggia and Cortina (2010) identified an integrated approach in for comparing municipalities in a region to assess and monitor the social, environmental and economic sub-sets of the sustainable development. The paper's proposed approach depends on Multi-Criteria Decision Analysis (MCDA) due to its effectiveness on the complex structures of a system such as sustainability development. The MCDA approach has been implemented to evaluate sustainability of 92 municipalities of the Umbria region in Italy.

Sustainability is mostly assessed on country level. In addition to the assessments of international organizations, for instance, Bolcárová and Kološta (2015) have proposed an aggregation index of the sustainable development to rank the 27 European Union (EU) countries. They utilize principal component analysis (PCA) to show relation between the index and with economic growth. Moreover, Golusin and Ivanovic (2009) have realized the sustainable development analysis according to basic sustainable development index for the countries of Southeastern Europe. Authors highlight that there is a need a new approach to identify the degree of sustainable development based on a certain degree of importance to each individual indicator. Similarly, Ivanovic et al. (2009) have determined the exist values of indicators of sustainable development in the Southeastern Europe countries. This study points the necessity of determining degree of importance of some indicators of sustainable development, particularly for beginning level of countries of the planning of strategy of development. The research showed that the relation between the values of indicators of economic and ecological subsystem is very sensitive due to the small changes in the value of any indicators cause different final results.

Related to the methods used for measuring sustainable development, a detailed review by Frini and BenAmor (2015) shows that most of the studies utilizes Multiple Criteria Decision Making (MCDM) methods to rank countries in terms of HDI, EPI, ESI. The most commonly used MCDM methods consist of respectively, AHP (27 %), mathematical programming (12 %), TOPSIS (10 %), ANP (8 %), PROMETHEE (7 %), VIKOR (3 %), ELECTRE (3 %), MULTIMOORA (2 %), multiple attribute utility theory (2 %), simple additive weighting (3 %). Additionally, goal programming and data envelopment analysis (DEA) are other preferred MCDM methods to evaluate sustainable development in various applications. DEA can be used as a benchmarking tool to evaluate organizations' performances according to different sustainable development fields such as energy, economy, health and environment. The analysed DEA models in the studies mostly developed to measure corporate sustainability management. Cluster analysis (Adamisin et al. 2015), factor analysis (Hao et al. 2006), PCA (Bolcárová and Kološta 2015) and conjoint analysis (Acosta et al. 2014) are mostly preferred other techniques to evaluate sustainable developments of the countries. The analysed studies mostly focus on respectively energy (30 %), construction (11 %), industry (9 %), transportation (7 %) and economy (8 %) as a sustainable development field.

In global manner, sustainable development has a substantial and complex structure due to the various stakeholders, incomplete knowledge, the multidimensional nature and diverse aspects of sustainable development as well as different purposes. Owing to the several challenges of the sustainable development, various tools have been developed in order to facilitate decision making process and to explore other fields of sustainable development. In particular, one of the great challenges of sustainable development is missing data problem (Gustavson et al. 1999). According to UNECE (2014) the availability of indicators in United Nations and Eurostat databases varies from 55 to 92 % for different sets of sustainability indicators. In measuring sustainable development, a difficulty that has to be addressed is the lack of complete and reliable information. To the best of our knowledge, there is no study to deal with missing values in the measuring sustainable development.

The complex sustainable development concept is difficult to analyse and model because of the nature of the complexity paradigm. Owing to the uncertainty and multi-dimensional nature of complex systems, we could not make decisions easily under such a huge data of many countries with respect to large number of criteria. In this study, we aim to evaluate sustainable development levels of countries using a Cumulative Belief Degree (CBD) approach, developed by Kabak and Ruan (2011a), in order to show sustainable development performance of countries according to different scales. The CBD methodology is also capable of handling incomplete or missing information (Kabak and Ruan 2011a), which is an important problem in the assessment of sustainable development.

In the proposed methodology, firstly the required data have been collected from various official sources to measure sustainable development of countries. Then, all kind of sustainable development indicators are aggregated to obtain overall sustainable development performance using the CBD approach. The rest of the chapter is organized as follows. Section 12.2, describes sustainable development indicators considered in the assessment. Section 12.3 explains the CBD approach. Section 12.4 provides the application on measuring sustainability of countries. Finally some concluding remarks and future research directions are given in Sect. 12.5.

12.2 Sustainable Development Indicators

In this chapter, measurement framework and the indicators recommended by UNECE (2014) are selected to assess sustainable development of countries. After efforts of academics and national statistical offices to create composite indicators and sustainable development indicator sets respectively, there are still big differences between the approaches. In order to harmonize these proposed ways of measurement, the Conference of European Statisticians (CES) set up in 2009 a joint UNECE, Eurostat and OECD. The Task Force has built its work on Measuring Sustainable Development which was published in 2009 by a previous UNECE/Eurostat/OECD Working Group.

UNECE (2014) presents a measurement framework and sets of indicators by considering several approaches and previous work of United Nations, Eurostat, OECD and individual countries. It takes into account three conceptual dimensions of sustainable development: human well-being of the present generation in one particular country referred to as “here and now”, the well-being of future generations referred to as “later”, and the well-being of people living in other countries “elsewhere”. The framework links these three dimensions defined in the Brundtland Report to policy relevant themes. Twenty theme propositions are used to measure environmental, social and economic aspects of sustainable development. The twenty themes and their relations to dimensions of sustainable development are given in Table 12.1.

The framework recommended by UNECE (2014) proposes three indicator sets. The large set of 60 indicators is for measurement of well-being according to dimensions “here and now”, “later” and “elsewhere”. The large set of 90 indicators proposes a thematic categorization based on policy relevance. The difference

Table 12.1 Linking the conceptual and thematic categorizations (UNECE 2014, p. 65)

	Dimensions		
	Human well-being (“Here and now”)	Capital (“Later”)	Transboundary impacts (“Elsewhere”)
TH1. Subjective well-being	X		
TH2. Consumption and income	X		X
TH3. Nutrition	X		
TH4. Health	X	X	
TH5. Labour	X	X	X
TH6. Education	X	X	
TH7. Housing	X		
TH8. Leisure	X		
TH9. Physical safety	X		
TH10. Land and ecosystems	X	X	X
TH11. Water	X	X	X
TH12. Air quality	X	X	
TH13. Climate		X	X
TH14. Energy resources		X	X
TH15. Mineral resources		X	X
TH16. Trust	X	X	
TH17. Institutions	X	X	X
TH18. Physical capital		X	X
TH19. Knowledge capital		X	X
TH20. Financial capital		X	X
Context: Population			
Economic capital-monetary		X	
Natural capital-monetary		X	
Human capital-monetary		X	
Social capital-monetary		X	

between two large sets is in their categorization principle. A theme can serve more than one dimension. For example, the themes "health" and "labour" are included to measure both the well-being dimensions of "here and now" and "later". The thematic set contains more indicators, because it includes policy relevant indicators, as well. Conceptual categorization identifies data gaps as it determines necessary elements of an ideal measurement; while the thematic categorization is helpful in policymaking and for the general public. Finally, a small set of 24 indicators derived from the large set of thematic categorization aims to cover essential messages and enable international comparison. Different from the existing very large sustainable development indicators sets, this small set is helpful in facilitating the focus on the most important aspects. Selection process of these indicators is based on their availability in international databases, the commonalities in the current sustainable development indicator sets and how well they are able to measure the phenomena that they stand for. While the order of selection criteria for two large sets is how ideal they are as an indicator and commonalities in existing sustainable development indicator sets; the data availability becomes the most important criterion for the small set. Commonalities are only considered if two possible indicators of a theme have the same data availability. This availability was analysed for only 46 countries (EU and OECD member countries and Brazil, Russian Federation, India, Indonesia, China, and South Africa). The availability of indicators in United Nations and Eurostat databases is 55 % for the large set of conceptual categorization, 69 % for the large set of thematic categorization and 92 % for the small set. A greater availability can be achieved when other international databases are included.

In the proposed approach the small set indicators derived from thematic categorization are used. 27 indicators for measuring 20 themes are selected based on UNECE (2014)'s recommendations and data availability. The themes and indicators are listed in Table 12.2. Sources of the data and number of recent available data for the indicators are also given in Table 12.2. Explanations related to themes and indicators are presented in the following sub-sections.

12.2.1 Theme 1: Subjective Well-Being

The literature on subjective well-being argues that human well-being is not only related to the consumption choices they make, but also to their evaluations on their own life. Subjective well-being encompasses cognitive evaluations of one's life, happiness, satisfaction, positive emotions such as joy and pride, and negative emotions such as pain and worry (UNECE 2014).

We use "Indicator 1. Life satisfaction" to measure subjective well-being. This indicator refers to the response to the question "All things considered, how satisfied are you with your life as a whole nowadays? Please answer using this card, where 0 means extremely dissatisfied and 10 means extremely satisfied". The data is taken from World Database of Happiness as suggested in UNECE (2014).

Table 12.2 List of indicators used in the proposed methodology

Theme	Indicator	Availability	Source
TH1. Subjective well-being	1. Life satisfaction	159	World Database of Happiness
TH2. Consumption and income	2.1. Final consumption expenditure per capita	165	World Bank
	2.2. Net official development assistance received per capita	140	World Bank
	2.3. Income Gini coefficient	138	United Nations
	2.4. Gender gap	142	World Economic Forum
TH3. Nutrition	3.1. Diabetes prevalence	206	World Bank
	3.2. Prevalence of undernourishment	139	UN Food and Agriculture Organization
TH4. Health	4. Life expectancy at birth	198	World Bank
TH5. Labour	5. Unemployment rate	174	World Bank
TH6. Education	6. Higher education and training	148	World Economic Forum
TH7. Housing	7. Slum population in percentage of urban	83	United Nations
TH8. Leisure	8. Working hours	74	International Labour Organization
TH9. Physical safety	9.1. Organized crime	148	World Economic Forum
	9.2. Reliability of police services	148	World Economic Forum
TH10. Land and ecosystems	10. Bird species threatened	212	World Bank
TH11. Water	11. Annual freshwater withdrawals per capita	180	World Bank
TH12. Air quality	12. PM2.5 air pollution, population exposed to levels exceeding World Health Organization guideline value (% of total)	185	World Bank
TH13. Climate	13. Total GHG emissions including land-use change and forestry	184	World Resources Institute
TH14. Energy resources	14. Energy use (kg of oil equivalent per capita)	140	World Bank
TH15. Mineral resources (excluding coal and peat)	15. Domestic material consumption per capita	184	WU: Global Material Flows Database
TH16. Trust	16. Transparency of government policymaking	148	World Economic Forum

(continued)

Table 12.2 (continued)

Theme	Indicator	Availability	Source
TH17. Institutions	17. Voter turnout	199	IDEA
TH18. Physical capital	18. Gross capital formation (% of Gross domestic product)	166	World Bank
TH19. Knowledge capital	19.1. Company spending on R&D	148	World Economic Forum
	19.2. University-industry collaboration in R&D	148	World Economic Forum
TH20. Financial capital	20. Total government debt stocks (% of gross national income)	186	International Monetary Fund

12.2.2 Theme 2: Consumption and Income

This theme refers to human well-being to show financial situation and material living standards. While subjective well-being is the subjective aspect of human well-being, consumption and income is the objective cross-cutting theme (UNECE 2014). Two indicators are used to measure this theme: Indicator 2.1. Final consumption expenditure per capita, Indicator 2.2. Official Development Assistance received per capita, Indicator 2.3. Income Gini coefficient, and Indicator 2.4. Gender gap.

According to the World Bank (2016), final consumption expenditure is the sum of household final consumption expenditure (private consumption) and general government final consumption expenditure (general government consumption). Since population is given as a contextual indicator, a "per capita" version of total final consumption expenditure is calculated.

Official Development Assistance (ODA) has been added as an indicator to measure how a country affects others. According to the definition of World Bank, net ODA per capita consists of disbursements of loans made on concessional terms and grants by official agencies of the members of the Development Assistance Committee (DAC), by multilateral institutions, and by non-DAC countries to promote economic development and welfare in countries and territories in the DAC list of ODA recipients; and is calculated by dividing net ODA received by the midyear population estimate. It includes loans with a grant element of at least 25 % (calculated at a rate of discount of 10 %) (World Bank 2016).

The Gini coefficient is a widely available and commonly used indicator. While "income inequality" is a proposed indicator for the theme "consumption and income" in UNECE (2014), "share of the poorest quintile in national consumption" is the alternative indicator worldwide for being the most widely available one. However, this global indicator is available until 2012 and it covers only 25 countries for that year. According to the definition of World Bank (2016), Gini index measures the extent to which the distribution of income (or, in some cases, consumption expenditure) among individuals or households within an economy deviates from a perfectly equal distribution. A Lorenz curve plots the cumulative percentages of total income received against the cumulative number of recipients, starting with the poorest individual or household. The Gini index measures the area between the Lorenz curve and a hypothetical line of absolute equality, expressed as a percentage of the maximum area under the line. Thus a Gini index of 0 represents perfect equality, while an index of 100 implies perfect inequality (World Bank 2016). Although the source of Gini index is the World Bank, the UN has a greater coverage for the year 2013 as they have used the data from previous years as well.

Gender pay gap is defined as the difference between men's and women's average earnings from employment, shown as a percentage of men's average earnings. It combines the gender differences in the wage rates as well as time worked and type of work performed (UNECE 2014). Gender pay gap is the most common indicator about distribution issue along with income inequality. The Rio+20 Conference stated that "we recognize that goals, targets and indicators, including where appropriate gender-sensitive indicators, are valuable in measuring and accelerating progress" (UNECE 2014). WEF publishes Gender Gap Index in their annual Global Gender Gap Report to provide information on the performance of countries on gender equality (Schwab and Sala-i Martín 2015). It gives a wider perspective on gender inequality than gender pay gap which focuses mainly on income distribution.

12.2.3 Theme 3: Nutrition

Nutrition is included as a theme due to the fact that it is a basic need according to Maslow and it is important for health and human well-being in general (UNECE 2014). According to UNECE (2014), "malnutrition prevalence" is a more relevant indicator than "obesity" worldwide as the latter is mainly important for high-income countries. Problems related to nutrition are different for every country. In some countries, both "malnutrition prevalence" and "obesity" might have a significant effect.

Data for underweight in children is available only for sub-regions in World Health Organization (WHO). WHO published a joint malnutrition dataset from UNICEF, WB and WHO, as well. However, since the data series of this indicator for the countries are not available for common years, it does not provide a basis for comparison. Therefore; we selected two below-explained indicators for this theme.

The first indicator is Indicator 3.1 Diabetes prevalence. World Bank (2016) defines diabetes prevalence refers to the percentage of people ages 20–79 who have type 1 or type 2 diabetes.

The second one is Indicator 3.2. Prevalence of Undernourishment. According to the definition of Food and Agriculture Organization (FAO) of the United Nations (FAO 2016), the prevalence of undernourishment expresses the probability that a randomly selected individual from the population consumes an amount of calories that is insufficient to cover her/his energy requirement for an active and healthy life. The indicator is computed by comparing a probability distribution of habitual daily dietary energy consumption with a threshold level called the minimum dietary energy Requirement. Both are based on the notion of an average individual in the reference population.

12.2.4 Theme 4: Health

Health is one of the themes of human capital. Health can be seen as a characteristic of labour force, as well. Expenditures on healthcare are regarded as investment in human capital as they generate welfare. It is one of the most common themes used in studies on human well-being.

Indicator 4. Life expectancy at birth is proposed for the theme "health". An ideal indicator for the theme "health" should measure physical and mental health of the society in total. Common indicators of current health status such as life expectancy are not enough for measuring the effects of future health outcomes, such as hypertension and obesity. Therefore, life expectancy is not the ideal indicator for the theme, but it is very commonly used in sustainable development index sets and better for international comparison (UNECE 2014). According to the definition of World Bank (2016), life expectancy at birth indicates the number of years a new-born infant would live if prevailing patterns of mortality at the time of its birth were to stay the same throughout its life.

12.2.5 Theme 5: Labour

Labour is one of the themes of human capital. In the production function literature, changes in labour and capital inputs cause changes in economic production. In the Solow growth model, Gross domestic product (GDP) is a function of labour, capital inputs and technology (UNECE 2014).

The theme "Labour" is measured by Indicator 5. Unemployment rate. An ideal measurement of labour requires both quantity and quality aspects. As job quality is more difficult to measure, unemployment is proposed as an important indicator of human well-being (2014). World Bank (2016) defines unemployment as the share of the labour force that is without work but available for and seeking employment.

12.2.6 Theme 6: Education

Education is one of the themes of human capital. It is a personal attribute which generate human well-being and it is transferred to future generations as a capital. UNDP takes into account education in its annual HDI, as well. According to Lomas (1998) and Healy (2001), higher human capital generated by health and education have bigger impact on subjective well-being than income and other factors (UNECE 2014).

Indicator 6. Higher education and training is the single indicator to measure this theme. UNECE (2014) proposed “educational attainment” as the indicator of the theme “education” in order to focus on labour quality. It was selected over other possible indicators such as “basic competencies”, “participation in education” and “lifelong learning” for being more widely available and a better indicator of overall level of education in the population.

The indicator is provided from the Global Competitiveness Report. Higher education and training pillar measures secondary and tertiary enrolment rates as well as the quality of education as evaluated by business leaders. The extent of staff training is also taken into consideration because of the importance of vocational and continuous on-the job training—which is neglected in many economies—for ensuring a constant upgrading of workers’ skills (Schwab and Sala-i Martín 2015). It is a suitable alternative indicator as UNECE (2014) focuses on the quality of labour in the theme “education”.

12.2.7 Theme 7: Housing

It is one of the themes in material conditions in OECD’s How’s life report (UNECE 2014). Other 4 reports on human well-being which UNECE (2014) analysed did not propose housing as a theme. But the Stiglitz-Sen-Fitoussi (SSF) report included housing in the category “personal activities” along with labour (UNECE 2014).

Although both quantity and quality of housing conditions are important, “the share of urban population living in slums” includes the largest number of countries worldwide (UNECE 2014). Therefore, we selected Indicator 7. Slum population in percentage of urban for the theme “housing”. It is measured by a proxy, using the statistics of households who have one of the following characteristics: (a) lack of access to improved water supply; (b) lack of access to improved sanitation; (c) overcrowding (3 or more persons per room); and (d) dwellings made of non-durable material (UNECE 2014).

12.2.8 Theme 8: Leisure

Nordhaus and Tobin (1973) included leisure time to their modified national income. Social cost regarding loss of leisure time is deducted for the measurement of the Genuine Progress Indicator (GPI) (UNECE 2014). The theme should be measured in quality and quantity. As it is difficult to measure the quality, time use surveys to measure the leisure time are suggested. It is defined as number of minutes per day spent on leisure (UNECE 2014).

The proposed indicator "leisure time" is the most problematic recommendation as only 20 countries have such data. Therefore; we used an alternative indicator Indicator 8. Working hours that is provided from International Labour Organization (ILO) (ILO 2016).

12.2.9 Theme 9: Physical Safety

In the Global Competitiveness Report, there are four indicators in the section related to physical safety (i.e., 5th section "Security" of the pillar "Institutions": 1.13. Business costs of terrorism, 1.14 Business costs of crime and violence, 1.15 Organized crime, and 1.16 Reliability of police services (Schwab and Sala-i Martín 2015). As there is not any focus on business costs in UNECE (2014), we have selected two indicators 1.15 and 1.16.

Indicator 9.1. Organized crime shows the results of The Executive Opinion Survey conducted by WEF and is derived from the answers to the question "In your country, to what extent does organized crime (mafia-oriented racketeering, extortion) impose costs on businesses?" (Schwab and Sala-i Martín 2015).

Indicator 9.2. Reliability of police services shows the results of The Executive Opinion Survey conducted by WEF and is derived from the answers to the question "In your country, to what extent can police services be relied upon to enforce law and order?" (Schwab and Sala-i Martín 2015).

12.2.10 Theme 10: Land and Ecosystems

"Land and ecosystems" is one of the themes of natural capital. Natural resources are essential to economic activities. But they provide an environment for living, recreation and leisure, as well. Therefore, they are directly related to human well-being (UNECE 2014).

Indicator 10. Bird species threatened refers to only a small part of the theme "land and ecosystems". There are many other aspects of this natural capital. But it was chosen by UNECE (2014) because of its wide availability. According to the definition of World Bank, birds are listed for countries included within their breeding or wintering ranges. Threatened species are the number of species classified by the International Union for Conservation of Nature (IUCN) as endangered, vulnerable, rare, indeterminate, out of danger, or insufficiently known (World Bank 2016).

12.2.11 Theme 11: Water

Water is one of the themes of natural capital. Global freshwater use is one of the nine estimations on current positions of planetary systems by Rockström et al. (2009). Other estimations concern climate change, ocean acidification, stratospheric ozone depletion, nitrogen and phosphorous cycles, change in land use, biodiversity loss, atmospheric aerosol loading and chemical pollution. Reaching biophysical thresholds in these systems can create great consequences (UNECE 2014).

"Gross freshwater abstracted" indicator by the UN is available until the year 2009 and has only 36 countries for that year. Therefore; we have selected Indicator 11. Annual freshwater withdrawals per capita for this theme World Bank has a wider availability in this indicator.

World Bank (2016) defines "annual freshwater withdrawals" as the total water withdrawals, not counting evaporation losses from storage basins. Withdrawals also include water from desalination plants in countries where they are a significant source. Withdrawals can exceed 100 % of total renewable resources where extraction from non-renewable aquifers or desalination plants is considerable or where there is significant water reuse. Withdrawals for agriculture and industry are total withdrawals for irrigation and livestock production and for direct industrial use (including withdrawals for cooling thermoelectric plants). Withdrawals for domestic uses include drinking water, municipal use or supply, and use for public services, commercial establishments, and homes.

12.2.12 Theme 12: Air Quality

Air quality is one of the themes of natural capital. Although the System of Environmental-Economic Accounting (SEEA) did not include air in natural capital, UNECE (2014) do along with other factors as explained in Theme 13: Climate.

Indicator 12. PM2.5 air pollution is used for the theme "Air quality". According to the definition of World Bank, percent of population exposed to ambient concentrations of PM2.5 that exceed the WHO guideline value is defined as the portion of a country's population living in places where mean annual concentrations of PM2.5 are greater than 10 μg per m^3, the guideline value recommended by the WHO as the lower end of the range of concentrations over which adverse health effects due to PM2.5 exposures have been observed (World Bank 2016).

12.2.13 Theme 13: Climate

Climate is one of the themes of natural capital. While the SEEA definition of natural capital includes only land, natural resources and ecosystems, UNECE (2014) adds other assets such as the climate system, air, marine waters and ozone layer. Because it has a global perspective on sustainability. Climate change is the most important environmental problem positon of which could be reflected by these global indicators (UNECE 2014).

Indicator 13. Total GHG emissions including land-use change and forestry is used to measure this theme. According to UNECE (2014), “CO_2 emissions” have a wider availability than “GHG emissions”. But, WRI has GHG emissions data for 187 countries, and the indicator “CO_2 emissions” was suggested an alternative only because of data availability. WRI uses data reported by countries to the United Nations Framework Convention on Climate Change (UNFCCC) and complements them with data from non-governmental sources.

12.2.14 Theme 14: Energy Resources

Energy resources is one of the themes of natural capital. In order to enable international comparison in this theme, choosing a global indicator is very important. For example, an indicator on fossil fuel resources can be accurate for some countries. But it would not be a good indicator for the countries which do not have such resources (UNECE 2014).

Indicator 14.1. Energy use per capita is suggested for this theme. World Bank (2016) defines energy use as the use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport.

12.2.15 Theme 15: Mineral Resources (Excluding Coal and Peat)

“Mineral resources” theme is one of the natural capital themes. Fossil fuels, metal and minerals are assets which are more easily measured. Although monetization of natural stocks is a controversial subject, stock is the core indicator from sustainability perspective. On the other hand, extraction, use and waste are more policy relevant and easier to measure (UNECE 2014).

Indicator 15. Domestic material consumption per capita is used for this theme. Domestic Material Consumption (DMC)—total amount of materials directly used by an economy; is defined as the annual quantity of raw materials extracted from the domestic territory, plus all physical imports minus all physical exports (UNECE 2014). Global Material Flows Database provides information on extraction, consumption, trade and productivity of materials.

12.2.16 Theme 16: Trust

Trust is one of the themes of social capital. According to World Bank (2016), it is an important determinant of economic growth and human well-being. Its meaning is close to "social connections and relationships" in SSF report (Stiglitz 2009) and "family relations; community & friends" in Layard's subjective well-being research (Layard 2005; UNECE 2014). Repeated interactions between people create "generalized trust", the proposed indicator.

According to UNECE (2014), the theme "trust" is measured well by some World Bank indicator series such as "public sector management". It is proposed as the alternative indicator to generalized trust for international comparison. We used a WEF indicator for this theme: Indicator 16. Transparency of government policymaking.

In the Global Competitiveness Report, among the five indicators in the "public sector management" section of the "Institutions", the indicator 1.12 Transparency of government policymaking is found to be a relevant alternative for measuring the theme "trust". This data shows the results of The Executive Opinion Survey conducted by WEF and is derived from the answers to the question "In your country, how easy is it for businesses to obtain information about changes in government policies and regulations affecting their activities?" (Schwab and Sala-i Martín 2015).

12.2.17 Theme 17: Institutions

Institutions is one of the themes of social capital. It was "political voice and governance" in the SSF report (Stiglitz 2009) and "personal freedom" (in terms of a democratic society) in Layard's subjective well-being research (2005) (UNECE 2014). Social capital is not directly linked to individuals as in human capital, but to interpersonal connections. Some approaches take institutions separately as they do not include it in social capital. Because there is a debate on whether formal institutions are a part of social capital (UNECE 2014).

In UNECE (2014), Indicator 17. Voter turnout is suggested as an indicator of the theme "institutions". It refers to voter turnout in national parliamentary elections in percentage of the eligible electorate. International Institute for Democracy and Electoral Assistance (International IDEA) is suggested as the source. It is an intergovernmental organization that supports sustainable democracy worldwide.

12.2.18 Theme 18: Physical Capital

Economic capital consists of physical capital, knowledge capital and financial capital. Its sustainability is important for human well-being "later". The System of National Accounts (SNA) does not directly show the measurement of capital stocks. But, the OECD manual Measuring Capital explains how to measure physical capital stocks. Physical capital includes stock of machinery, equipment, buildings and infrastructure on national level. But Indicator 18. gross capital formation is the proposed global indicator as it is more policy relevant and common in some sustainable development indicator sets.

According to World Bank (2016), gross capital formation (formerly gross domestic investment) consists of outlays on additions to the fixed assets of the economy plus net changes in the level of inventories. Fixed assets include land improvements (fences, ditches, drains, and so on); plant, machinery, and equipment purchases; and the construction of roads, railways, and the like, including schools, offices, hospitals, private residential dwellings, and commercial and industrial buildings. Inventories are stocks of goods held by firms to meet temporary or unexpected fluctuations in production or sales, and "work in progress." According to the 1993 SNA, net acquisitions of valuables are also considered capital formation (World Bank 2016).

12.2.19 Theme 19: Knowledge Capital

Although knowledge capital is one of the themes of economic capital, OECD defines human capital as "the knowledge, skills, competencies and attributes embodied in individuals that facilitate the creation of personal, social and economic well-being" (UNECE 2014). Even if R&D and innovation statistics provide a narrow perspective, they are often used in knowledge estimation.

"Gross domestic expenditure on research and development (GERD), as a percentage of GDP", the recommended indicator for the theme "knowledge capital" from United Nations has the record for only 75 countries for 2012, 61 countries for 2013 and 2 countries for 2014. On the other hand, in the Global Competitiveness Report (Schwab and Sala-i Martín 2015), the 12th pillar "Innovation" is directly related to this theme. Among the indicators in the "innovation" pillar, we have selected 12.03 Company spending on R&D, and 12.04 University-industry collaboration in R&D due to the recommended indicator focuses on R&D and expenditures on this matter.

Indicator 19.1. Company spending on R&D shows the results of The Executive Opinion Survey conducted by WEF and is derived from the answers to the question "In your country, to what extent do companies spend on research and development (R&D)?" (Schwab and Sala-i Martín 2015).

Indicator 19.2. University-industry collaboration in R&D shows the results of The Executive Opinion Survey conducted by WEF and is derived from the answers to the question “In your country, to what extent do business and universities collaborate on research and development (R&D)?”(Schwab and Sala-i Martín 2015).

12.2.20 Theme 20: Financial Capital

Financial capital is one of the themes of economic capital. Financial assets and their distribution is important for sustainable development. Recent financial crisis has shown the importance of sustainable financial capital. Financial assets include currency and other forms of bank deposits, stocks and bonds, derivatives, accounts receivable, pension funds, gold reserves and insurance reserves (UNECE 2014).

Indicator 20. Total government debt stocks is used for this theme. According to the definition of World Bank (2016), debt is the entire stock of direct government fixed-term contractual obligations to others outstanding on a particular date. It includes domestic and foreign liabilities such as currency and money deposits, securities other than shares, and loans. It is the gross amount of government liabilities reduced by the amount of equity and financial derivatives held by the government. Gross national income (GNI, formerly GNP) is the sum of value added by all resident producers plus any product taxes (less subsidies) not included in the valuation of output plus net receipts of primary income (compensation of employees and property income) from abroad (World Bank 2016).

12.3 Cumulative Belief Degrees Approach

In this study, a CBD approach is proposed to assess sustainable development of countries. The CBD approach is developed firstly for the evaluation of nuclear safeguards, based on fuzzy linguistic terms and belief structure (Kabak and Ruan 2011a). This approach is based on representing any information by a belief structure that uses linguistic terms. Hence all types of expert evaluations or information in different scales or with different linguistic terms, can be utilized without the loss of any information. The CBD approach is also capable of aggregation data under vagueness and uncertain information environment. Moreover, the CBD approach can also address values that are missing because of a lack of expertise or a scarcity of information.

The CBDs are developed to make operations on belief structures. CBD at certain linguistic term levels can be defined as the aggregated belief degrees of greater or equal terms of the related linguistic term (Kabak et al. 2013). For the case of measuring sustainability problem, suppose that the minimum sustainable development performance score of a country with respect to an indicator is determined according to a threshold value, which is determined as one of the linguistic terms.

Then the belief degrees of the terms that are greater than, or equal to the threshold would give the total belief on the minimum performance of countries.

Fuzzy linguistic terms are used to represent the information by the belief structure. Let $S = \{s_k\},\ k \in \{0,\ldots,K\}$ be a finite and totally ordered term set. Any label s_k, represents a possible value for a linguistic variable. The semantics of the finite term set S is given by fuzzy numbers, which are defined in the [0, 1] interval, and by their membership functions. Linguistic term sets can be defined according to the nature of the problem. For measuring the sustainable development of countries, a five-term set, $S = \{s_k\},\ k \in \{0,\ldots,4\}$, in which the following meanings to the terms are assigned as follows: s_0: very poor (VP), s_1: poor (P), s_2: fair (F), s_3: good (G), s_4: very good (VG) is used to evaluate sustainable development of countries.

The proposed CBD approach for measuring sustainable development performance of countries involves the following steps: (1) Transformation of the data to the belief structure, (2) Calculation of the CBDs, (3) Aggregation of CBDs, and (4) Interpretation of resulting CBDs.

12.3.1 Transformation of the Data to the Belief Structure

In this study, the belief structure is used to represent the data of the countries with respect to indicators. For measuring sustainable development of countries, the belief structure can be defined as follows:

$$\mathrm{B}_{ij} = \left\{ \left(\beta_{ij}^{k}, s_k \right), \quad k = 0,\ldots,K \right\} \ \forall i, \forall j \tag{12.1}$$

$$\sum_{k=0}^{K} \beta_{ij}^{k} \leq 1 \quad \forall i, \forall j \tag{12.2}$$

where β_{ij}^{k} is the belief degree for ith country with respect to jth theme at s_k level.

In the proposed approach, all the collected data of countries related to themes are represented with the belief structure. Kabak and Ruan (2011a) suggests transformation formulas for linguistic terms, interval value and numerical value evaluations. For the performance ratings of countries, the normalized ratings (r_{ij}) are transformed to belief degrees based on the membership functions associated to linguistic terms (μ_{s_k}) as follows:

$$\beta_{ij}^{k} = \mu_{s_k}\left(r_{ij}\right), \quad \forall k, \forall i, \forall j \tag{12.3}$$

For this transformation; triangular fuzzy numbers are used to define membership degrees related to linguistic terms based on standard linguistic hierarchical structures.

12.3.2 Calculation of the CBDs

After the data of countries related to themes is transformed to belief structures, CBDs for country i with respect to theme j is can be calculated as follows:

$$\mathrm{C}_{ij} = \left\{ \left(\gamma_{ij}^{k}, s_k \right), k = 0, \ldots, K \right\} \quad \forall i, \forall j \tag{12.4}$$

$$\gamma_{ij}^{k} = \sum_{p=k}^{K} \beta_{ij}^{p} \quad \forall i, \forall j \tag{12.5}$$

where γ_{ij}^{k} is the CBD for ith country with respect to jth theme at s_k level.

12.3.3 Aggregation of CBDs

After the information related to themes are combined as CBDs, they are aggregated to find the total sustainable development performance of each country. In most of such methods, subjective weights provided from expert judgments are used to represent the importance of the indicators. However, the elicitation of weights is a cognitively demanding task that is subject to different biases, and the elicited numbers can be heavily dependent on the method of assessment and the experts who makes the judgments (Riabacke et al. 2012). Therefore; in this study, an objective weighting procedure based on OWA (Order Weighted Averaging) operator is used to aggregate theme scores for each country. An OWA operator is defined as follows:

An OWA operator of dimension $(J - \Omega_i)$ is a mapping OWA: $R^{(J-\Omega_i)\times(K+1)} \rightarrow R^{K+1}$ that has an associated $(J - \Omega_i)$ vector $w = \left(w_1, w_2, \ldots, w_{(J-\Omega_\mathrm{i})}\right)$ such that $w_j \in [0, 1], j = 1, 2, \ldots, J - \Omega_i$ considering Ω_i is number of missing data of country i.

$$\sum_{j=1}^{J-\Omega_i} w_j = 1, \quad \forall i \tag{12.6}$$

$$OWA_{w}^{i,k}\left(\gamma_{i1}^{k}, \gamma_{i2}^{k}, \ldots, \gamma_{iJ-\Omega_i}^{k}\right) = \sum_{j=1}^{J-\Omega_i} w_j\, b_{ij}^{k}, \quad \forall i, \quad k = 0, 1, 2\ldots, K \tag{12.7}$$

where b_{ij}^{k} is the jth ranked γ_{ij}^{k}, $\forall i, \forall k$.

The most important issue in the OWA operator is to determine its associated weights. In this study, the following equations are used to generate OWA weights (Kabak and Ruan 2011b).

$$\upsilon_1 = 1.$$

$$\upsilon_j = \upsilon_{j-1}\alpha, \quad j = 2, 3, \ldots, (J - \Omega_i) \tag{12.8}$$

$$w_j = \frac{\upsilon_j}{\sum_{j=1}^{J-\Omega_i} \upsilon_j}, \quad \forall i \tag{12.9}$$

In these formulas, the higher values of α becomes, the higher weights of the low scores are, and the more α approaches to 0, the more weights of the high scores are. OWA operators are classified based on their location between *and* and *or*. A measure of *orness* in a unit interval is introduced for the classification (Yager 1988). If *orness* of an operator approaches to 1, it behaves like an *or* operator, while if *orness* approaches to 0, the operator behaves like an *and* operator. *Orness* of the proposed weight set is defined as follows (based on Yager 1988).

$$orness(W) = \sum_{j=1}^{J-\Omega_i} ((J - \Omega_i) - j)w_j, \quad \forall i \tag{12.10}$$

The key point here is to determine *orness* value. In this study, *orness* is selected as 0.25 to give more importance to lower indicator scores and less importance to higher indicator scores because of the structure of the sustainable development problem.

Finally, total sustainable development performance of *i*th country at s_k linguistic term set level γ_i^k is shown as follows:

$$\mathrm{C}_i = \left\{ \left(\gamma_i^k, s_k\right), \quad k = 0, \ldots, K \right\}, \ \forall i \tag{12.11}$$

where $\gamma_i^k = OWA_w^{i,k}\left(\gamma_{i1}^k, \gamma_{i2}^k, \ldots, \gamma_{iJ-\Omega_i}^k\right)$.

12.3.4 Interpretation of Resulting CBDs

In this study, two approaches are used to compare the sustainability of countries. The first approach is rank ordering of countries according to a certain s_k level. CBD at s_k level is considered as the aggregated belief degrees of greater or equal terms of the related linguistic term. It gives a threshold level that is associated to the satisfaction of the sustainable development performance. In this study, s_3 (*good*) level is set as the threshold level. It represents the belief degrees of sustainable development performance of countries at least "good" level (i.e., sum of belief degrees of "good" and "very good").

The second approach is to assign expectation values for the linguistic terms to aggregate them. For this approach, suppose that ω_k indicates an expectation value for the linguistic term s_k, and then the aggregated score (AS) for each country that gives the total expectation can be found by the following formula (based on (Kabak and Ruan 2011a):

$$AS_i = \sum_{k=0}^{K} \omega_k \left(\gamma_i^k - \gamma_i^{k+1}\right), \quad \forall i \tag{12.12}$$

where γ_i^k indicates total sustainable development performance of ith country at s_k linguistic term set level. If any other weighting scheme is not suggested, expectation values can be considered as $\omega_k = k, \;\; k = 0, \ldots, \mathrm{K}$.

12.4 Measuring Sustainable Development Performance of Countries

While measuring the sustainability of countries using the CBDs approach, initially, data required for evaluation are collected and normalized. Then the normalized data is transformed to belief degrees and CBDs, respectively. Finally, CBDs for the indicators are aggregated to a single CBD structure that represents the sustainable development performance of a country.

12.4.1 Data Collection and Normalization

After the specification of the indicators for measuring sustainable development performance as mentioned in Sect. 12.2, required data related to the indicators are collected from world wide databases (see Table 12.2 for the sources of indicator data). While collecting the data sets, data series of the indicators for the recent years are examined. Since the number of available data in the year 2013 is higher compared to the years 2014 and 2015, all the indicator data of the countries are collected for the year 2013. Although the proposed methodology can deal with the missing data, if the number of missing values for a country is high, the results will not reflect the true performance of the country. Therefore, we have selected the countries that have at least 21 indicator data (out of 27 indicators) for the assessment. A total number of 138 countries are selected in this way.

To obtain comparable scales for the indicators, they are normalized to dimensionless units. The data are normalized to [0, 1] interval according to minimum and maximum scores and type of indicator using the following equations:

$$r_{ij} = \left(x_{ij} - Min_j\right) / \left(Max_j - Min_j\right) \quad \text{for benefit indicators} \tag{12.13}$$

$$r_{ij} = \left(Max_j - x_{ij}\right) / \left(Max_j - Min_j\right) \quad \text{for cost indicators} \tag{12.14}$$

where x_{ij} is value of indicator j for country i, and r_{ij} is the corresponding normalized value. Max_j and Min_j are maximum and minimum values of indicator j, respectively. Notice that to get a less skewed distribution of the normalized data, outliers are not considered in setting maximum or minimum values. To illustrate the normalization; normalized indicator values and theme scores of Turkey are given in Table 12.3. For instance, normalized value for indicator 1.1 is calculated using Eq. 12.13 as follows:

$$r_{TR,1.1} = (6.1 - 2.5)/(8.5 - 2.5) = 0.600.$$

Then theme scores are calculated as the average of the normalized values of the indicators in the related theme. For instance; Theme 2 score is calculated as the average of normalized values of indicators 2.1, 2.2, 2.3, and 2.4. If one indicator represents a theme, its score is considered as the theme score.

12.4.2 Transformation of the Data to the Belief Structure and Calculation of the CBDs

To apply the proposed methodology, the normalized theme scores are transformed to belief structures using Eq. 12.3. For instance, the performance rating for Turkey with respect to 2nd theme is equal to 0.484. According to the triangular fuzzy sets in Fig. 12.1, membership degrees are found as follows:

$$\mu_{s_1}(0.484) = 0.06, \mu_{s_2}(0.484) = 0.94, \mu_{s_0}(0.484) = \mu_{s_3}(0.484) = \mu_{s_4}(0.484) = 0$$

Thus, corresponding belief structure is $\{(0.06, s_1)(0.94, s_2)\}$.

After the normalized scores are transformed to belief structures for each country, CBDs for country i with respect to theme j is calculated using Eq. 12.5. For instance, the belief structure of Turkey with respect to 2nd theme is transformed to CBD as $\{(1, s_0), (1, s_1), (0.94, s_2), (0, s_3), (0, s_4)\}$. Belief degrees and CBDs related to all themes for Turkey are given in Table 12.4.

12.4.3 Aggregation of CBDs

In order to aggregate the CBDs of a county's scores from 20 themes, OWA based operator is used. OWA weights are calculated for each country according to number of the available data for that country. For Turkey, for instance, data for all themes are available, therefore the OWA weights presented in Table 12.5 are used setting

Table 12.3 List of indicators and Turkey's data related to each indicator

Theme	Indicator	Indicator type*	Max	Min	Indicator value	Normalized value	Theme score
TH1	IND 1. Life satisfaction	+	8.5	2.5	6.1	0.600	0.600
TH2	IND 2.1 Final consumption expenditure per capita	+	63266.8	232.6	9427.7	0.146	0.484
	IND 2.2 Official development assistance received per capita	−	479.8	−6.7	36.5	0.911	
	IND 2.3 Gini index	−	63.9	25.0	40.0	0.614	
	IND 2.4 Gender Gap Index	+	0.9	0.5	0.6	0.264	
TH3	IND 3.1 Diabetes prevalence	−	21.2	1.5	14.8	0.325	0.662
	IND 3.2 Prevalence of undernourishment	−	40.2	5.0	5.0	1.000	
TH4	IND 4. Life expectancy at birth	+	83.0	50.0	75.0	0.758	0.758
TH5	IND 5. Unemployment rate	−	27.6	0.3	9.9	0.648	0.648
TH6	IND 6. Higher education and training	+	6.3	2.0	4.3	0.535	0.535
TH7	IND 7. Slum population as percentage to urban	−	88.2	5.5	11.9	0.923	0.923
TH8	IND 8. Working hours	−	54.0	27.4	46.9	0.267	0.267
TH9	IND 9.1 Organized crime	−	6.9	2.4	4.6	0.503	0.471
	IND 9.2 Reliability of police services	+	6.7	1.9	4.0	0.439	
TH10	IND 10. Bird species threatened	−	113.0	1.0	14.0	0.884	0.884
TH11	IND 11. Annual freshwater withdrawals per capita	−	1.1E−06	8.6E−09	5.3E−07	0.650	0.650
TH12	IND 12. PM2.5 Air pollution	−	100.0	8.4	97.6	0.026	0.026
TH13	IND 13. Total GHG emissions	−	2887.1	−19.0	390.9	0.859	0.859
TH14	IND 14. Energy use per capita	−	795.0	1.0	1.6	0.999	0.999
TH15		−	26.7	0.0	0.2	0.992	0.992

(continued)

Table 12.3 (continued)

Theme	Indicator	Indicator type*	Max	Min	Indicator value	Normalized value	Theme score
	IND 15. Domestic material consumption per capita						
TH16	IND 16. Transparency	+	6.1	2.6	4.6	0.557	0.557
TH17	IND 17. Voter turnout	+	1.0	0.2	0.9	0.841	0.841
TH18	IND 18. Gross capital formation	+	53.0	10.0	21.0	0.256	0.256
TH19	IND 19.1 Company spending on R&D	+	6.0	1.9	3.1	0.300	0.388
	IND 19.2 University-industry collaboration in R&D	+	5.8	2.1	3.9	0.477	
TH20	IND 20. Total government debt	−	174.3	−67.6	34.1	0.580	0.580

*(+) benefit, (−) cost

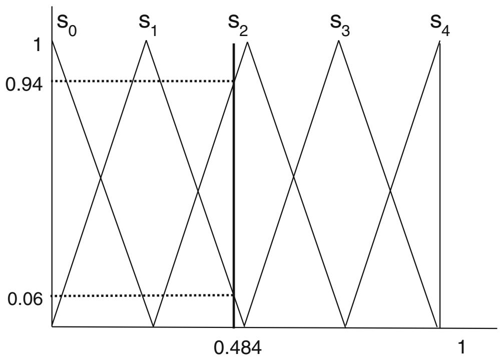

Fig. 12.1 Transformation of a performance rating to the belief structure

Table 12.4 Belief degrees and CBDs for Turkey

Theme	Normalized theme score	Belief degrees					Cumulative belief degrees				
		s_0	s_1	s_2	s_3	s_4	s_0	s_1	s_2	s_3	s_4
Theme 1	0.600	0	0	0.6	0.4	0	1	1	1	0.4	0
Theme 2	0.484	0	0.06	0.94	0	0	1	1	0.94	0	0
Theme 3	0.662	0	0	0.35	0.65	0	1	1	1	0.65	0
Theme 4	0.758	0	0	0	0.97	0.03	1	1	1	1	0.03
Theme 5	0.648	0	0	0.41	0.59	0	1	1	1	0.59	0
Theme 6	0.535	0	0	0.86	0.14	0	1	1	1	0.14	0
Theme 7	0.923	0	0	0	0.31	0.69	1	1	1	1	0.69
Theme 8	0.267	0	0.93	0.07	0	0	1	1	0.07	0	0
Theme 9	0.471	0	0.11	0.89	0	0	1	1	0.89	0	0
Theme 10	0.884	0	0	0	0.46	0.54	1	1	1	1	0.54
Theme 11	0.650	0	0	0.40	0.60	0	1	1	1	0.60	0
Theme 12	0.026	0.90	0.10	0	0	0	1	0.10	0	0	0
Theme 13	0.859	0	0	0	0.56	0.44	1	1	1	1	0.44
Theme 14	0.999	0	0	0	0	1.00	1	1	1	1	1.00
Theme 15	0.992	0	0	0	0.03	0.97	1	1	1	1	0.97
Theme 16	0.557	0	0	0.77	0.23	0	1	1	1	0.23	0
Theme 17	0.841	0	0	0	0.64	0.36	1	1	1	1	0.36
Theme 18	0.256	0	0.98	0.02	0	0	1	1	0.02	0	0
Theme 19	0.388	0	0.45	0.55	0	0	1	1	0.55	0	0
Theme 20	0.528	0	0	0.68	0.32	0	1	1	1	0.32	0

$\alpha = 1.16879$ in Eqs. 12.8 and 12.9 to obtain *orness* to be equal to 0.25. Notice that OWA operator associates weights to ranked scores instead of indicators in the classical weighting operators. Therefore, initially, CBDs are ranked for each linguistic level (i.e., s_1, s_2, …, s_4) then multiplied by the related OWA weight. The

Table 12.5 Aggregation of CBDs for Turkey

Rank	Ranked CBDs					OWA Weights	Weighted CBDs				
	s_0	s_1	s_2	s_3	s_4		s_0	s_1	s_2	s_3	s_4
# 1	1	1	1	1	1	0.008	0.008	0.008	0.008	0.008	0.008
# 2	1	1	1	1	0.97	0.009	0.009	0.009	0.009	0.009	0.009
# 3	1	1	1	1	0.69	0.011	0.011	0.011	0.011	0.011	0.007
# 4	1	1	1	1	0.54	0.012	0.012	0.012	0.012	0.012	0.007
# 5	1	1	1	1	0.44	0.015	0.015	0.015	0.015	0.015	0.006
# 6	1	1	1	1	0.36	0.017	0.017	0.017	0.017	0.017	0.006
# 7	1	1	1	1	0.03	0.020	0.020	0.020	0.020	0.020	0.001
# 8	1	1	1	0.65	0	0.023	0.023	0.023	0.023	0.015	0
# 9	1	1	1	0.60	0	0.027	0.027	0.027	0.027	0.016	0
# 10	1	1	1	0.59	0	0.032	0.032	0.032	0.032	0.019	0
# 11	1	1	1	0.40	0	0.037	0.037	0.037	0.037	0.015	0
# 12	1	1	1	0.32	0	0.043	0.043	0.043	0.043	0.014	0
# 13	1	1	1	0.23	0	0.051	0.051	0.051	0.051	0.011	0
# 14	1	1	1	0.14	0	0.059	0.059	0.059	0.059	0.008	0
# 15	1	1	0.94	0	0	0.069	0.069	0.069	0.065	0	0
# 16	1	1	0.89	0	0	0.081	0.081	0.081	0.072	0	0
# 17	1	1	0.55	0	0	0.095	0.095	0.095	0.052	0	0
# 18	1	1	0.07	0	0	0.111	0.111	0.111	0.007	0	0
# 19	1	1	0.02	0	0	0.129	0.129	0.129	0.003	0	0
# 20	1	0.10	0	0	0	0.151	0.151	0.016	0	0	0
						Score	1.000	0.865	0.563	0.190	0.044

resulting aggregate CBD for Turkey is calculated as $\{(1, s_0), (0.865, s_1), (0.563, s_2), (0.190, s_3), (0.044, s_4)\}$. CBDs related to all countries are calculated similarly.

12.4.4 Sustainable Development Performance of Countries

As a result; sustainable development performance of all 138 countries are measured in CBDs structure. See Table 12.6 for the sustainable development performance of selected countries. The results provided in CBDs can give more information regarding the performance of the countries. CBDs presented with distributions on linguistic levels enable to see the weak and strong aspects of a performance at the same time. According to the results, more than 50 % of their indicator scores of the first five ranked countries are at least "good" level. For Norway, for instance, 62 % of its indicator scores are at least "good". For the first three ranked countries, CBDs of "very poor" and "poor" levels are equal to 1, which indicates that these countries do not have any "very poor" performing indicators. For the 2nd ranked Sweden, 65 % of its indicator scores are at least "good", therefore if threshold level is set as

Table 12.6 Ranking of the selected countries with CBDs

Rank	Country	Aggregated score (AS)↓	s_0 Very poor	s_1 Poor	s_2 Fair	s_3 Good	s_4 Very good
1	Norway	2.75	1	1	0.95	0.62	0.19
2	Sweden	2.70	1	1	0.86	0.65	0.19
3	Finland	2.64	1	1	0.85	0.61	0.19
4	Denmark	2.42	1	0.97	0.84	0.49	0.12
5	Panama	2.37	1	1	0.89	0.39	0.09
10	United Kingdom	2.13	1	0.95	0.69	0.42	0.08
19	Australia	1.97	1	0.84	0.73	0.33	0.07
29	France	1.88	1	0.94	0.63	0.26	0.05
30	Germany	1.87	1	0.85	0.59	0.36	0.07
45	Turkey	1.66	1	0.86	0.56	0.19	0.04
46	Russian Fed.	1.65	1	0.98	0.50	0.14	0.02
49	Japan	1.62	1	0.75	0.57	0.25	0.05
51	Spain	1.62	1	0.84	0.53	0.20	0.05
56	Brazil	1.59	1	0.84	0.55	0.18	0.03
65	China	1.54	1	0.70	0.61	0.20	0.03
67	Romania	1.54	1	0.85	0.47	0.18	0.04
80	Bulgaria	1.43	1	0.84	0.43	0.12	0.04
101	United States	1.31	1	0.68	0.40	0.18	0.05
103	Serbia	1.30	1	0.79	0.39	0.09	0.04
107	India	1.25	1	0.69	0.48	0.06	0.01
127	Greece	1.02	1	0.54	0.31	0.11	0.05
134	Sierra Leone	0.87	1	0.45	0.22	0.14	0.05
135	Angola	0.80	1	0.48	0.22	0.08	0.02
136	Chad	0.77	1	0.40	0.27	0.07	0.04
137	Haiti	0.76	1	0.49	0.16	0.07	0.03
138	Mauritania	0.69	1	0.44	0.17	0.06	0.03

"good", Sweden becomes the highest performer. The results for United States (US), ranked in 101st out of 138, are quite interesting. 68 % of its indicator scores are more than "poor" that means that 32 % of its performance is "very poor" while 18 % of its indicator scores are more than "good". This results show that US has not only "good" indicators but also "very poor" indicators. For Turkey, 56 % of its performance is more than or equal to "fair", which may be considered as an acceptable performance.

For comparison purposes, AS and CBD at s_3 level of countries are calculated. See Appendix for the ranking of all countries. The rankings obtained by the proposed methodology are similar to the results of RobecoSAM (2015), which evaluates 60 countries on a broad range of environmental, social and governance factors. Top performing countries are Scandinavian countries: Norway, Sweden, Finland, and Denmark. European countries along with Panama and New Zealand constitute the top 10. The ranks of the economically powerful countries are disappointing: Germany ranked 30th, Japan 49th, Russian Federation 46th, China 65th, US 101st, and India 107th. Only United Kingdom, 10th, is performing well. Compared to the other European countries, the countries in Southeast Europe perform surprisingly low: Albania 112th, Bulgaria 80th, Greece 127th, Moldova 110th, Macedonia 92th, Montenegro 52nd, Romania 67th, and Serbia 103th. Two central American countries, Panama 5th, and Costa Rica 11th performs well.

12.5 Conclusions

This chapter proposes a CBDs approach for measuring sustainable development of countries. In this respect, we have collected data for the indicators to measure the 20 themes recommended in UNECE (2014). One of the main problems in such an evaluation is the missing data for the indicator values of the countries. The proposed CBDs approach deals with the missing data problem by taking into account only the available data and assigning OWA weights accordingly. One other strong feature of the proposed approach is the presentation of the results in CBDs with distributions to linguistic terms. By this way, more information related to the sustainable development performance of a country can be provided to decision makers. For comparison purposes a single performance value can also be obtained based on the resulting CBDs.

The resulting CBDs and AS related to the sustainable development performance of countries can be used for assisting policy makers on their decisions to reach sustainable development goals. For this aim, comparative analysis can be conducted for a specific country to benchmark similar or high performing countries. Moreover, if the performances of the countries are calculated through the years, countries can track their progress and develop policies accordingly.

As a further study, sensitivity analysis can be conducted to test the validity and robustness of the methodology. For this aim, methodology can be applied to a smaller set of countries. For instance, only European countries can be selected and ranked or irrelevant countries (e.g., last 20 in the ranking) are eliminated from evaluation. Different OWA weight sets can also be tried to investigate the effect of the weights on the evaluation.

Appendix: Sustainable Development Performance of Countries

Rank	Country	Aggregated score (AS)	s_3 level (rank)	Rank	Country	Aggregated score (AS)	s_3 level (rank)
1	Norway	2.754	0.619 (2)	70	South Africa	1.523	0.136 (83)
2	Sweden	2.702	0.65 (1)	71	Rwanda	1.520	0.126 (88)
3	Finland	2.642	0.607 (3)	72	Sri Lanka	1.514	0.118 (93)
4	Denmark	2.416	0.489 (4)	73	Italy	1.506	0.235 (33)
5	Panama	2.375	0.394 (12)	74	Bhutan	1.489	0.144 (74)
6	Iceland	2.225	0.404 (10)	75	Cabo Verde	1.475	0.182 (48)
7	Ireland	2.200	0.446 (6)	76	Bolivia	1.475	0.132 (85)
8	New Zealand	2.159	0.336 (15)	77	Ukraine	1.467	0.177 (52)
9	Switzerland	2.146	0.429 (8)	78	Colombia	1.456	0.148 (67)
10	United Kingdom	2.134	0.42 (9)	79	Namibia	1.453	0.098 (118)
11	Costa Rica	2.130	0.267 (24)	80	Bulgaria	1.427	0.121 (91)
12	Luxembourg	2.094	0.472 (5)	81	Dominican Republic	1.419	0.099 (117)
13	Austria	2.081	0.4 (11)	82	Zambia	1.419	0.056 (138)
14	Chile	2.064	0.263 (26)	83	Indonesia	1.416	0.159 (59)
15	Trinidad and Tobago	2.053	0.275 (23)	84	Iran, Islamic Rep.	1.415	0.144 (73)
16	Netherlands	2.043	0.433 (7)	85	Nepal	1.414	0.13 (87)
17	Estonia	2.004	0.304 (21)	86	Morocco	1.410	0.116 (96)
18	Malta	1.984	0.333 (16)	87	Cambodia	1.409	0.133 (84)
19	Australia	1.967	0.325 (18)	88	Peru	1.398	0.15 (64)
20	Mongolia	1.950	0.194 (43)	89	Bosnia and Herzegovina	1.397	0.103 (109)
21	Canada	1.950	0.264 (25)	90	Kuwait	1.392	0.17 (53)
22	Uruguay	1.938	0.241 (31)	91	Cameroon	1.381	0.146 (70)
23	Malaysia	1.937	0.243 (30)	92	Macedonia, FYR	1.378	0.102 (113)
24	Singapore	1.934	0.321 (19)	93	Uganda	1.372	0.1 (116)
25	Mauritius	1.932	0.166 (58)	94	Senegal	1.367	0.103 (111)
26	Oman	1.931	0.298 (22)	95	Algeria	1.366	0.19 (46)
27	United Arab Emirates	1.927	0.34 (14)	96	Vietnam	1.361	0.122 (90)
28	Belgium	1.894	0.329 (17)	97	Gabon	1.333	0.104 (107)
29	France	1.884	0.259 (27)	98	Malawi	1.331	0.138 (80)
30	Germany	1.868	0.356 (13)	99	Lebanon	1.330	0.149 (66)
31	Mexico	1.866	0.137 (82)	100	El Salvador	1.326	0.117 (94)

(continued)

(continued)

Rank	Country	Aggregated score (AS)	s_3 level (rank)	Rank	Country	Aggregated score (AS)	s_3 level (rank)
32	Israel	1.858	0.315 (20)	101	United States	1.308	0.182 (49)
33	Latvia	1.835	0.183 (47)	102	Tunisia	1.306	0.121 (92)
34	Nicaragua	1.825	0.191 (44)	103	Serbia	1.303	0.091 (123)
35	Kazakhstan	1.803	0.238 (32)	104	Liberia	1.301	0.104 (108)
36	Czech Republic	1.793	0.232 (34)	105	Paraguay	1.281	0.153 (62)
37	Philippines	1.768	0.124 (89)	106	Armenia	1.251	0.107 (103)
38	Guyana	1.768	0.117 (95)	107	India	1.248	0.06 (136)
39	Argentina	1.733	0.243 (29)	108	Georgia	1.246	0.107 (102)
40	Slovenia	1.716	0.205 (38)	109	Tanzania	1.240	0.076 (130)
41	Lithuania	1.712	0.166 (57)	110	Moldova	1.234	0.111 (101)
42	Korea, Rep.	1.694	0.217 (36)	111	Ethiopia	1.211	0.111 (100)
43	Jordan	1.678	0.168 (54)	112	Albania	1.196	0.057 (137)
44	Portugal	1.663	0.145 (71)	113	Gambia, The	1.195	0.114 (97)
45	Turkey	1.662	0.19 (45)	114	Myanmar	1.185	0.167 (56)
46	Russian Fed.	1.649	0.142 (77)	115	Pakistan	1.178	0.061 (135)
47	Honduras	1.641	0.196 (42)	116	Madagascar	1.172	0.09 (125)
48	Thailand	1.640	0.139 (79)	117	Burkina Faso	1.147	0.106 (104)
49	Japan	1.623	0.251 (28)	118	Azerbaijan	1.146	0.102 (112)
50	Slovak Republic	1.622	0.15 (65)	119	Benin	1.136	0.094 (119)
51	Spain	1.619	0.2 (40)	120	Kyrgyz Rep.	1.115	0.103 (110)
52	Montenegro	1.609	0.142 (76)	121	Bangladesh	1.096	0.102 (114)
53	Lao PDR	1.605	0.151 (63)	122	Yemen, Rep.	1.089	0.086 (127)
54	Saudi Arabia	1.602	0.168 (55)	123	Zimbabwe	1.086	0.101 (115)
55	Cyprus	1.596	0.229 (35)	124	Mali	1.075	0.106 (105)
56	Brazil	1.593	0.177 (51)	125	Mozambique	1.044	0.089 (126)
57	Jamaica	1.588	0.143 (75)	126	Lesotho	1.039	0.091 (124)
58	Venezuela, RB	1.577	0.156 (60)	127	Greece	1.018	0.113 (98)
59	Ecuador	1.576	0.137 (81)	128	Swaziland	1.007	0.093 (120)
60	Guatemala	1.573	0.208 (37)	129	Guinea	1.006	0.105 (106)
61	Suriname	1.571	0.132 (86)	130	Cote d'Ivoire	0.997	0.079 (128)
62	Ghana	1.562	0.146 (68)	131	Nigeria	0.946	0.091 (122)
63	Kenya	1.549	0.092 (121)	132	Egypt	0.921	0.063 (133)
64	Poland	1.542	0.2 (41)	133	Burundi	0.904	0.112 (99)
65	China	1.539	0.204 (39)	134	Sierra Leone	0.870	0.144 (72)
66	Hungary	1.537	0.155 (61)	135	Angola	0.796	0.077 (129)
67	Romania	1.536	0.182 (50)	136	Chad	0.772	0.068 (132)
68	Croatia	1.527	0.146 (69)	137	Haiti	0.756	0.07 (131)
69	Botswana	1.524	0.142 (78)	138	Mauritania	0.691	0.061 (134)

References

Acosta, L. A., Eugenio, E. A., Enano, N. H, Jr., et al. (2014). Sustainability trade-offs in bioenergy development in the Philippines: An application of conjoint analysis. *Biomass and Bioenergy, 64*, 20–41. doi:10.1016/j.biombioe.2014.03.015

Adamisin, P., Vavrek, R., & Pukala, R. (2015). Cluster analysis of central and Southeast Europe countries via selected indicators of sustainable development. In *SGEM2015 Conference Proceedings* (pp. 135–140).

Agenda 21. (1992). United Nations Conference on Environment & Development, New York.

Blancard, S., & Hoarau, J.-F. (2013). A new sustainable human development indicator for small island developing states: A reappraisal from data envelopment analysis. *Economic Modelling, 30*, 623–635. doi:10.1016/j.econmod.2012.10.016

Boggia, A., & Cortina, C. (2010). Measuring sustainable development using a multi-criteria model: A case study. *Journal of Environmental Management, 91*, 2301–2306. doi:10.1016/j.jenvman.2010.06.009

Bolcárová, P., & Kološta, S. (2015). Assessment of sustainable development in the EU 27 using aggregated SD index. *Ecological Indicators, 48*, 699–705. doi:10.1016/j.ecolind.2014.09.001

Country Sustainability Ranking | RobecoSAM. (2015) .http://www.robecosam.com/en/sustainability-insights/about-sustainability/country-sustainability-ranking/. Accessed May 4, 2016.

FAO. (2016). Food security indicators. http://www.fao.org/economic/ess/ess-fs/ess-fadata/en/#.Vyk0-nqvjB5. Accessed May 3, 2016.

Frini, A., & BenAmor, S. (2015). A TOPSIS multi-criteria multi-period approach for selecting projects in sustainable development context. In *2015 International Conference on Industrial Engineering and Operations Management (IEOM)* (pp. 1–9).

Golusin, M., & Ivanović, O. M. (2009). Definition, characteristics and state of the indicators of sustainable development in countries of Southeastern Europe. *Agriculture, Ecosystems & Environment, 130*, 67–74. doi:10.1016/j.agee.2008.11.018

Gustavson, K. R., Lonergan, S. C., & Ruitenbeek, H. J. (1999). Selection and modeling of sustainable development indicators: A case study of the Fraser River Basin, British Columbia. *Ecological Economics, 28*, 117–132. doi:10.1016/S0921-8009(98)00032-9

Hao, W., Xiaoling, C., Ying, H., et al. (2006). Modeling indicator systems for evaluating environmental sustainable development based on factor analysis. *Wuhan University Journal of Natural Sciences, 11*, 997–1002. doi:10.1007/BF02830200

Harris, J. M. (2000). Basic principles of sustainable development.

Healy, T. (2001). *Health promotion and social capital*. Galway: National University of Ireland.

Hsu, A., Rosengarten, C., Schwartz, J. D., & Alexandre, N. (2016). *2016 Environmental performance index*. New Haven, CT: Yale University.

Iddrisu, I., & Bhattacharyya, S. C. (2015). Sustainable energy development index: A multi-dimensional indicator for measuring sustainable energy development. *Renewable and Sustainable Energy Reviews, 50*, 513–530. doi:10.1016/j.rser.2015.05.032

ILO. (2016). LABORSTA internet: Main statistics (annual)—Hours of work (E). http://laborsta.ilo.org/applv8/data/c4e.html. Accessed May 3, 2016.

Ivanovic, O. D. M., Golusin, M. T., Dodic, S. N., & Dodic, J. M. (2009). Perspectives of sustainable development in countries of Southeastern Europe. *Renewable and Sustainable Energy Reviews, 13*, 2079–2087. doi:10.1016/j.rser.2009.03.004

Kabak, Ö., Cinar, D., & Hoge, G. Y. (2013). A cumulative belief degree approach for prioritization of energy sources: Case of Turkey. In F. Cavallaro (Ed.), *Assessment and simulation tools for sustainable energy systems* (pp. 129–151). London: Springer London.

Kabak, O., & Ruan, D. (2011a). A cumulative belief degree-based approach for missing values in nuclear safeguards evaluation. *IEEE Transactions on Knowledge and Data Engineering, 23*, 1441–1454. doi:10.1109/TKDE.2010.60

Kabak, Ö., & Ruan, D. (2011b). A comparison study of fuzzy MADM methods in nuclear safeguards evaluation. *Journal of Global Optimization, 51*, 209–226. doi:10.1007/s10898-010-9601-1

Layard, R. (2005). Happiness: Lessons from a new science.

Lomas, J. (1998). Social capital and health: Implications for public health and epidemiology. *Social Science and Medicine, 47*, 1181–1188. doi:10.1016/S0277-9536(98)00190-7

Meadows, D. H., Club of Rome. (Eds.). (1972). *The limits to growth*. New York: Universe Books.

Munda, G. (2005). "Measuring Sustainability": A multi-criterion framework. *Environment, Development and Sustainability, 7*, 117–134. doi:10.1007/s10668-003-4713-0

Nationen, V. (Ed.). (2015). Work for human development. New York, NY: United Nations Development Programme.

Nordhaus, W. D., & Tobin, J. (1973). Is growth obsolete? In *NBER Chapters* (pp. 509–564).

Parris, T. M., & Kates, R. W. (2003). Characterizing and measuring sustainable development. *Annual Review of Environment and Resources, 28*, 559–586. doi:10.1146/annurev.energy.28.050302.105551

Riabacke, M., Danielson, M., & Ekenberg, L. (2012). State-of-the-art prescriptive criteria weight elicitation. *Advances in Decision Sciences, 2012*, 1–24. doi:10.1155/2012/276584

Rockström, J., Steffen, W., Noone, K., et al. (2009). A safe operating space for humanity. *Nature, 461*, 472–475. doi:10.1038/461472a

Schwab, K., & Sala-i Martín, X. (Eds.). (2015). World economic forum's global competitiveness report, 2015–2016.

Soubbotina, T. P. (2004). *Beyond economic growth: An introduction to sustainable development* (2nd ed.). Washington: The World Bank.

Stiglitz, J. E. (2009). Report by the Commission on the Measurement of Economic Performance and Social Progress.

UNECE. (2014). United Nations Economic Commission for Europe. *Conference of European Statisticians Recommendations on Measuring Sustainable Development*. New York: Geneva. http://www.unece.org/fileadmin/DAM/stats/publications/2013/CES_SD_web.pdf

United Nations. (Ed.). (2007). Indicators of sustainable development: Guidelines and methodologies (3rd ed.). New York: United Nations.

Waas, T., Hugé, J., Verbruggen, A., & Wright, T. (2011). Sustainable development: A bird's eye view. *Sustainability, 3*, 1637–1661. doi:10.3390/su3101637

Wackernagel, M., & Rees, W. E. (1996). *Our ecological footprint: Reducing human impact on the earth*. Gabriola Island, BC; Philadelphia, PA: New Society Publishers.

World Bank. (2016). World development indicators 2016. http://data.worldbank.org. Accessed May 4, 2016.

World Commission on Environment and Development. (Ed.). (1987). Our common future. Oxford, New York: Oxford University Press.

Yager, R. R. (1988). On ordered weighted averaging aggregation operators in multicriteria decisionmaking. *IEEE Transactions on Systems, Man, and Cybernetics, 18*, 183–190. doi:10.1109/21.87068

Chapter 13
Sustainable Supply Chains and Risk Management for E-Commerce Companies Using Fuzzy Inference System

Sultan Ceren Oner and Basar Oztaysi

Abstract Risk management has become a significant issue for enterprises due to the increasing global trading. In this constantly changing economic environment, it could be very hard to focus on a specific purpose and monitor the entire supply chain. This paper describes possible supply chain risk factors in which both physical objects and information are taken into account by considering the whole e-commerce elements. In modeling process, rule based fuzzy inference system approach is applied by the virtue of the dynamic structure of sustainable supply chain. The conceptual model consists of three tiers of critical decision making elements in e commerce; supplier, manufacturer and retailer. Describing the relations between input and output variables, model intends to monitor the minimization of different kinds of risk and maximization of the entire system performance.

13.1 Introduction

Supply chain management is a continuous and integrated process that begins with attaining the raw material and ends up the final customer's purchasing goods or final customer after-sales service (Giannakis and Louis 2010). Hence, supply chain management includes not only suppliers, manufacturers and retailers' own activities, but also the relations between these elements (Özbayrak et al. 2007). First of all, supply chain behavior is altering continuously in accordance with different players. For instance, supplier's main objective for selling raw material or semi-finished product is to make a better profit while the manufacturer aims to take the material in a cheap way. In addition to the diverse purposes, supply chains are

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affected from the realities of world events that cause uncertainties (Nagurney et al. 2005). External factors such as tax regulations, high inflation rates, final customer demand etc. give rise to indefiniteness and high risk potential in supply chains. To include all of the external and internal factors, sustainable supply chain management must consider the relations between various supply chain phases supported with proper input and output variables (Kull and Talluri 2008).

In this dynamic environment, supply chain members should think about other supply chain members' decisions and make contacts for coordination mechanism and external economic or environmental factors that could affect the whole chain (Su et al. 2015). Therefore, Ritchie and Brindley (2007) referred a centralized supply chain risk management model for accurate decision making. Besides that, risk management and defining risk performance criteria become a major element for supply chain activities. In this respect, Ritchie and Brindley (2007) proposed a supply chain risk management concept consists of five components: Risk triggers, risk management factors, decision making characteristics, risk management responses and performance outcomes. They emphasized that aggregated risk comprises of node concentric risk and chain diversified risk that are combined with risk management activities. According to Azaron et al. (2007) described uncertain parameters in supply chain such as demand, supply, processing, transportation, lack of material and capacity. Other risk factors could be given as financial risk, backlogged risk, overstock and out of stock risk and foreign indebtment risk (Sodhi and Tang 2009). Additionally, Ivanov et al. (2011) remarked risk control parameters as resource, lead time, capacity and inventory level. In accordance with Kull and Talluri (2008), supply chain risk consists of five factors: delivery lateness, over priced materials or goods, quality failures, confidence and flexibility problems.

Models used for various purposes in the literature generally utilized different optimization tools such as linear programming, stochastic modeling, ANP, SOM and deterministic modeling (Liang et al. 2012; Azaron et al. 2007; Kull and Talluri 2008: Pham et al. 2012) Because of the shortcoming of interpretation of the results, they do not provide sufficient information about system behavior (Hanafizadeh and Sherkat 2009). Additionally, some of the authors are also mentioned that there is a lack of the models that discuss interactions among the risk components should be viewed (Ritchie and Brindley 2007; Nagurney et al. 2005; Chatzidimitriou et al. 2008). Due to the emerging and dynamic virtual relations between supply chain members, models should acquire sudden changes and cope with uncertainties and provide continuous monitoring. From the point of this view, fuzzy based models that formulize supply chain elements could cope with the difficulties such as instant variations and continuous monitoring of the entire system (Ngai and Wat 2004). In addition to the static structure, interactions and variations could not be shown in mathematical modeling. Therefore, models such as fuzzy ANN, ANP and DEMATEL are more suitable for determining causal relationships and control parameters that have direct influence on system behavior.

The paper focuses on showing the most non-negligible risk factors of the sustainable supply chain that consists of three tiers: supplier, manufacturer and retailer for e-commerce firms. In addition to this, relations among the risk factors and risk areas are presented by fuzzy inference system approach by synthesizing of previous studies to extract proper rules.

This study is organized as follows: In Sect. 13.2, brief information is given for the understanding supply chain risk management and risk factors. In Sect. 13.3, fuzzy inference system and the role of fuzzy inference system in supply chain risk management is mentioned. Section 13.3 also presents the rule based formulization of the proposed model. A sensitivity analysis is applied for the validation of the model in Sect. 13.4. The paper comes to an end in Sect. 13.5, in which summary of the study and suggestions of future research are presented.

13.2 Sustainable Supply Chain Management and Risk Factors

As mentioned above, supply chain management is a process that comprises of raw material procurement from its source, processing raw material in manufacturing and distribution of the finished goods or post-sales services to the final customer. Additionally, supply chain management is a paradigm that aspires to the integration of the entire chain by controlling and monitoring information and material flow (Nagurney et al. 2005).

Supply chain has been in the focus of academic researches and there are various papers in the literature (Tan 2001; Cevik and Ates 2008; Cevik Onar 2012; Gunesekaran 2012; Cevik Onar et al. 2013; Oztaysi et al. 2013; Brandenburg et al. 2014; Oztaysi and Isik 2014; Bolturk and Oztaysi 2014; Oztaysi and Surer 2014; Wang et al. 2015). In recent years, supply chain management progresses to effective management approach that regards instable external factors and interactions among them rather than supply chain planning. This new paradigm was named "sustainable supply chain risk management". The main question is how key performances interact with each other and how these interactions affect the whole system (Özbayrak et al. 2007). From this point of view, risk management and assessment for supply chains becomes significant. With respect to Ngai and Wat (2004), there is a need and absence of companies' overall risk level evaluation in the literature.

Although "risk" has no agreed universe definition, it can be described as "the possibility of loss or failure" (Ngai and Wat 2004). Correspondingly to this definition, risk originates three components: the information of loss-making event, the probability of existing risk and the effect of the event (Ellegard 2008). Risk management is a systematic way of management includes determining uncertainties and processes that could cause failures and troubles in a system and monitoring these processes and indicators continuously (Lavastre et al. 2012). In this sense, supply chain risk management should incorporate financial risks which implies cost and profit balance, demand uncertainty and fluctuation which causes butterfly effect, inventory level risk which infers over or under stock level and finally, tardiness and delays in supply chain (Sodhi and Tang 2009; Kull and Talluri 2008; Gunasekaran et al. 2002). According to Giannakis and Louis (2010), demand fluctuation, inventory risk and delays risk should be evaluated with profit maximization in supply chain risk management process. Also, Georgiadis and Michaloudis (2012) and Tesfamariam and Lindberg (2005) claimed that high rate of cancelations, new orders, long lead times and machine breakups should be considered. Azadeh and Alem (2010) affirmed that uncertain demand, unexpected prices, indefinite lead and delivery times could be risk parameters for a supply chain. Kull and Talluri (2008) added quality, cost, reliability and flexibility risk types for entire supply chain besides demand, delays and inventory risk. Finally, Ellegard (2008)'s risk factors such as logistics risk which means delays risk indirectly and capacity risk which denotes supplier could not satisfy orders could also be evaluated as risk criteria when determining whole supply chain risk. Recent studies in supply chain risk management are listed in Table 13.1.

Sustainable supply chain risk management program in a company should be comprised of determination of risk factors, evaluation and prioritization of these factors with respect to environmental, economic and organizational specifications. The main purpose of constructing supply chain risk management is taking preventive actions in order to adopt the whole organization against sudden changes and uncertainties (Behret et al. 2011). According to ISO 31000, risk management procedure could be described as in Fig. 13.1.

Table 13.1 Recent studies in supply chain risk management

Topic	Study	Authors	Specific point of the study
Sustainability related risks	Supply chain sustainability: a risk management approach	Giannakis and Papadopoulos (2016)	FMEA based sustainable risk management methodology
	Corporate sustainability approaches and governance mechanisms in sustainable supply chain management	Formentini and Taticchi (2016)	Governance mechanisms for corporate sustainability
Alternative selection	Interpretive structural modeling-analytic network process integrated framework for evaluating sustainable supply chain management alternatives	Hussain et al. (2016)	Structural modeling-analytic network process
Sustainable supply chains	Sustainable supply chain management in emerging economies: environmental turbulence, institutional voids and sustainability trajectories	Silvestre (2015)	Supply chain learning
	Sustainable supply chain management when focal firms are complex: a network perspective	Frostenson and Prenkert (2015)	Retailer network and environment
Stock out and backordering	Hurdles in implementing sustainable supply chain management: an analysis of indian automobile sector	Luthra et al. (2015)	Genetic algorithm

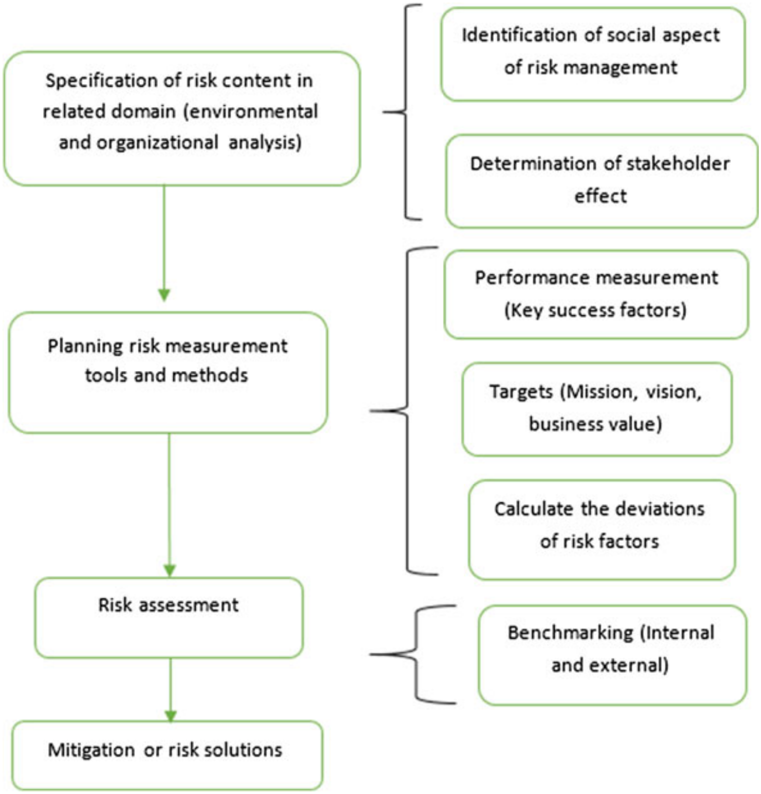

Fig. 13.1 Process of risk management according to ISO 31000

From the reflections of literature review, academic studies mainly focused on the development of risk management in supply chain critical parts that were determined by Forrester (1961), Morecroft (2007) and Campuzano and Mula (2011). Forrester (1961) analyzed four supply chain elements: manufacturer, distributor, retailer and wholesaler. In spite of Forrester, Campuzano and Mula (2011) only investigated manufacturer and retailer level. This paper is interested in both supply and demand side: supplier, manufacturer, retailer and final customer. In this respect, all critical parts of supply chain could be observed in a holistic view.

Recent studies generally emphasize on electronic commerce as a new supply chain channel. Low operational costs and simplified procedures are the main attractors of e-commerce channel use. Additionally, this channel helped increasing productivity in manufacturers and physical retailers' activities within a distribution system. (Lu and Liu 2015). Thus, supply chain risk management is getting more and more critical for both pure play and brick and mortar companies using e-commerce as an additional channel. Regarding the critical success and risk factors, an effective supply chain risk management should be considered for including

Table 13.2 Recent studies in e-commerce based sustainable supply chain risk management

Topic	Study	Authors	Specific point of the study
Dual channel supply chain	Effects of e-commerce channel entry in a two-echelon supply chain: a comparative analysis of single- and dual-channel distribution systems	Lu and Liu (2015)	Multi-channel marketing and distribution
	Pricing policies of a competitive dual-channel green supply chain	Li et al. (2016)	Pricing policies and channel coordination
	The effects of e-commerce on the demand for commercial real estate	Zhang et al. (2016)	Comparison of single and dual channels of the companies that uses e-commerce channel
E-commerce service platform	On the supply chain management supported by e-commerce service platform for agreement based circulation of fruits and vegetables	Bao et al. (2012)	Agreement based supply chain management
B2B e-commerce	B2B e-commerce supply chain integration and performance: a contingency fit perspective on the role of environment	Iyer et al. (2009)	Contingency theory
	A qualitative study of business-to-business electronic commerce adoption within the Indonesian grocery industry: a multi-theory perspective	Kurnia et al. (2015)	Technology adoption
Trade incentive programs	Designing e-commerce cross-border distribution networks for small and medium-size enterprises incorporating Canadian and U.S. trade incentive programs	Gessner and Snodgrassa (2015)	Cross border distribution

the balance between supply and demand sides (Zhang et al. 2016). Table 13.2 represents recent studies in e-commerce based sustainable supply risk management.

As shown in Fig. 13.2, total supply chain risk for e-commerce companies is a cumulative sum of supplier, manufacturer and retailer side risks. In other words, chain risk depends on retailer risk score, retailer risk is related to manufacturer risk and manufacturer risk is affected from supplier risk. Using this approach, risk management in enormous and complex supply chains could be implemented more effectively and sources of the problems should be carefully determined. Supply chain risk management subcomponents appeared in Fig. 13.2 are compiled from literature reviews and some of the essential variables stored in databases are represented in Table 13.3.

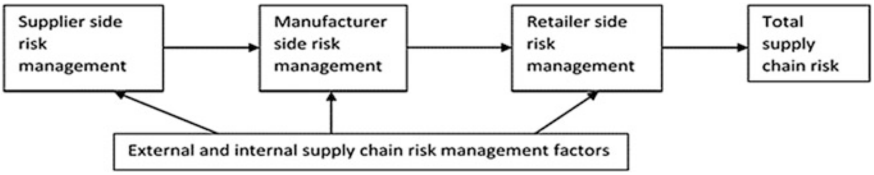

Fig. 13.2 Overall supply chain risk management system

Table 13.3 Supply chain risk management variables stored in databases for e-commerce firms

Supplier-retailer process variables	Lead time, order quantity, optimal order quantity, manufacturer delivery time, shipment capacity, order costs, raw material lead time, actual sales, quality, supplier raw material price and expected price, shipment frequency, transportation capacity, transportation costs
Manufacturer process variables	Planned production, labor capacity, machine capacity, the number of off workers, production times, time between machine failures, malfunction unit costs, production costs, transportation costs, transportation capacity, delayed goods quantity, the number of maintenances, manufacturer lead time, manufacturer order quantity, optimal order quantity, retailer delivery time, manufacturer shipment capacity, order costs, manufacturer actual sales, manufacturer quality, manufacturer finished good price and expected price, expected raw material price, manufacturer transfer capacity, retailer demands, defective goods rate, shipment frequency
Inventory control policy variables (for manufacturer, supplier and retailer levels)	ROP, over and out of stock levels, finished good—raw material—WIP inventory levels, desired inventory levels; stock unit rent cost, inventory costs
Demand strategy and policy variables (for manufacturer, supplier and retailer levels)	Order due date, service priority, order control policy, service policies, demand forecasting results, mass order discounts
External factors	Minimum market price

Figure 13.3 presents the combination of various risk factors extracted from literature reviews with final chain risk. With this respect, a powerful supply chain risk management model includes delays risk, demand fluctuation risk, quality risk and price fluctuation risk as total supply chain risk. Like in the previous papers, delays risk means not being able to satisfy customer needs on time. Secondly, demand fluctuation risk appears not being able to clearly forecast customer needs in advance. Besides, quality risk indicates that supplier could not send the finished goods in keeping with customer requirements. Finally, price fluctuation risk is the difference between

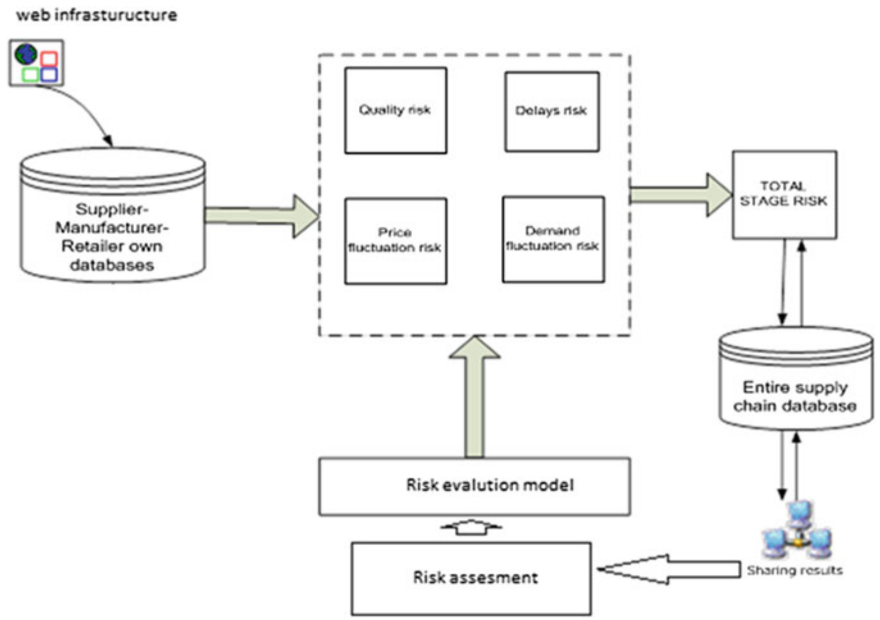

Fig. 13.3 Supply chain risk management system in e-commerce companies

expected price and actual price. As distinct from former studies, this model involves service level as a main indicator of total stage risk. In conclusion, all these risk factors comprise total stage risk appeared from service level which is effectuated by demand fluctuation risk, delays risk and indirectly from quality risk which constitutes actual sales in the model.

13.3 Supply Chain Management and Fuzzy Theory

13.3.1 Supply Chain Risk Management and Fuzzy Systems

As mentioned before, supply chain management is a continuous and integrated process that is triggered with procurement of the raw material and finishes with the final customer's purchasing goods or final customer after-sales service (Giannakis and Louis 2010) Thus, this system includes uncertainties which could cause risks. In order to cope with imprecise information appeared in supply chain processes, authors mainly emphasized on defining linguistic variables which provide the identification of the problem for continuous monitoring. With this respect, fuzzy based models which obtain membership functions between 0 and 1 enable the formulization of supply chain risk processes reflecting the instant variations as seen from Table 13.4. For instance, competitiveness of the companies could be modeled

Table 13.4 Recent studies for supply chain risk management based on fuzzy logic

Topic	Study	Authors	Specific point of the study
Assessing uncertainty	Assessing the competitive priorities within sustainable supply chain management under uncertainty	Lin and Tseng (2016)	Interval-valued triangular fuzzy number
Sustainable supplier selection	A new fuzzy DEA model for evaluation of efficiency and effectiveness of suppliers in sustainable supply chain management context	Azadi et al. (2015)	Fuzzy data envelopment analysis
Supply chain network	Robust and fuzzy goal programming optimization approaches for a novel multi-objective hub location-allocation problem: a supply chain overview	Ghodratnama et al. (2015)	Fuzzy goal programming
Green supply chain management (GSCM)	Risk analysis in green supply chain using fuzzy AHP approach: a case study	Mangla et al. (2015)	Fuzzy AHP
	Intuitionistic fuzzy based DEMATEL method for developing green practices and performances in a green supply chain	Govindan et al. (2015)	Intuitionistic fuzzy based DEMATEL method
	Application of fuzzy VIKOR for evaluation of green supply chain management practices	Rostamzadeh et al. (2015)	Fuzzy Vikor

using different types of fuzzy numbers (Lin and Tseng 2016). For supplier selection problems, fuzzy data envelopment analysis and fuzzy AHP methods are applicable on account of the determination of ambiguous priorities. In addition to that, fuzzy goal programming is really useful for following up and minimizing the deviations between actual and targeted values of risk factors. In some cases, intuitionistic fuzzy number based approaches introduce membership and non-membership values for explaining hesitancy in a specific problem.

13.3.2 *Fuzzy Inference Systems*

The underlying idea in fuzzy inference systems is to be able to use knowledge in terms of linguistic variables to match input variables with respect to the relation of output variables. (Mamdani 1974). The process is initiated with the determination of input and output variables and fuzzification of these variables in accordance with linguistic explanations. After then, the procedure proceeds to rule generation phase. Let x_i denotes input variables, y_i denotes output variables. Rules are specified using IF-THEN operator as follows:

$$IF\ ''x_1'' \ is\ \beta_i^1\ AND/OR\ ''x_2''\ is\ \beta_i^2\ AND/ \\ OR\ ''x_3''\ is\ \beta_i^3\ldots,\ THEN\ ''y_1''\ is\ \beta_i^n\ AND\ ''y_2''\ is\ \beta_i^{n+1} \quad for\ 1,2,\ldots i \tag{13.1}$$

where $n + 1$ input and output variables are included.

Next step includes fuzzy inference process construction. For extracting conclusion from given rules, Mamdani or Sugeno models could be applied (Behret et al. 2011). The main difference between these models is the utilization of training data. In Sugeno model, data training is essential for constructing membership functions by minimizing training error. On the other hand, Mamdani model requires to organizing rules one by one and rules are introduced with respect to expert knowledge. The fundamental step is the aggregation of membership functions and deduction method (minimization) is adopted to attain proper consequences. Finally, all outputs are integrated using maximization operator. Relevant process is explained in the following formulation:

$$\mu_\beta^n = \max_n \left[\min\left[\left[\mu_{\beta 1}^n(x_1), \mu_{\beta 2}^n(x_2), \ldots, \mu_{\beta n}^n(x_n) \right] \right] \right. \tag{13.2}$$

The last milestone for fuzzy inference systems is the defuzzification phase (Behret et al. 2011). Generally, Yager's center of gravity approach was utilized in order to defuzzify the aggregation results. Algebraic representation could be structured as follows:

$$x^* = \frac{\int \mu_\beta(x).x\,dx}{\int \mu_\beta(x)\,dx},\ \mathrm{x} \in \mathrm{X}\ , \tag{13.3}$$

As seen from previous section, supply chain risk management based studies could not cope with reflecting dynamic changes and uncertainties (Vanany et al. 2009) In imprecise environment, as seen in supply chain risk management, fuzzy logic assists fuzzy inference systems methodology by reflecting uncertainty, knowledge adaptation, linguistic expressions and explanation abilities. Thus, in the literature, fuzzy logic based studies have been increasing far and wide. At that point, fuzzy inference systems set a good example by the combination of the advantages of fuzzy logic and mathematical modeling. In addition to that, fuzzy inference system tries to handle problems by imitating the representation of input and output variables which enables learning from the inferences and acquires knowledge from the given data, as appeared in Sugeno model. As a consequence of that, computation and sensitivity studies for the knowledge expression of fuzzy systems provides maintainability. On the other hand, data modeling procedure takes considerable amount of time, inability of reaching global optima and defuzzification issues are the main problems of fuzzy inference systems. To sum up, fuzzy inference systems become more explicit, just as fuzzy systems become more practicable for learning from data training (Ayadi et al. 2013) (Table 13.5).

Table 13.5 Recent studies for fuzzy inference systems

Topic	Study	Authors	Specific point of the study
Information sharing	A decision support system assessing the trust level in supply chains based on information sharing dimensions	Ayadi et al. (2013)	Fuzzy inference based decision support system
Disaster management	Fuzzy inference systems for disaster response	Oztaysi et al. (2013)	Fuzzy rule based system for volunteer management in disaster response
Debt collection	Early collection system design using fuzzy rule based inference	Cevik Onar et al. (2014)	Fuzzy rule based system for possibility of payment
Supply chain risk management	A fuzzy-based integrated framework for supply chain risk assessment	Aqlan and Lam (2015)	Risk predictability based on fuzzy inference systems
	A fuzzy inference system for supply chain risk management	Behret et al. (2011)	Risk assessment of supply chains
	A software application for rapid risk assessment in integrated supply chains	Aqlan (2016)	Fuzzy inference systems with risk priorities
Supply chain management	Designing fuzzy-genetic learner model based on multi-agent systems in supply chain management	Hanafizadeh and Sherkat (2009)	SOM and genetic algorithm integrated fuzzy inference systems
	An adaptive multi-agent system for cost collaborative management in supply chains	Fu and Fu (2015)	Fuzzy inference system application for multi agent supply chains

13.4 Application

For measuring supply chain risk management with respect to e-commerce firms, identification of risk factors is the most important step. While determining risk factors, online processing of purchasing data is evaluated considering both manufacturer and retailer sides. Thus, lead time of retailer and manufacturer delay time are obtained in the purposed model for reflecting online processing and physical delivery. Additionally, manufacturer capacity, retailer inventory level and order quantity should be balanced. In order to monitor demand changes in a specific time period, change in order quantity becomes a key factor. For measuring quality satisfaction level, returned goods and inspection frequency are investigated. Finally, price-cost balance could be reflected with the comparison of minimum market price and unit cost. All these indicators assists the determination of quality risk, delay risk, price fluctuation risk and demand fluctuation risk as seen in Fig. 13.4. By aggregating the indicators, overall supply chain risk management for e-commerce firms could be reached.

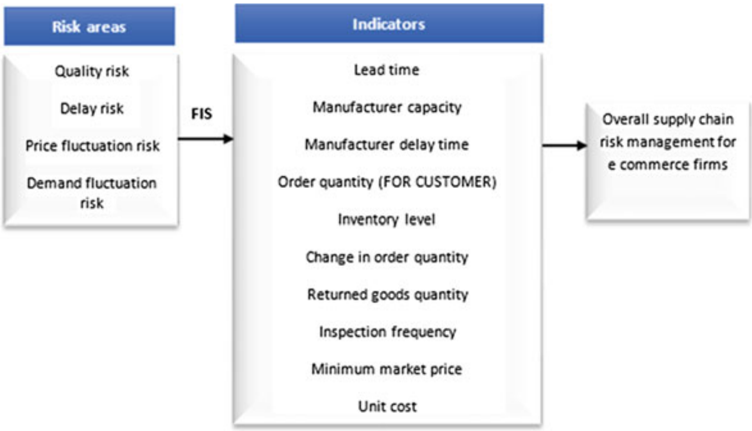

Fig. 13.4 Supply chain risk management methodology

Table 13.6 Input variables of fuzzy inference system

Input variables	Fuzzy variables	Fuzzy numbers
Lead time	High	(1.45, 1.8, 2)
Manufacturer capacity		
Manufacturer delay time		
Order quantity (for customers)	Medium	(1.2, 1.45, 1.65)
Inventory level		
Change in order quantity		
Returned goods quantity		
Inspection frequency	Low	(1, 1.2, 1.35)
Minimum market price		
Unit cost		

Note that all these variables should be normalized with respect to the given interval [1,2]

Table 13.7 Output variables of fuzzy inference system

Output variables	Fuzzy variables	Fuzzy numbers
Price fluctuation risk	High risk	(0.65, 0.80, 1)
Demand fluctuation risk	Medium risk	(0.3, 0.5, 0.75)
Delay risk	Low risk	(0, 0.2, 0.4)
Quality risk		

Note that all these variables should be normalized with respect to the given interval [0,1]

In application phase, a fuzzy inference system is adopted which begins with fuzzification step by identifying membership functions of input (indicators) and output (risk areas) variables with respect to linguistic definition. Input variables generally represent risk sources and cause the variation in output variables which indicates potential risks in supply chain. Linguistic variables are defined in triangular fuzzy numbers as given in Tables 13.6 and 13.7.

After defining linguistic variables in fuzzy numbers, fuzzy inference rules should be extracted by the analysis of the given system and relation between risk indicators. Fuzzy inference rules structured with respect to "If Then" rules and "and" and "or" operators could be used for reflecting the relation between input and output variables. To monitor the variation in risk areas, 33 rules are determined. By entering appropriate and logical rules, output values could be extracted. Some of the rules are given as follows:

IF "lead time" is high and "manufacturer delay time" is high, THEN "delay risk" is high, "demand fluctuation risk" is high, "price fluctuation risk" is medium and "quality risk" is high.
IF "manufacturer capacity" is low and "manufacturer delay time" is high, THEN "delay risk" is high, "demand fluctuation risk" is high, "price fluctuation risk" is medium and "quality risk" is medium.

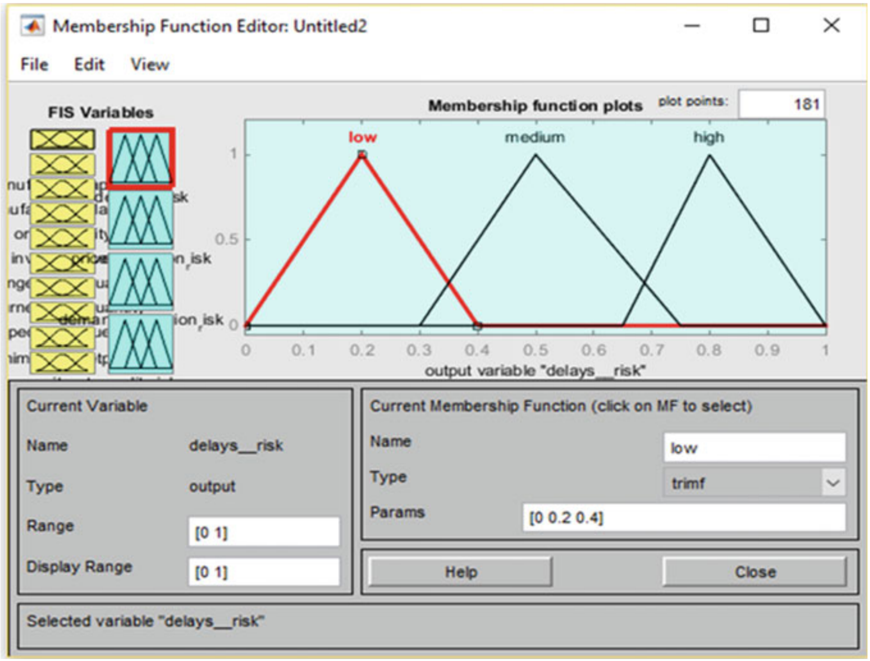

Fig. 13.5 FIS interface for the determination of membership function

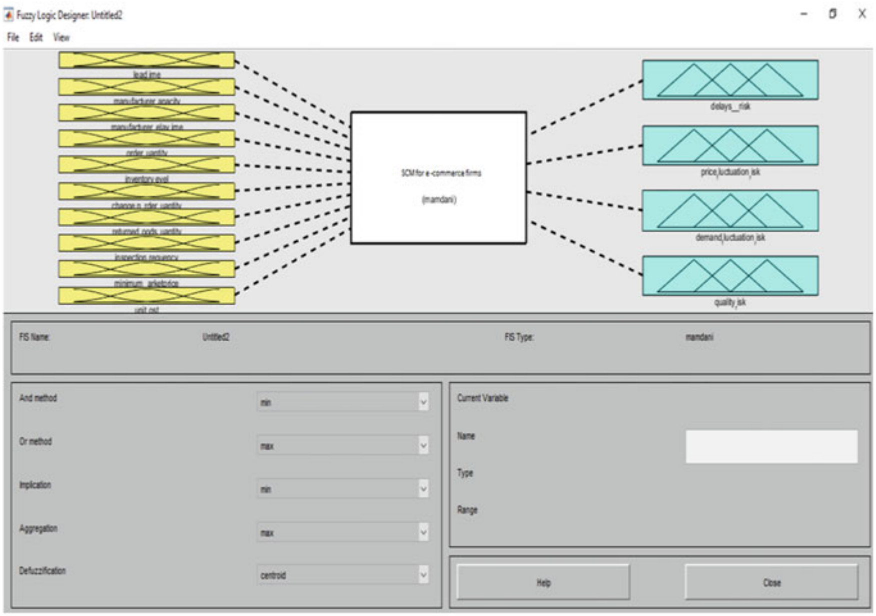

Fig. 13.6 FIS interface for supply chain risk management of e-commerce firms

Table 13.8 Input and output variables value for fuzzy inference system

Input	Risk value	Output	Risk value
Lead time	1.55	Price fluctuation risk	0.25
Manufacturer capacity	1.3	Demand fluctuation risk	0.33
Manufacturer delay time	1.38	Delay risk	0.68
Order quantity (for customer)	1.44	Quality risk	0.24
Inventory level	1.5		
Change in order quantity	1.2		
Returned goods quantity	1.2		
Inspection frequency	1.28		
Minimum market price	1.21		
Unit cost	1.3		

IF “order quantity” is high and “inventory level” is low, THEN “delay risk” is high, “demand fluctuation risk” is high, “price fluctuation risk” is medium and “quality risk” is medium.

Subsequent to the definition of fuzzy inference rules, fuzzy inference system is adopted. For this purpose, MATLAB Fuzzy Logic ToolboxTM is utilized and Mamdani method is preferred to extract outcomes given in Fig. 13.5.

FIS interface for supply chain risk management of e-commerce firms is presented in Fig. 13.6. For reflecting how fuzzy inference system works, input and output values are given as seen in Table 13.8. The risk areas are investigated with respect to high risk value in “lead time” and medium risk value in “manufacturer delay time”. According to the results, overall supply chain risk management for e-commerce firms’ value is gathered by applying arithmetic mean.

By applying arithmetic mean operator, overall risk value is found as 0.375 which could be evaluated as medium risk for the evaluation of overall risk. According to different values of input and output variables, overall supply chain risk value could appear in diversified levels.

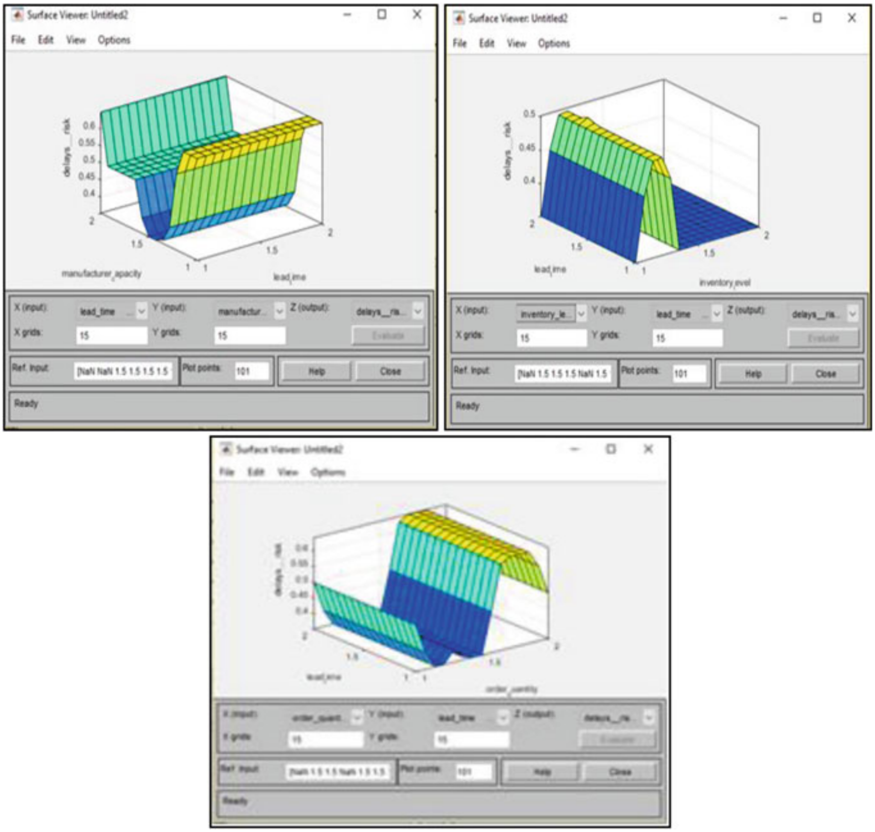

Fig. 13.7 Evaluation of delay risk with respect to different input factors

13.5 Three Dimensional Sensitivity Analysis and Discussion

Different tests are applied in order to prove the validity of the fuzzy inference rules. MATLAB Fuzzy Logic Toolbox TM Surface Viewer is utilized for 3D representation of the sensitivity of the purposed rules. Initially, delay risk-lead time and manufacturer capacity relation is evaluated. As seen in Fig. 13.7, *delay risk* and *lead time risk* directly effect each other and manufacturer capacity has adverse effect on delay risk. If the linguistic value of lead time is changed as (1.75, 1.85, 2), the contribution of lead time is dramatically increases. On the contrary, manufacturer capacity is not as sensible as lead time in this case. Similarly, if inventory level is considered as a critical factor, high values of inventory levels minimize delay risk. When economies of scale is taken into account, order quantity becomes substantial factor and optimal value of order quantity minimizes delay risk. If small changes are applied for the linguistic value of order quantity such as (1.22, 1.48, 1.54) subsequently, delay risk suddenly increases. This factor indicates the sensitivity of order quantity for delays risk.

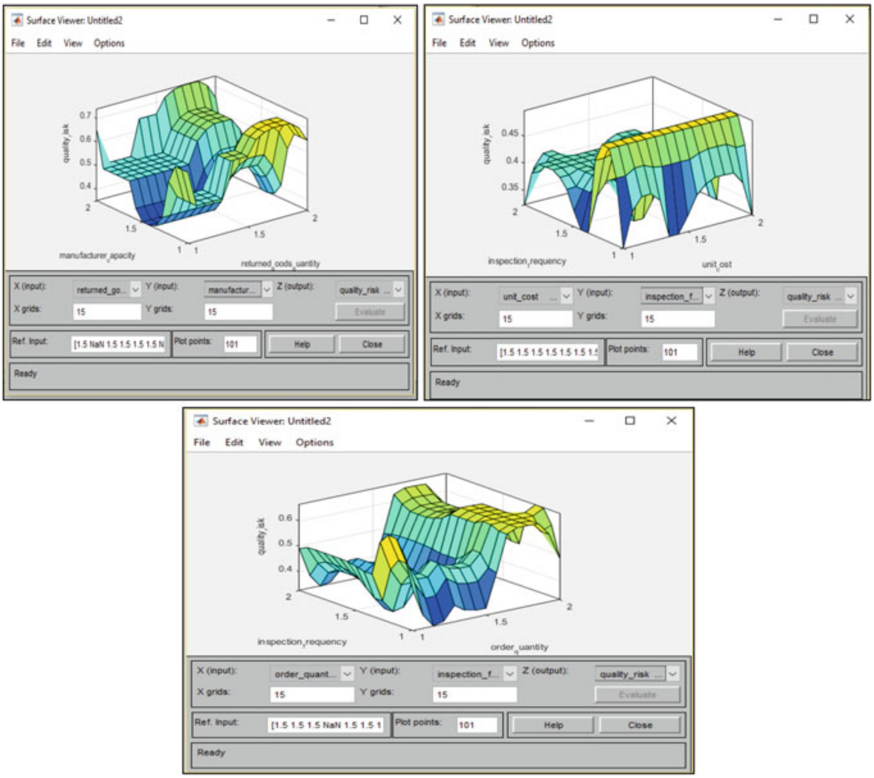

Fig. 13.8 Evaluation of quality risk with respect to different input factors

In addition, manufacturer capacity and returned goods quantity are other risk factors for the measurement of quality risk. In order to represent the contribution of returned goods quantity, different values (1.33, 1.65, 1.85) of linguistic variables (medium) are selected. If high values are recorded for returned goods quantity and low levels of inspection frequency, quality risk directly increases. Surprisingly, unit cost has not an important influence on quality risk for low levels and quality risk increases when related firm attains high level of unit cost. This situation generally occurs due to the ineffectiveness in cost management of production planning. Similarly, since inadequate balance of economies of scale, quality risk increases with high level of order quantity. Evaluation of quality risk with respect to different input factors is presented in Fig. 13.8.

Figure 13.9 presents the evaluation of price fluctuation risk with respect to minimum market price, unit cost, manufacturer capacity and change in order quantity. At this point, economies of scale and revenue-cost balance are highly important issues and e-commerce companies should optimize their supply chains

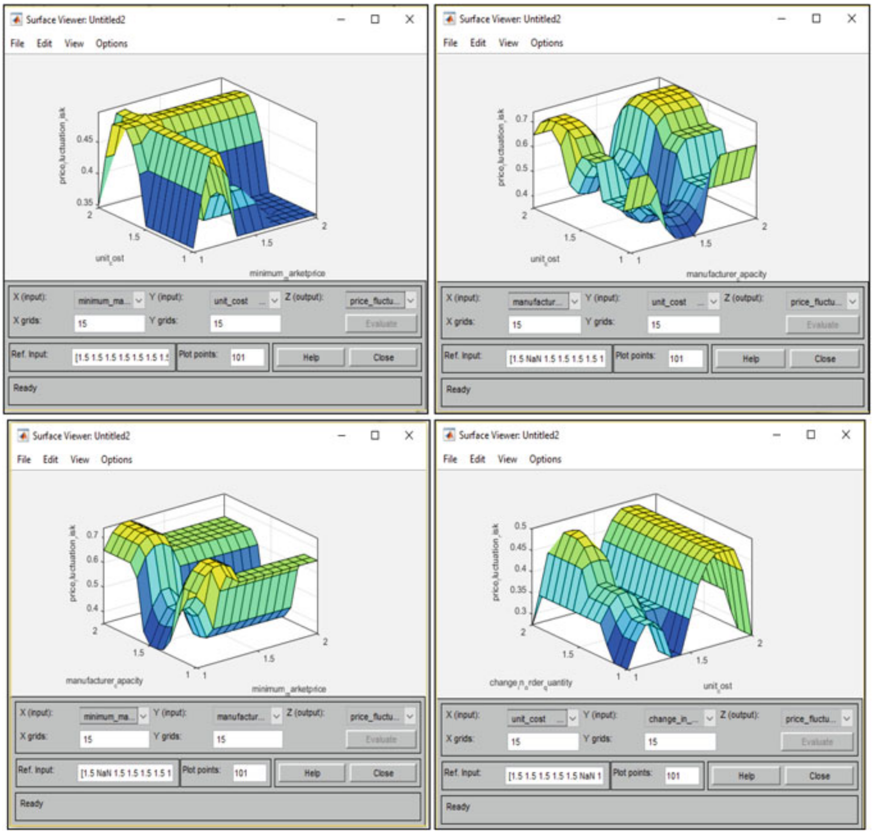

Fig. 13.9 Evaluation of price fluctuation risk with respect to different input factors

according to the order trends and production-transportation capacity. Thus, minimum market price and unit cost should be initially balanced. As seen from the following figure, high level of unit cost and low level of minimum market price cause high level of price fluctuation risk and high level of manufacturer capacity and high level of change in order quantity occur out of control situation in the management of economies of scale. If these variables are all fixed in lower levels such as (1, 1, 1.12), again price fluctuation risk appears. In this case, optimal value of unit cost and manufacturer capacity should be adopted in accordance with minimum market price and change in order quantity.

Figure 13.10 demonstrates the assessment of demand fluctuation risk considering lead time, order quantity, change in order quantity, manufacturer delay time and inventory level. Again, optimal level of order quantity provides lower demand fluctuation risk. Lead time does not directly influence demand variations. Moreover, if manufacturer delay time and order quantity are stated at a lower level such

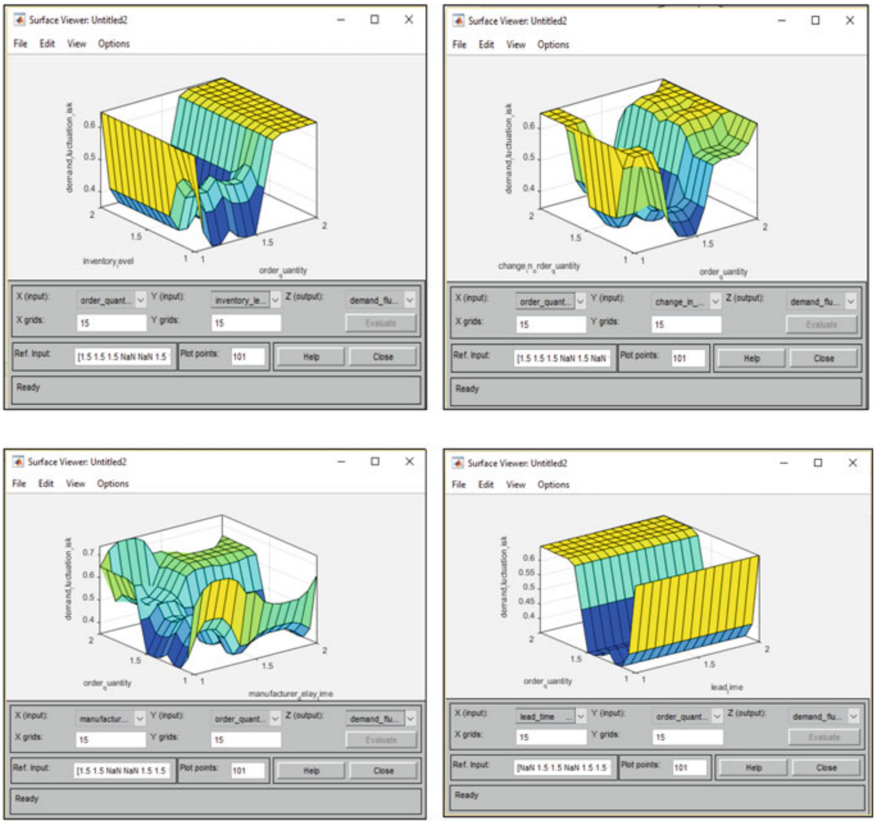

Fig. 13.10 Evaluation of demand fluctuation risk with respect to different input factors

as (1, 1, 1.15), demand variations still appear. Both high and low levels of order quantity and change in order quantity have significant reflection to demand variety.

In conclusion, this study ensures the assessment of diversified supply chain risk factors and investigates the risk sources with rule based fuzzy inference system for e-commerce firms. The contributions could be sequentially given as (a) Determination of risk sources and levels with the consideration of linguistic definitions, (b) Relations between variables are listed with rule based approach (IF-THEN rules), (c) Sensitivity analysis is performed for the validation of purposed rules. Results indicate that optimality of order quantity and manufacturer capacity satisfy acceptable levels of risk. Additionally, cost-revenue balance provides environmental-organizational adaptation of e-commerce firm in order to cope with the tight race of assuring convenient price to the end customer. Finally, one could conclude that future work could be implemented by regarding more critical risk factors as input variable. Additionally, online information sharing process should be investigated in details rather than presenting this concept physically which is hard to reflect into the model.

13.6 Conclusion

In this chapter supply chain risk management is evaluated with respect to diversified risk factors since it is one of the most important issues for sustainable supply chains. The study particularly focused on the e-commerce channel which is an emerging application area for supply chain. FIS is utilized in order to deal with the uncertainties inherented in an e-commerce supply chain.

The proposed FIS is composed of fuzzy rules where the input and output parameters are both represented by triangular fuzzy numbers. In the proposed FIS, Mamdani type inference is used in which the knowledge is obtained by extracting information thoroughly from experts. For further research, other type of inference systems are suggested based on data driven approaches including adaptive learning mechanisms such as Sugeno type inference system. FIS can also be used for other risk management issues such as project risk management, software risk management, and operations risk management.

References

Aqlan, F. (2016). A software application for rapid risk assessment in integrated supply chains. *Expert Systems with Applications, 43*, 109–116.

Aqlan, F., & Lam, S. S. (2015). A fuzzy-based integrated framework for supply chain risk assessment. *International Journal of Production Economics, 161*, 54–63.

Ayadi, O., Cheikhrouhou, N., & Masmoudi, F. (2013). A decision support system assessing the trust level in supply chains based on information sharing dimensions. *Computers & Industrial Engineering, 66*, 242–257.

Azadeh, A., & Alem, S. M. (2010). A flexible deterministic, stochastic and fuzzy data envelopment analysis approach for supply chain risk and vendor selection problem: Simulation analysis. *Expert Systems with Applications, 37*, 7438–7448.

Azadi, M., Jafarian, M., Saen, R. F., & Mirhedayatian, S. M. (2015). A new fuzzy DEA model for evaluation of efficiency and effectiveness of suppliers in sustainable supply chain management context. *Computers & Operations Research, 54*, 274–285.

Azaron, A., Brown, K. N., Tarim, S. A., & Modarres, M. (2007). A multi-objective stochastic programming approach for supply chain design considering risk. *International Journal Production Economics, 116*, 129–138.

Bao, L., Huang, Y., Ma, Z., Zhang, J., & Lv, Q. (2012). On the supply chain management supported by e-commerce service platform for agreement based circulation of fruits and vegetables. *Physics Procedia, 33*, 1957–1963.

Behret, H., Oztaysi, B., & Kahraman, C. (2011). A fuzzy inference system for supply chain risk management. In Y. Wang & T. Li (Eds.), *Practical applications of intelligent systems, AISC 124* (pp. 429–438). Berlin, Heidelberg: Springer.

Boltürk, E., & Oztaysi, B. (2014). Fuzzy methods for demand forecasting in supply chain management. In C. Kahraman, & B. Öztayşi (Eds.), *Supply chain management under fuzziness* (pp. 243–268). Berlin: Springer.

Brandenburg, M., Govindan, K., Sarkis, J., & Seuring, S. (2014). Quantitative models for sustainable supply chain management: Developments and directions. *European Journal of Operational Research, 233*(2), 299–312.

Campuzano, F., & Mula, J. (2011). *Supply chain simulation*. London: Springer.

Cevik Onar, S. (2012). Evaluating purchasing decisions via benefits of socially responsible purchasing. *International Journal of Applied Management Science, 4*(4), 407–424.

Cevik Onar, S., Aktas, E., Topçu, İ., & Doran, D. (2013). An analysis of supply chain related graduate programmes in Europe. *Supply Chain Management: An International Journal, 18*(4), 398–412.

Cevik Onar, S., Oztaysi, B., & Kahraman, C. (2014). Early collection system design using fuzzy rule based inference. In *11th International FLINS Conference on Decision Making and Soft Computing (FLINS2014)*, doi:10.1142/9789814619998_0005

Çevik, S., & Ateş, N. Y. (2008). A fuzzy model for operational supply chain optimization problems. *Journal of Multiple-Valued Logic and Soft Computing, 3–5*(14), 355–370.

Chatzidimitriou, C., Symeonidis, A. L., Kontogounis, I., & Pericles, M. (2008). Agent Mertacor: A robust design for dealing with uncertainty and variation in SCM environments. *Expert Systems with Applications, 35*, 591–603.

Ellegard, C. (2008). Supply risk management in a small company perspective. *Supply Chain Management: An international Journal, 13*(6), 425–434.

Formentini, M., & Taticchi, P. (2016). Corporate sustainability approaches and governance Mechanisms in sustainable supply chain management. *Journal of Cleaner Production, 12*(3), 1920–1933.

Forrester, J. W. (1961). *Industrial dynamics*. Massachusetts: The M.I.T. Press.

Frostenson, M., & Prenkert, F. (2015). Sustainable supply chain management when focal firms are complex: A network perspective. *Journal of Cleaner Production, 107*, 85–94.

Fu, J., & Fu, Y. (2015). An adaptive multi-agent system for cost collaborative management in supply chains. *Engineering Applications of Artificial Intelligence, 44*, 91–100.

Georgiadis, P., & Michaloudis, C. (2012). Real-time production planning and control system for job-shop manufacturing: A system dynamics analysis. *European Journal of Operational Research, 216*, 94–104.

Gessner, G. H., & Snodgrass, C. R. (2015). Designing e-commerce cross-border distribution networks for small and medium-size enterprises incorporating Canadian and U.S. trade incentive programs. *Research in Transportation Business & Management, 16*, 84–94.

Ghodratnama, A., Tavakkoli-Moghaddam, R., & Azaron, A. (2015). Robust and fuzzy goal programming optimization approaches for a novel multi-objective hub location-allocation problem: A supply chain overview. *Applied Software Computing, 37*, 255–276.

Giannakis, M., & Louis, M. (2010). A multi-agent based framework for supply chain risk management. *Journal of Purchasing & Supply Management, 17*, 23–31.

Giannakis, M., & Papadopoulos, T. (2016). Supply chain sustainability: A risk management approach. *International Journal of Production Economics, 171*(4), 455–470.

Govindan, K., Khodaverdi, R., & Vafadarnikjoo, A. (2015). Intuitionistic fuzzy based DEMATEL method for developing green practices and performances in a green supply chain. *Expert Systems with Applications, 42*(20), 7207–7220.

Gunasekaran, A. (2012). Decision support systems for logistics and supply chain management. *Decision Support Systems, 52*(4), 777–778.

Gunasekaran, A., Marri, H. B., McGaughey, R. E., & Nebhwani, M. D. (2002). E-commerce and its impact on operations management. *Internatioanl Journal of Production Economics, 75*, 185–197.

Hanafizadeh, P., & Sherkat, M. H. (2009). Designing fuzzy-genetic learner model based on multi-agent systems in supply chain management. *Expert Systems with Applications, 36*(6), 10120–10134.

Hussain, M., Awasthi, A., & Tiwari, M. K. (2016). Interpretive structural modeling-analytic net process integrated framework for evaluating sustainable supply chain management alternatives. *Applied Mathematical Modelling, 40*(5–6), 3671–3687.

Ivanov, D., Dolgui, A., & Sokolov, B. (2011). Applicability of optimal control theory to adaptive supply chain planning and scheduling. *Annual Reviews in Control, 36*, 73–84.

Iyer, K. N. S., Germain, R., & Claycomb, C. (2009). B2B e-commerce supply chain integration and performance: A contingency fit perspective on the role of environment. *Information & Management, 46*(6), 313–322.

Kull, T. J., & Talluri, S. (2008). A supply risk reduction model using integrated multi criteria decision making. *IEEE Transactions on Engineering Management, 55*(3), 409–419.

Kurnia, S., Karnali, R. J., & Rahim, M. M. (2015). A qualitative study of business-to-business electronic commerce adoption within the Indonesian grocery industry: A multi-theory perspective. *Information & Management, 52*(4), 518–536.

Lavastre, O., Gunasekaran, A., & Spalanzani, A. (2012). Supply chain risk management in French companies. *Decision Support Systems, 52*, 828–838.

Li, B., Zhu, M., Jiang, Y., & Li, Z. (2016). Pricing policies of a competitive dual-channel green supply chain. *Journal of Cleaner Production, 112*(3), 2029–2042.

Liang, W., Huang, C., Tseng, T., Lin, Y., & Tseng, J. (2012). The evaluation of intelligent agent performance: An example of B2C e-commerce negotiation. *Computer Standards & Interfaces, 34*, 439–446.

Lin, Y. H., & Tseng, M. L. (2016). Assessing the competitive priorities within sustainable supply chain management under uncertainty. *Journal of Cleaner Production, 112*(3), 2133–2144.

Lu, Q., & Liu, N. (2015). Effects of e-commerce channel entry in a two-echelon supply chain: A comparative analysis of single- and dual-channel distribution systems. *International Journal of Production Economics, 165*, 100–111.

Luthra, S., Luthra, S., & Haleem, A. (2015). Hurdles in implementing sustainable supply chain management: An analysis of indian automobile sector. *Procedia—Social and Behavioral Sciences, 189*, 175–183.

Mamdani, E. H. (1974). Application of fuzzy algorithms for control of simple dynamic plant. *IEEE Proceeding, 12*(121), 1585–1588.

Mangla, S. K., Kumar, P., & Barua, M. K. (2015). Risk analysis in green supply chain using fuzzy AHP approach: A case study. *Resources*, *Conservation and Recycling, 104*(B), 375–390.

Morecroft, J. (2007). *Strategic modeling and business dynamics: A feedback systems approach*. Sussex: Wiley.

Nagurney, A., Cruz, J., Dong, J., & Zhang, D. (2005). Supply chain networks, electronic commerce, and supply side and demand side risk. *European Journal of Operational Research, 164*, 120–142.

Ngai, E. W. T., & Wat, F. K. T. (2004). Fuzzy decision support system for risk analysis in e-commerce development. *Decision Support Systems, 40*, 235–255.

Özbayrak, M., Papadopoulou, T. C., & Akgün, M. (2007). Systems dynamics modeling of a manufacturing supply chain system. *Simulation Modeling Practice and Theory, 15*, 1338–1355.

Oztaysi, B., Behret, H., Kabak, Ö., Sarı, I. U., & Kahraman, C. (2013). Fuzzy inference systems for disaster response. In B. Vitoriano, J. Montero, & D. Ruan (Eds.), *Decision aid models for disaster management and emergencies*. Atlantis Press, pp. 75–94, http://link.springer.com/chapter/10.2991%2F978-94-91216-74-9_4

Oztaysi, B., & Işık, M. (2014). Supplier evaluation using fuzzy clustering. In C. Kahraman, & B. Oztaysi (Eds.), *Supply chain management under fuzziness* (pp. 61–79). Berlin: Springer.

Oztaysi, B., & Sürer, Ö. (2014). Supply chain performance measurement using a SCOR based fuzzy VIKOR approach. In C. Kahraman, & B. Oztaysi (Eds.), *Supply chain management under fuzziness* (pp. 199–224). Berlin: Springer.

Pham, H. V., Cooper, E. W., Cao, T., & Kamei, K. (2012). Hybrid Kansei-SOM model using risk management and company assessment for stock trading. *Information Science* doi:10.1016/j.ins.2011.11.036

Ritchie, B., & Brindley, C. (2007). An emergent framework for supply chain risk management and performance measurement. *Journal of the Operational Research Society, 58*, 1398–1411.

Rostamzadeh, R., Govindan, K., Esmaeili, A., & Sabaghi, M. (2015). Application of fuzzy VIKOR for evaluation of green supply chain management practices. *Ecological Indicators, 49*, 188–203.

Silvestre, B. S. (2015). Sustainable supply chain management in emerging economies: Environmental turbulence, institutional voids and sustainability trajectories. *International Journal of Production Economics, 167*, 156–169.

Sodhi, M. S., & Tang, C. S. (2009). Modeling supply chain planning under demand uncertainty using stochastic programming: A survey motivated by asset–liability management. *International Journal of Production Economics, 121*, 728–738.

Su, C. M., Horng, D. J., Tseng, M. L., Chiu, A. S. F., Wu K, J., & Chen, H. P. (2015). Improving sustainable supply chain management using a novel hierarchical grey-DEMATEL approach. *Journal of Cleaner Production*, In Press, Available online May 30, 2015. doi:10.1016/j.jclepro.2015.05.080

Tan, K. C. (2001). A framework of supply chain management literature. *European Journal of Purchasing & Supply Management, 7*(1), 39–48.

Tesfamariam, D., & Lindberg, B. (2005). Aggregate analysis of manufacturing systems using system dynamics and ANP. *Computers & Industrial Engineering, 49*, 98–117.

Vanany, I., Zailani, S., & Pujawan, I. N. (2009). Supply chain risk management literature review and future research. *International Journal of Information Systems and Supply Chain Management, 2*(1), 16–33.

Wang, Y., Wallace, S. W., Shen, B., & Choi, T. M. (2015). Service supply chain management: A review of operational models. *European Journal of Operational Research, 247*(3), 685–698.

Zhang, D., Zhu, P., & Ye, Y. (2016). The effects of e-commerce on the demand for commercial real estate. *Cities, 51*, 106–120.

Part VI
Environmental Economics

Chapter 14
Fuzzy Economic Analysis Methods for Environmental Economics

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Abstract Environmental economics is an area of economics that studies the financial impact of environmental policies to determine the theoretical or empirical effects of these policies on the economy. In this chapter, engineering economy techniques are developed under fuzziness to be employed in environmental problems. Ordinary fuzzy sets, type-2 fuzzy sets, intuitionistic fuzzy sets, and hesitant fuzzy sets are handled in the development of fuzzy engineering economy analyses. For each of these fuzzy sets, an application related to environmental economics is given.

14.1 Introduction

Environmental economics is an area of engineering economics which is concerned with the environmental issues. By the increasing attention on the environmental sustainability the environmental investments have become a current issue for the companies and governments. They concentrate on the investments which will increase the environmental sustainability by decreasing their environmental impacts. Companies who want to invest on environmental investments are concerned more on the economic aspect of the investment projects because of that each investment which has been made takes from their profits. In that point, the analysis methods used to evaluate an environmental investment which shows the cost equivalences of the investment projects have significant importance to represent the actual situation.

In environmental economics, engineering economic analysis methods are used to determine the best alternative for an environmental investment decision. The discounting cash flow methods are very common economic analysis methods which focus on the time value of the cash flows which occur in different periods. Net

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present worth, annual worth, net future worth, benefit cost ratio and internal rate of return are the most common discounting cash flows methods. Although the usage of discounting cash flows analysis methods is very common, their success on uncertain environments has to be discussed. In an environmental economics analysis most of the parameters contains uncertain information. Therefore, the methods which take into account the uncertainty should be preferred to achieve more accurate results.

Intelligence is the ability to think and understand instead of doing things by instinct or automatically. The basic ideas of intelligence are the studying thought processes of humans, dealing with representing and duplicating those processes via machines, and exploring the behavior by a machine but performed by human being. An Intelligent System (IS) is developed to help decision makers during different phases of decision making by integrating modeling tools and human knowledge. ISs are tools to help decision making process where uncertainty or incomplete information exists and where decisions involving risk must be made using human judgment and preferences. IS is used to support decision making and not intended to replace the decision maker's task. In addition, IS works under an assumption that the decision maker is familiar with the problem to be solved. IS is an interactive system, flexible, adaptable and specifically developed to support the solution of a non-structured management problem for improved decision-making (Quintero et al. 2005).

In this chapter detailed information on intelligent environmental economics techniques are given. Chapter focuses on the fuzzy discounted cash flow analysis methods which become more popular due to their relatively easy calculations among the intelligent environmental economics methods. The most common techniques using different types of fuzzy numbers are detailed to prepare guidance to the researchers.

The chapter is organized as follows. In Sect. 14.2 a detailed literature review on environmental engineering techniques is given. In Sect. 14.3 fuzzy environmental economics techniques are determined which uses different types of fuzzy numbers in calculations. In Sect. 14.4, a numerical illustration is done using different types of the fuzzy numbers. Finally, in Sect. 14.5, the chapter is concluded with the suggestions for further research in environmental economics.

14.2 Literature Review

Due to the environmental economics covers a huge application area there are lots of papers. In literature review the papers are grouped in two main groups which uses classical environmental economics approaches and intelligent environmental economics approaches. In the first main group which uses classical techniques, it is observed that most of the papers are used present worth and benefit cost ratio methods.

Some of the papers which utilize net present worth analysis in their evaluation process are summarized as follows. Sharda et al. (2015) evaluated economic performance of two land configuration systems through an experimental study. Espinoza and Rojo (2015) proposed decoupled net present value (NPV) method that decouples the time value of money from the risk associated with the project is used to value an investment on a solar project. Cooke et al. (2014) used NPV to compute the value of information of climate observing systems. Baral et al. (2014) assessed total economic value for five important ecosystem goods and services under five future land-use scenarios using varying levels of costs, prices and discount rates. Wicke et al. (2013) explored the greenhouse gas balance and the economic performance of agroforestry and forestry systems on salt-affected soils based on three case studies in South Asia. Chinowsky et al. (2013) developed an approach for estimating climate-related changes in road maintenance and construction costs such that the current level of service provided by roads is maintained over time. Nepal et al. (2013) evaluated the potential effectiveness of future carbon reserve scenarios, where U.S. forest landowners would hypothetically be paid to sequester carbon on their timberland and forego timber harvests for 100 years. Zhang et al. (2013) investigated to investigate integrated algae bioenergy production and nutrient management on small dairy farms using NPV, life cycle assessment and life cycle costing. Hardisty et al. (2013) examined options for treatment and discharge of wastewater in regional Western Australia from the perspective of overall sustainability and social net benefit.

Some of the papers which utilize benefit cost ratio analysis are summarized as follows. Winans et al. (2015) compared the carbon sequestration potential and cost benefit of four cultivation systems in southern Quebec, Canada. Tim Chamen et al. (2015) reviewed and analyzed the costs and benefits of soil compaction mitigation based on soil types. Sheley et al. (2014) evaluated the cost/benefit of a single herbicide application or targeted grazing of invasive annual grasses during restoration of partially invaded sagebrush steppe ecosystems used for livestock production. Jiang et al. (2014) examined the costs and benefits of reduction measures for the shipping industry to comply with the forthcoming sulphur emission regulations. Sulphur scrubbers and marine gas oil are two promising alternatives for ship owners. Duke et al. (2014) provided a practical, applied analysis of optimal targeting in agricultural land preservation, comparing the performance of four alternative targeting strategies. Becker et al. (2014) presented estimation on the economic benefits of river rehabilitations and compared them to the estimated costs.

A few articles used annual worth analysis on their studies. Wolf et al. (2015) estimated the potential annual value of six metro nature benefits, and cautiously extrapolate to a national scale, based on best available data and research using a life course approach. Carrasco and Papworth (2014) compared tropical countries' contributions by estimating carbon sequestration services versus emissions disservices. Singh and Mishra (2014) characterized the relationships between Forest Cover, water quality and cost of water treatment in the Western Ghats of peninsular using time series data and multivariate analysis. Ahman and Holmgren (2006) analyzed the impact of allocation to new entrants in the energy sector, and identified options for improved regulation in the field of EU emission trading scheme.

Some of the papers which use intelligent techniques on environmental economics are summarized as follows. Kahraman et al. (2016) developed interval-valued intuitionistic fuzzy benefit-cost analysis for the evaluation of wind energy technology investments. Petkovic et al. (2016) constructed a process that selected the most influential wind farm parameters on the NPV with adaptive neuro-fuzzy (ANFIS) method to assess the investment risk of wind power project. Sheen (2014a) proposed fuzzy profit models to value the wind power project. Sheen (2014b) used the fuzzy real option analysis to evaluate project's economic effectiveness for highly uncertain wind power investment. Milanesi et al. (2014) introduces a fuzzy forestry investment decision-making tool using fuzzy numbers and real option values to represent ambiguous net present values. Shamshirband et al. (2014) applied an intelligent optimization scheme based on the adaptive neuro-fuzzy inference system (ANFIS) in order to achieve the maximal net profit of a wind farm. Vahdat–Aboueshagh et al. (2014) proposed a novel framework for assessing economic life cycle costs of dams considering system's performance from sustainability aspect. Azeez et al. (2013) developed life cycle cost models using fuzzy and simulation approaches that deal with vague, imprecise, qualitative, linguistic, or incomplete data for evaluating sewer rehabilitation alternatives. Lia et al. (2011) used the fuzzy and grey comprehensive method and the technology cost-benefit analysis method for evaluation of water treatment technologies applied in the petrochemical industry. Sheen (2009) derived a fuzzy engineering economic decision model to evaluate the investment feasibility of wind generation project. Dai et al. (2016) proposed a valuation model based on fuzzy cash flow and real option models to evaluate the brownfield redevelopment projects in mining cites. Kunsch and Vander Straeten (2015) presented a fuzzy methodology for the valuation of ambiguous criteria and used in practice for the cost and financial analysis of radioactive-waste-management projects. Zhao and Guo (2015) applied a hybrid MCDM method to evaluate the external benefits of China's renewable energy power and used fuzzy grey relation analysis for ranking alternatives. You et al. (2014) developed an interval-fuzzy regional ecosystem management model based on an interval fuzzy linear programming technique which can handle uncertainties expressed as fuzzy sets and discrete intervals and incorporates ecosystem service valuation directly into the optimization process.

In the literature review, it is seen that usage of intelligent techniques on environmental economics is limited although they are very useful for the evaluation process of unknown parameters, which are highly met on environmental management. Therefore, in this chapter, it is aimed to introduce recently developed fuzzy environmental economics methods and make them easily applicable for the environmental researchers with an application.

14.3 Fuzzy Discounted Cash Flows Methods in Environmental Engineering

Fuzzy logic is a useful tool which takes the uncertainty into account. It enables the analysts to determine linguistic assumptions in mathematical form. In fuzzy logic there are different types of fuzzy numbers which differs by the way of their determination of the linguistic terms. In this section the most common environmental economic analysis methods are given for different types of fuzzy numbers.

14.3.1 Ordinary Fuzzy Environmental Economics Methods

In this sub section first the basic concept of ordinary fuzzy sets and numbers are defined. Then ordinary fuzzy net present worth and type-fuzzy annual worth methods are introduced.

14.3.1.1 Introduction to Ordinary Fuzzy Sets

The fuzzy set theory is founded by Zadeh in 1965. A fuzzy set is defined as a class of objects with a continuum of grades of membership, which is characterized by a membership function that assigns to each object a grade of membership ranging between zero and one. A fuzzy set A in U is characterized by a membership function $\mu_A(x)$ which associates with each point in U a real number in interval [0,1], with the value of $\mu_A(x)$ at x representing "the grade of membership" of x in A (Zadeh 1965).

A formula for a membership function $\mu(x)$ of fuzzy number $\tilde{x}$ is given in Eq. 14.1, where a, b and c denotes real numbers (Ross 1995):

$$\mu_{\tilde{A}}(x) = \mu_{\tilde{A}}(x; a, b, c) = \begin{cases} \frac{x-a}{b-a}; & a \leq x \leq b \\ \frac{c-x}{c-b}; & b \leq x \leq c \\ 0; & otherwise \end{cases} \tag{14.1}$$

A triangular fuzzy number (TFN) is one of the most frequently used fuzzy numbers because of its simple membership function. Hanss (2005) defined the membership function for a TFN $\tilde{\mathrm{M}} = (\mathrm{m_l}, \mathrm{m_m}, \mathrm{m_r})$ in Eq. 14.2:

$$\mu(x) = \begin{cases} 0 & & x \leq m_l \\ 1 + \frac{x-m_m}{m_m-m_l} & & m_l < x < m_m \\ 1 - \frac{x-m_m}{m_r-m_m} & if & m_m \leq x < m_r \\ 0 & & x \geq m_r \end{cases} \tag{14.2}$$

Algebraic operations for TFNs $\tilde{M} = (m_l, m_m, m_r)$ and $\tilde{N} = (n_l, n_m, n_r)$ are given by following equations with the order of summation, subtraction, multiplication, division and multiplication by a scalar (Chen et al. 1992):

$$\tilde{M} \oplus \tilde{N} \cong (m_l + n_l, m_m + n_m, m_r + n_r) \quad (14.3)$$

$$\tilde{M} \ominus \tilde{N} \cong (m_l - n_r, m_m - n_m, m_r - n_l) \quad (14.4)$$

$$\tilde{M} \otimes \tilde{N} \cong \begin{cases} (m_l n_l, m_m n_m, m_r n_r) & & (m_l, m_m, m_r) \geq 0, (n_l, n_m, n_r) \geq 0 \\ (m_l n_r, m_m n_m, m_r n_l) & if & (m_l, m_m, m_r) \leq 0, (n_l, n_m, n_r) \geq 0 \\ (m_r n_r, m_m n_m, m_l n_l) & & (m_l, m_m, m_r) \leq 0, (n_l, n_m, n_r) \leq 0 \end{cases} \quad (14.5)$$

$$\tilde{M} \o \tilde{N} \cong \begin{cases} \left(\frac{m_l}{n_r}, \frac{m_m}{n_m}, \frac{m_r}{n_l}\right) & & (m_l, m_m, m_r) \geq 0, (n_l, n_m, n_r) \geq 0 \\ \left(\frac{m_r}{n_r}, \frac{m_m}{n_m}, \frac{m_l}{n_l}\right) & if & (m_l, m_m, m_r) \leq 0, (n_l, n_m, n_r) \geq 0 \\ \left(\frac{m_r}{n_l}, \frac{m_m}{n_m}, \frac{m_l}{n_r}\right) & & (m_l, m_m, m_r) \leq 0, (n_l, n_m, n_r) \leq 0 \end{cases} \quad (14.6)$$

$$\lambda \otimes \tilde{M} \cong \begin{cases} (\lambda m_l, \lambda m_m, \lambda m_r) & if & \lambda \geq 0 \\ (\lambda m_r, \lambda m_m, \lambda m_l) & & \lambda \leq 0 \end{cases} \quad \forall \lambda \in R \quad (14.7)$$

There are lots of defuzzification methods which are focused on different criteria. In this paper the three criteria ranking method which is proposed by Kaufmann and Gupta (1988) is preferred to defuzzify triangular fuzzy numbers. In that method the fuzzy numbers are ranked according to their ordinary numbers which are calculated by Eq. 14.8. If the ordinary numbers of two fuzzy numbers are same then the modes of the fuzzy numbers becomes identifier. At last if both of the ordinary numbers and the modes of two fuzzy numbers are same, the one which has larger range is preferred. The defuzzification of a triangular fuzzy number $\tilde{M} = (m_l, m_m, m_r)$ is given in Eq. 14.8

$$M = \frac{m_l + 2 \times m_m + m_r}{4} \quad (14.8)$$

14.3.1.2 Triangular Fuzzy Net Present Worth Method

Chiu and Park (1994) defined the formula of triangular fuzzy net present value $(\widetilde{NPV})$ as given in Eq. 14.9, where $\tilde{F}_i == (f_{t_l}; f_{t_m}; f_{t_r})$, denotes net cash flows occurred in time period t and $\tilde{i}_t = (i_{t_l}; i_{t_m}; i_{t_r})$ denotes the fuzzy interest rate.

$$\widetilde{NPV} = \left(\sum_{t=0}^{n} \left(\frac{\max(f_{t_l};0)}{\prod_{t'=0}^{t}(1+i_{t'_r})} + \frac{\min(f_{t_l};0)}{\prod_{t'=0}^{t}(1+i_{t'_l})} \right); \sum_{t=0}^{n} \frac{f_{t_m}}{\prod_{t'=0}^{t}\left(1+i_{t'_m}\right)}; \sum_{t=0}^{n} \left(\frac{\max(f_{t_r};0)}{\prod_{t'=0}^{t}\left(1+i_{t'_l}\right)} + \frac{\min(f_{t_r};0)}{\prod_{t'=0}^{t}\left(1+i_{t'_r}\right)} \right) \right) \tag{14.9}$$

14.3.1.3 Triangular Fuzzy Annual Worth Method

Kahraman et al. (2002) proposed the fuzzy equivalent uniform annual value ($\widetilde{EUAV}$) formula that converts all incomes and disbursements into an equivalent uniform annual amount, which is the same each period. Equation 14.10 represents the formula of fuzzy annual worth of an investment where $\widetilde{NPV} = (N\mathrm{PV}_l, N\mathrm{PV}_m, N\mathrm{PV}_r)$ is the fuzzy net present value of the cash flows, $\tilde{i} = (i_l, i_m, i_r)$ is the interest rate and n represents the period.

$$\widetilde{EUAV} = \left(N\mathrm{PV}_l \frac{(1+i_r)^n i_r}{(1+i_r)^n - 1}; N\mathrm{PV}_m \frac{(1+i_m)^n i_m}{(1+i_m)^n - 1}; N\mathrm{PV}_r \frac{(1+i_l)^n i_l}{(1+i_l)^n - 1} \right) \tag{14.10}$$

Equation 14.10 can be rewritten in terms of cash flows as shown in Eq. 14.11.

$$\widetilde{EUAV} = \left(\sum_{t=0}^{n} \left(\frac{\max(f_{t_l};0)}{\prod_{t'=0}^{t}(1+i_{t'_r})} + \frac{\min(f_{t_l};0)}{\prod_{t'=0}^{t}\left(1+i_{t'_l}\right)} \right) \times \frac{(1+i_r)^n i_r}{(1+i_r)^n - 1}; \sum_{t=0}^{n} \frac{f_{t_m}}{\prod_{t'=0}^{t}(1+i_{t'_m})} \times \frac{(1+i_m)^n i_m}{(1+i_m)^n - 1}; \sum_{t=0}^{n} \left(\frac{\max(f_{t_r};0)}{\prod_{t'=0}^{t}\left(1+i_{t'_l}\right)} + \frac{\min(f_{t_r};0)}{\prod_{t'=0}^{t}(1+i_{t'_r})} \right) \times \frac{(1+i_l)^n i_l}{(1+i_l)^n - 1} \right) \tag{14.11}$$

14.3.2 Type-2 Fuzzy Environmental Economics Methods

In this section, at first the basic information on interval type-2 fuzzy sets is given than the formulas need for fuzzy net present worth analysis and fuzzy annual worth analysis are determined.

14.3.2.1 Introduction to Type-2 Fuzzy Sets

The concept of a type-2 fuzzy set was introduced by Zadeh as an extension of the concept of an ordinary fuzzy set called an ordinary fuzzy set (Zadeh 1974). Such sets are fuzzy sets whose membership grades themselves are ordinary fuzzy sets; they are very useful in circumstances where it is difficult to determine an exact membership function for a fuzzy set; hence, they are useful for incorporating linguistic uncertainties, e.g., the words that are used in linguistic knowledge can mean different things to different people (Karnik and Mendel 2001).

A type-2 fuzzy set $\tilde{\tilde{A}}$ in the universe of discourse X can be represented by a type-2 membership function $\mu_{\tilde{\tilde{A}}}$, shown as follows (Zadeh 1975):

$$\tilde{\tilde{A}} = \{((x,u), \mu_{\tilde{\tilde{A}}}(x,u)|\forall x \in X, \forall u \in J_x \subseteq [0,1], 0 \le \mu_{\tilde{\tilde{A}}}(x,u) \le 1\} \tag{14.12}$$

where J_x denotes an interval [0,1].

Triangular interval type-2 fuzzy sets are the most used interval type-2 fuzzy sets in the literature. A triangular interval type-2 fuzzy set is illustrated as $\tilde{\tilde{A}}_i = \left(\left(a_{il}^U, a_{im}^U, a_{ir}^U; H\left(\tilde{A}_i^U\right)\right), \left(a_{il}^L, a_{im}^L, a_{ir}^L; H\left(\tilde{A}_i^L\right)\right)\right)$ where $\tilde{A}_i^L$ and $\tilde{A}_i^U$ are ordinary fuzzy sets, $a_{il}^U, a_{im}^U, a_{ir}^U, a_{il}^L, a_{im}^L$ and a_{ir}^L are the references points of the interval type-2 fuzzy set $\tilde{\tilde{A}}_i$, $H\left(\tilde{A}_i^U\right)$ denotes the membership value of the element a_i^U in the upper triangular membership function $\tilde{A}_i^U$, $H\left(\tilde{A}_i^L\right)$ denotes the membership value of the element a_i^L in the lower triangular membership function $\tilde{A}_i^L$, $H\left(\tilde{A}_i^U\right) \in [0,1], H\left(\tilde{A}_i^L\right) \in [0,1]$ and $1 \le i \le 2$.

The basic algebraic operations which are addition, subtraction, multiplication, multiplication with a scalar $k > 0$, division, inverse and root operations of type-2 fuzzy sets $\tilde{\tilde{A}}_1 = \left(\left(a_{1l}^U, a_{1m}^U, a_{1r}^U; H\left(\tilde{A}_1^U\right)\right), \left(a_{1l}^L, a_{1m}^L, a_{1r}^L; H\left(\tilde{A}_1^L\right)\right)\right)$ and $\tilde{\tilde{A}}_2 = \left(\left(a_{2l}^U, a_{2m}^U, a_{2r}^U; H\left(\tilde{A}_2^U\right)\right), \left(a_{2l}^L, a_{2m}^L, a_{2r}^L; H\left(\tilde{A}_2^L\right)\right)\right)$ are given in Eqs. 14.13–14.19 respectively (Kuo-Ping, 2011):

$$\begin{aligned}\tilde{\tilde{A}}_1 \oplus \tilde{\tilde{A}}_2 = (&\left(a_{1l}^U + a_{2l}^U; a_{1m}^U + a_{2m}^U; a_{1r}^U + a_{2r}^U; \min\left(H\left(\tilde{A}_1^U\right); H\left(\tilde{A}_2^U\right)\right)\right), \\ &\left(a_{1l}^L + a_{2l}^L; a_{1m}^L + a_{2m}^L; a_{1r}^L + a_{2r}^L; \min\left(H\left(\tilde{A}_1^L\right); H\left(\tilde{A}_2^L\right)\right)\right)\end{aligned} \tag{14.13}$$

$$\begin{aligned}\tilde{\tilde{A}}_1 - \tilde{\tilde{A}}_2 = (&\left(a_{1l}^U - a_{2r}^U; a_{1m}^U - a_{2m}^U; a_{1r}^U - a_{2l}^U; \min\left(H\left(\tilde{A}_1^U\right); H\left(\tilde{A}_2^U\right)\right)\right), \\ &\left(a_{1l}^L - a_{2r}^L; a_{1m}^L - a_{2m}^L; a_{1r}^L - a_{2l}^L; \min\left(H\left(\tilde{A}_1^L\right); H\left(\tilde{A}_2^L\right)\right)\right)\end{aligned} \tag{14.14}$$

$$\begin{aligned}\tilde{\tilde{A}}_1 \otimes \tilde{\tilde{A}}_2 \cong (&\left(a_{1l}^U \times a_{2l}^U; a_{1m}^U \times a_{2m}^U; a_{1r}^U \times a_{2r}^U; \min\left(H\left(\tilde{A}_1^U\right); H\left(\tilde{A}_2^U\right)\right)\right), \\ &\left(a_{1l}^L \times a_{2l}^L; a_{1m}^L \times a_{2m}^L; a_{1r}^L \times a_{2r}^L; \min\left(H\left(\tilde{A}_1^L\right); H\left(\tilde{A}_2^L\right)\right)\right)\end{aligned} \tag{14.15}$$

$$k\tilde{\tilde{A}}_1 = \left(\left(k \times a_{1l}^U; k \times a_{1m}^U; k \times a_{1r}^U; H\left(\tilde{A}_1^U\right)\right), \left(k \times a_{1l}^L; k \times a_{1m}^L; k \times a_{1r}^L; H\left(\tilde{A}_1^L\right)\right)\right) \tag{14.16}$$

$$\frac{\tilde{\tilde{A}}_1}{\tilde{\tilde{A}}_2} \cong \left(\left(\frac{a_{1l}^U}{a_{2r}^U}, \frac{a_{1m}^U}{a_{2m}^U}, \frac{a_{1r}^U}{a_{2l}^U}; \min\left(H\left(\tilde{A}_1^U\right), H\left(\tilde{A}_1^U\right)\right)\right), \left(\frac{a_{1l}^L}{a_{2r}^L}, \frac{a_{1m}^L}{a_{2m}^L}, \frac{a_{1r}^L}{a_{2l}^L}; \min\left(H\left(\tilde{A}_1^L\right); H\left(\tilde{A}_2^L\right)\right)\right)\right) \tag{14.17}$$

$$\frac{1}{\tilde{\tilde{A}}_1} \cong \left(\left(\frac{1}{a_{1r}^U}, \frac{1}{a_{1m}^U}, \frac{1}{a_{1l}^U}; H\left(\tilde{A}_1^U\right)\right), \left(\frac{1}{a_{1r}^L}, \frac{1}{a_{1m}^L}, \frac{1}{a_{1l}^L}; H\left(\tilde{A}_1^L\right)\right)\right) \tag{14.18}$$

$$\sqrt[n]{\tilde{\tilde{A}}_1} = \left(\left(\sqrt[n]{a_{1l}^U}, \sqrt[n]{a_{1m}^U}, \sqrt[n]{a_{1r}^U}; H\left(\tilde{A}_1^U\right)\right), \left(\sqrt[n]{a_{1l}^L}, \sqrt[n]{a_{1m}^L}, \sqrt[n]{a_{1r}^L}; H\left(\tilde{A}_1^L\right)\right)\right) \tag{14.19}$$

Defuzzification of a type-2 fuzzy set consists of two steps. In the first step, a type-2 fuzzy set is determined as an ordinary fuzzy set by using type reduction process. Then one of the defuzzification methods for ordinary (type-1) fuzzy sets is used to find the equivalence of the type-2 fuzzy set (Karnik and Mendel 2001). There is a lot of type reduction methods proposed in the literature. In this chapter type reduction indices which are proposed by Niewiadomski et al. (2006) are used to determine a type-2 fuzzy set as an ordinary fuzzy set and then mode of the ordinary fuzzy set is taken to determine the crisp equivalent of the type-2 fuzzy set.

Niewiadomski et al. (2006) proposed optimistic, pessimistic, realistic and weighted average indices which determine different points of view for the type reduction of interval type-2 fuzzy sets. If $\tilde{\tilde{A}}$ is an interval-valued fuzzy set in the universe X, and $\underline{\mu}_{\tilde{A}}(x), \bar{\mu}_{\tilde{A}}(x)$ are its lower and upper membership functions, Eqs. 14.20–14.23 which transform $\tilde{\tilde{A}}$ into an ordinary fuzzy set are type-reductions. $TR_{opt}(\tilde{\tilde{A}})$ determines optimistic type reduction of $\tilde{\tilde{A}}$, $TR_{pess}(\tilde{\tilde{A}})$ determines pessimistic type reduction of $\tilde{\tilde{A}}$, $TR_{re}(\tilde{\tilde{A}})$ determines realistic type reduction of $\tilde{\tilde{A}}$ and $TR_{wa}(\tilde{\tilde{A}})$ determines weighted average type reduction of $\tilde{\tilde{A}}$.

$$TR_{opt}(\tilde{\tilde{A}}) = \bar{\mu}_{\tilde{A}}(x), \quad x \in X \tag{14.20}$$

$$TR_{pess}(\tilde{\tilde{A}}) = \underline{\mu}_{\tilde{A}}(x), \quad x \in X \tag{14.21}$$

$$TR_{re}(\tilde{\tilde{A}}) = \frac{\underline{\mu}_{\tilde{A}}(x) + \bar{\mu}_{\tilde{A}}(x)}{2}, \quad x \in X \tag{14.22}$$

$$TR_{wa}(\tilde{\tilde{A}}) = w_1\underline{\mu}_{\tilde{A}}(x) + w_2\bar{\mu}_{\tilde{A}}(x), \quad x \in X \tag{14.23}$$

where w_1, w_2 are coefficients which satisfy the equation "$w_1 + w_2 = 1$".

The type reduction indices method allows us to determine an interval type-2 fuzzy set in the terms of an ordinary fuzzy set. To rank the ordinary fuzzy sets there are lots of defuzzification methods in the literature. In this chapter, mode of an ordinary fuzzy set which is one of the easiest defuzzification method for an interval ordinary fuzzy set is used. The purpose of this method is to find the value which divides the area below the membership function into two equal areas. In Eq. 14.24 mode of an interval fuzzy set $\tilde{M} = [M_L; M_R]$ is determined:

$$\mathrm{Mode}_{\tilde{M}} = \frac{M_L + M_R}{2} \tag{14.24}$$

14.3.2.2 Type-2 Fuzzy Net Present Worth Method

Type-2 fuzzy net present worth method is proposed by Uçal Sarı and Kahraman in 2015 for the first time. Triangular interval type-2 fuzzy net present value $\left(\widetilde{\widetilde{NPV}}\right)$ is formulized in Eq. 14.25 where $\tilde{\tilde{F}}_t = \left(f_{tl}^U, f_{tm}^U, f_{tr}^U; H\left(\tilde{f}_t^U\right)\right), \left(f_{tl}^L, f_{tm}^L, f_{tr}^L; H\left(\tilde{f}_t^L\right)\right)$ denotes the cash flow occurred at time t and $\tilde{\tilde{i}}_t = \left(i_{tl}^U, i_{tm}^U, i_{tr}^U; H\left(\tilde{i}_t^U\right)\right), \left(i_{tl}^L, i_{tm}^L, i_{tr}^L; H\left(\tilde{i}_t^L\right)\right), \forall \tilde{i} > 0$ denotes the discount rate at time t:

$$\begin{aligned}
\widetilde{\widetilde{NPV}} = {} & \Bigg(\Bigg(\sum_{t=0}^{n}\left(\frac{\max\left(f_{tl}^U, 0\right)}{\prod_{t'=0}^{t}\left(1+i_{t'r}^U\right)} + \frac{\min\left(f_{tl}^U, 0\right)}{\prod_{t'=0}^{t}\left(1+i_{t'l}^U\right)}\right), \sum_{t=0}^{n}\frac{f_{tm}^U}{\prod_{t'=0}^{t}\left(1+i_{t'm}^U\right)}, \\
& + \sum_{t=0}^{n}\left(\frac{\max\left(f_{tr}^U, 0\right)}{\prod_{t'=0}^{t}\left(1+i_{t'l}^U\right)} \frac{\min\left(f_{tr}^U, 0\right)}{\prod_{t'=0}^{t}\left(1+i_{t'r}^U\right)}\right); \min\left(H\left(\tilde{f}_t^U\right), H\left(\tilde{i}_t^U\right)\right)\Bigg), \\
& \Bigg(\sum_{t=0}^{n}\left(\frac{\max\left(f_{tl}^L, 0\right)}{\prod_{t'=0}^{t}\left(1+i_{t'r}^L\right)} + \frac{\min\left(f_{tl}^L, 0\right)}{\prod_{t'=0}^{t}\left(1+i_{t'l}^L\right)}\right), \sum_{t=0}^{n}\frac{f_{tm}^L}{\prod_{t'=0}^{t}\left(1+i_{t'm}^L\right)}, \\
& \sum_{t=0}^{n}\left(\frac{\max\left(f_{tr}^L, 0\right)}{\prod_{t'=0}^{t}\left(1+i_{t'l}^L\right)} + \frac{\min\left(f_{tr}^L, 0\right)}{\prod_{t'=0}^{t}\left(1+i_{t'r}^L\right)}\right); \min\left(H\left(\tilde{f}_t^L\right), H\left(\tilde{i}_t^L\right)\right)\Bigg)\Bigg)
\end{aligned} \tag{14.25}$$

14.3.2.3 Type-2 Fuzzy Annual Worth Method

Type-2 fuzzy annual worth method is also proposed by Uçal Sarı and Kahraman in 2015. Triangular interval type-2 fuzzy equivalent uniform annual value $\left(\widetilde{\widetilde{EUAV}}\left(\tilde{A}_n\right)\right)$ is formulized in Eq. 14.26 where $\widetilde{\widetilde{NPV}} = (NPV_l^U, NPV_m^U, NPV_r^U; H(N\tilde{P}V^U)), (NPV_l^L, NPV_m^L, NPV_r^L; H(N\tilde{P}V^L))$ denotes triangular interval type-2 fuzzy net present value of an investment and $\tilde{\tilde{i}}_t = (i^U_{tl}, i^U_{tm}, i^U_{tr}; H(\tilde{i}^U_t)),(i^L_{tl}, i^L_{tm}, i^L_{tr}; H(\tilde{i}^L_t)), \forall \tilde{i} > 0$ denotes the discount rate at time t:

$$\widetilde{\widetilde{EUAV}} = ((NPV^U_l \frac{(1+i^U_r)^n i^U_r}{(1+i^U_r)^n - 1}, NPV^U_m \frac{(1+i^U_m)^n i^U_m}{(1+i^U_m)^n - 1}, NPV^U_r \frac{(1+i^U_l)^n i^U_l}{(1+i^U_l)^n - 1}; \min(H(\widetilde{NPV}^U), H(\tilde{i}^U))), (NPV^L_l \frac{(1+i^L_r)^n i^L_r}{(1+i^L_r)^n - 1}, NPV^L_m \frac{(1+i^L_m)^n i^L_m}{(1+i^L_m)^n - 1}, NPV^L_r \frac{(1+i^L_l)^n i^L_l}{(1+i^L_l)^n - 1}; \min(H(N\tilde{P}V^L), H(\tilde{i}^L))) \tag{14.26}$$

14.3.3 Intuitionistic Fuzzy Environmental Economics Methods

Intuitionistic fuzzy engineering economics methods are first proposed by Kahraman et al. in 2015. In that paper intuitionistic fuzzy net present worth and intuitionistic fuzzy annual worth formulas are generated. In this section first a brief background information on triangular intuitionistic fuzzy numbers is given than the most common engineering economics methods which are triangular intuitionistic fuzzy net present worth and triangular intuitionistic fuzzy annual worth methods are detailed.

14.3.3.1 Introduction to Triangular Intuitionistic Fuzzy Numbers

A triangular intuitionistic fuzzy number (TIFN) $\tilde{A}$ which is proposed by Atanassov (1986), which takes into account the membership value as well as the non-membership value for describing any x in X such that the sum of membership and non-membership is less than or equal to 1, has following membership function ($\mu_{\tilde{A}}(x)$) and non-membership function ($v_{\tilde{A}}(x)$):

$$\mu_{\tilde{A}}(x) = \begin{cases} \frac{x-l}{m-l}, & for\ l \le x \le m \\ \frac{u-x}{u-m}, & for\ m \le x \le u \\ 0, & otherwise \end{cases} \tag{14.27}$$

and

$$v_{\tilde{A}}(x) \begin{cases} \frac{m-x}{m-\acute{l}}, & for\ \acute{l} \le x \le \acute{m} \\ \frac{x-\acute{m}}{\acute{u}-\acute{m}}, & for\ \acute{m} \le x \le \acute{u} \\ 1, & otherwise \end{cases} \tag{14.28}$$

where $l \leq m \leq u$, $\acute{l} \leq \acute{m} \leq \acute{u}$, $0 \leq \mu_{\tilde{A}}(x) + v_{\tilde{A}}(x) \leq 1$ and it is denoted by

$$\tilde{A}_{TIFN} = \left((l, m, u), \left(\acute{l}, \acute{m}, \acute{u}\right)\right). \tag{14.29}$$

The basic algebraic operations which are addition, subtraction, multiplication, multiplication by a scalar λ where $\lambda > 0$, division, operations of triangular intuitionistic fuzzy numbers $\tilde{A}_{TIFN} = \left((l^A, m^A, u^A), \left(\acute{l}^A, \acute{m}^A, \acute{u}^A\right)\right)$ and $\tilde{B}_{TrIFN} = \left((l^B, m^B, u^B), \left(\acute{l}^B, \acute{m}^B, \acute{u}^B\right)\right)$ are given in Eqs. 14.30–14.34 respectively (Atanassov 2012; Kumar and Hussein 2014; Mahapatra and Roy 2009):

$$\tilde{A}_{TIFN} \oplus \tilde{B}_{TrIFN} = \left((l^A + l^B, m^A + m^B, u^A + u^B)\right), \left(\acute{l}^A + \acute{l}^B, \acute{m}^A + \acute{m}^B, \acute{u}^A + \acute{u}^B\right) \tag{14.30}$$

$$\tilde{A} \ominus \tilde{B} = \left(\left(l^A - u^B, m^A - m^B, u^A - l^B\right), \left(\acute{l}^A - \acute{u}^B, \acute{m}^A - \acute{m}^B, \acute{u}^A - \acute{l}^B\right)\right) \tag{14.31}$$

$$\tilde{A} \otimes \tilde{B} \cong \left(\left(l^A l^B, m^A m^B, u^A u^B\right), \left(\acute{l}^A \acute{l}^B, \acute{m}^A \acute{m}^B, \acute{u}^A \acute{u}^B\right)\right) \tag{14.32}$$

$$\lambda\tilde{A} = \left(\left[1 - \left(1 - \mu_1^-\right)^{\lambda}, 1 - \left(1 - \mu_1^+\right)^{\lambda}\right], \left[\left(v_1^-\right)^{\lambda}, \left(v_1^+\right)^{\lambda}\right]\right) \tag{14.33}$$

$$\tilde{A} ø \tilde{B} \cong \left(\left(l^A/u^B, m^A/m^B, u^A/l^B\right), \left(\acute{l}^A/\acute{u}^B, \acute{m}^A/\acute{m}^B, \acute{u}^A/\acute{l}^B\right)\right) \tag{14.34}$$

In this chapter the deffuzzification method which is proposed by Kahraman et al. (2015) is used to determine the rankings of triangular intuitionistic fuzzy numbers.

The rank of a TIFN $\tilde{A} = \left((l, m, u), \left(\acute{l}, \acute{m}, \acute{u}\right)\right)$ is determined as follows:

$$R(\tilde{A}) = \frac{1}{2}\left(\frac{l + 2m + u}{4} + \frac{\acute{l} + 2\acute{m} + \acute{u}}{4}\right) = \frac{l + \acute{l} + 2m + 2\acute{m} + u + \acute{u}}{8} \tag{14.35}$$

Aggregation operators for triangular intuitionistic fuzzy numbers have been defined in the literature. Let $\tilde{A}_j = \left(\left(l_j, m_j, u_j\right), \left(\acute{l}_j, \acute{m}_j, \acute{u}_j\right)\right)$, j = 1,2, …, n be a set of Triangular Fuzzy Number Intuitionistic Fuzzy Numbers (*TFNIFN*) and $w = (w_1, w_2, \ldots, w_n)$ is the weighting vector where $w_j > 0$ and $\sum_{j=1}^{n} w_j = 1$.

Triangular fuzzy number intuitionistic fuzzy weighted geometric ($TFNIFWG_w$) operator given in Eq. 14.36 can be used for aggregating triangular intuitionistic fuzzy sets (Chen et al. 2010).

$$TFNIFWG_w\left(\tilde{A}_1, \tilde{A}_2, \ldots, \tilde{A}_n\right) = \left(\left(\prod_{j=1}^{n} l_j^{w_j}, \prod_{j=1}^{n} m_j^{w_j}, \prod_{j=1}^{n} u_j^{w_j}\right), \left(1 - \prod_{j=1}^{n} (1 - \underset{j}{l})^{w_j}, 1 - \prod_{j=1}^{n} (1 - \underset{j}{m})^{w_j}, 1 - \prod_{j=1}^{n} (1 - \underset{j}{u})^{w_j}\right)\right) \tag{14.36}$$

14.3.3.2 Triangular Fuzzy Intuitionistic Net Present Worth Method

The handled parameters are first cost (FC), uniform annual cost (UAC), uniform annual benefit (UAB), project life (n), interest rate (i), and salvage value (SV). These parameters are expressed by triangular fuzzy intuitionistic fuzzy sets as follows, assuming that *m* evaluations for each parameter are made:

$$\widetilde{FC}_{T,I} = \left\{ \begin{array}{c} \langle fc_1, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle, \\ \langle fc_2, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle \\ , \ldots, \\ \langle fc_k, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle \end{array} \right\} \tag{14.37}$$

$$\widetilde{UAC}_{T,I} = \left\{ \begin{array}{c} \langle uac_1, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle, \\ \langle uac_2, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle \\ , \ldots, \\ \langle uac_k, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle \end{array} \right\} \tag{14.38}$$

$$\widetilde{UAB}_{T,I} = \left\{ \begin{array}{c} \langle uab_1, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle, \\ \langle uab_2, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle \\ , \ldots, \\ \langle uab_k, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle \end{array} \right\} \tag{14.39}$$

$$\widetilde{SV}_{T,I} = \left\{ \begin{array}{c} \langle sv_1, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle, \\ \langle sv_2, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle, \\ , \ldots, \\ \langle sv_k, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle \end{array} \right\} \tag{14.40}$$

$$\tilde{i}_{T,I} = \left\{ \begin{array}{c} \langle i_1, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle, \\ \langle i_2, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle \\ , \ldots, \\ \ldots, \langle i_k, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle \end{array} \right\} \tag{14.41}$$

$$\tilde{n}_{T,I} = \left\{ \begin{array}{c} \langle n_1, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle, \\ \langle n_2, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle \\ , \ldots, \\ , \langle n_k, \left(TFN_1, T\acute{F}N_1\right), \ldots, \left(TFN_m, T\acute{F}N_m\right)\rangle \end{array} \right\} \tag{14.42}$$

Using the triangular intuitionistic fuzzy parameters above, the intuitionistic fuzzy present worth $(\widetilde{PW}_{T,I})$ of an investment alternative can be calculated using the following equations.

$$\begin{aligned} \widetilde{PW}_{T,I} = & -\widetilde{FC}_{T,I} \\ & - \widetilde{UAC}_{T,I}\left(\frac{P}{A}, \tilde{i}_{T,I}, \tilde{n}_{T,I}\right) + \widetilde{UAB}_h\left(\frac{P}{A}, \tilde{i}_{T,I}, \tilde{n}_{T,I}\right) + \widetilde{SV}_h\left(\frac{P}{F}, \tilde{i}_{T,I}, \tilde{n}_{T,I}\right) \end{aligned} \tag{14.43}$$

or

$$\widetilde{PW}_{T,I} = -\widetilde{FC}_{T,I} - \widetilde{UAC}_{T,I}\left[\frac{\left(1+\tilde{i}_{T,I}\right)^{\tilde{n}_{T,I}}-1}{\tilde{i}_{T,I}\left(1+\tilde{i}_{T,I}\right)^{\tilde{n}_{T,I}}}\right] + \widetilde{UAB}_{T,I}\left[\frac{\left(1+\tilde{i}_{T,I}\right)^{\tilde{n}_{T,I}}-1}{\tilde{i}_{T,I}\left(1+\tilde{i}_{T,I}\right)^{\tilde{n}_{T,I}}}\right] + \widetilde{SV}_{T,I}\left(1+\tilde{i}_{T,I}\right)^{-\tilde{n}_{T,I}} \tag{14.44}$$

where

$$\begin{aligned} \widetilde{FC}_{T,I} &= \bigcup_{j=1}^{k} TFNIFWG_w\left(\left\langle \begin{array}{c} fc_j, \left(TFN_1, T\acute{F}N_1\right), \\ \ldots, \left(TFN_m, T\acute{F}N_m\right) \end{array} \right\rangle\right) \\ \widetilde{UAC}_{T,I} &= \bigcup_{j=1}^{k} TFNIFWG_w\left(\left\langle \begin{array}{c} uac_j, \left(TFN_1, T\acute{F}N_1\right), \\ \ldots, \left(TFN_m, T\acute{F}N_m\right) \end{array} \right\rangle\right), \\ \widetilde{UAB}_{T,I} &= \bigcup_{j=1}^{k} TFNIFWG_w\left(\left\langle \begin{array}{c} uab_j, \left(TFN_1, T\acute{F}N_1\right), \\ \ldots, \left(TFN_m, T\acute{F}N_m\right) \end{array} \right\rangle\right), \\ \widetilde{SV}_{T,I} &= \bigcup_{j=1}^{k} TFNIFWG_w\left(\left\langle \begin{array}{c} sv_j, \left(TFN_1, T\acute{F}N_1\right), \\ \ldots, \left(TFN_m, T\acute{F}N_m\right) \end{array} \right\rangle\right), \\ \tilde{i}_{T,I} &= \bigcup_{j=1}^{k} TFNIFWG_w\left(\left\langle \begin{array}{c} i_j, \left(TFN_1, T\acute{F}N_1\right), \\ \ldots, \left(TFN_m, T\acute{F}N_m\right) \end{array} \right\rangle\right), \\ \tilde{n}_{T,I} &= \bigcup_{j=1}^{k} TFNIFWG_w\left(\left\langle \begin{array}{c} n_j, \left(TFN_1, T\acute{F}N_1\right), \\ \ldots, \left(TFN_m, T\acute{F}N_m\right) \end{array} \right\rangle\right). \end{aligned}$$

The defuzzified values of these parameters are needed for further calculations. For instance, the defuzzified value of $\widetilde{FC}_{T,I}$ is obtained by the following process:

$$TFNIFWG_w\left(\left\langle \begin{matrix} fc_j, \left(TFN_1, T\acute{F}N_1\right), \\ \ldots, \left(TFN_m, T\acute{F}N_m\right) \end{matrix} \right\rangle\right) = \tilde{\mu}_{\mathrm{fc_j}} \\ = \left(\left(\mu_{fc_{jl}}, \mu_{fc_{jm}}, \mu_{fc_{ju}}\right), \left(\mu'_{fc_{jl}}, \mu'_{fc_{jm}}, \mu'_{fc_{ju}}\right)\right), j \\ = 1, \ldots, k \tag{14.45}$$

Defuzzified value of $\left(\left(\mu_{fc_{jl}}, \mu_{fc_{jm}}, \mu_{fc_{ju}}\right), \left(\mu'_{fc_{jl}}, \mu'_{fc_{jm}}, \mu'_{fc_{ju}}\right)\right)$ is $Def(\tilde{\mu}_{\mathrm{fc_j}})$ which is obtained by Eq. 14.35. The defuzzified value of $\widetilde{FC}_{T,I}$ is obtained by Eq. 14.46:

$$Def\,\widetilde{FC}_{T,I} = \frac{\sum_{j=1}^{k} fc_j \left(Def\left(\tilde{\mu}_{\mathrm{fc_j}}\right)\right)^2}{\sum_{j=1}^{k}\left(Def\left(\tilde{\mu}_{\mathrm{fc_j}}\right)\right)^2} \tag{14.46}$$

The defuzzification of the other parameters is realized similar to the above calculations.

14.3.3.3 Triangular Intuitionistic Fuzzy Annual Worth Analysis

Using the triangular intuitionistic fuzzy parameters, $\widetilde{EUAW}_{T,I}$ is calculated as in Eq. 14.47.

$$\widetilde{EUAW}_{T,I} = -\widetilde{FC}_{T,I}\left(\frac{A}{P}, \tilde{i}_{T,I}, \tilde{n}_{T,I}\right) - \widetilde{UAC}_{T,I} + \widetilde{UAB}_{T,I} + \widetilde{SV}_{T,I}\left(\frac{A}{F}, \tilde{i}_{T,I}, \tilde{n}_{T,I}\right) \tag{14.47}$$

or

$$\widetilde{EUAW}_{T,I} = -\widetilde{FC}_{T,I}\left[\frac{\tilde{i}_{T,I}\left(1+\tilde{i}_{T,I}\right)^{\tilde{n}_{T,I}}}{\left(1+\tilde{i}_{T,I}\right)^{\tilde{n}_{T,I}}-1}\right] \\ - \widetilde{UAC}_{T,I} + \widetilde{UAB}_{T,I} + \widetilde{SV}_{T,I}\left[\frac{\tilde{i}_{T,I}}{\left(1+\tilde{i}_{T,I}\right)^{\tilde{n}_{T,I}}-1}\right] \tag{14.48}$$

Aggregation of triangular intuitionistic fuzzy parameters is performed as the previous subsection on triangular fuzzy intuitionistic net present worth method. Later the defuzzified values of the parameters are substituted into Eq. 14.48.

14.3.3.4 Introduction to Interval-Valued Intuitionistic Fuzzy Numbers (IVIFN)

In the fuzzy set theory, the membership of an element to a fuzzy set is a single value between zero and one. However, the degree of non-membership of an element in a fuzzy set may not be equal to 1 minus the membership degree since there may be some hesitation degree. Therefore, a generalization of fuzzy sets was proposed by Atanassov (1986) as intuitionistic fuzzy sets (IFS) which incorporate the degree of hesitation, which is defined as 1 minus the sum of membership and non-membership degrees.

Let $\mathrm{D}\subseteq[0,1]$ be the set of all closed subintervals of the interval and X be a universe of discourse. An interval-valued intuitionistic fuzzy set $\tilde{\mathrm{A}}$ over X is an object having the form

$$\tilde{\mathrm{A}} = \left\{\left\langle \mathrm{x}, \mu_{\tilde{\mathrm{A}}}(\mathrm{x}), \mathrm{v}_{\tilde{\mathrm{A}}}(\mathrm{x})\right\rangle | \mathrm{x} \in \mathrm{X}\right\}, \tag{14.49}$$

where $\mu_{\tilde{A}} \to \mathrm{D}\subseteq[0,1]$, $\mathrm{v}_{\tilde{\mathrm{A}}}(\mathrm{x}) \to \mathrm{D}\subseteq[0,1]\mathrm{D}\subseteq[0,1]$ with the condition $0 \leq \sup\mu_{\tilde{A}}(x) + \sup v_{\tilde{A}}(x) \leq 1, \forall x \in X$.

The intervals $\mu_{\tilde{A}}(x)$ and $v_{\tilde{A}}(x)$ denote the membership function and the non-membership function of the element x to the set $\tilde{\mathrm{A}}$ respectively. Thus for each $\in X$, $\mu_{\tilde{A}}(x)$ and $v_{\tilde{A}}(x)$ are closed intervals and their starting and ending points are denoted by $\mu_{\tilde{A}}^{-}(x)$, $\mu_{\tilde{A}}^{+}(x)$, $v_{\tilde{A}}^{-}(x)$ and $v_{\tilde{A}}^{+}(x)$, respectively. Interval-valued intuitionistic fuzzy set $\tilde{\mathrm{A}}$ is then denoted by

$$\tilde{\mathrm{A}} = \left\{\left\langle \mathrm{x}, \left[\mu_{\tilde{\mathrm{A}}}^{-}(\mathrm{x}),\ \mu_{\tilde{\mathrm{A}}}^{+}(\mathrm{x})\right], \left[\mathrm{v}_{\tilde{\mathrm{A}}}^{-}(\mathrm{x}), \mathrm{v}_{\tilde{\mathrm{A}}}^{+}(\mathrm{x})\right]\right\rangle | \mathrm{x} \in \mathrm{X}\right\}, \tag{14.50}$$

where $0 \leq \mu_{\tilde{A}}^{+}(x) + v_{\tilde{A}}^{+}(x) \leq 1,\ \mu_{\tilde{A}}^{-}(x) \geq 0,\ v_{\tilde{A}}^{-}(x) \geq 0$.

For each element x, we can compute the unknown degree (hesitancy degree) of an interval-valued intuitionistic fuzzy set of $x \in X$ in $\tilde{A}$ defined as follows:

$$\pi_{\tilde{A}}(x) = 1 - \mu_{\tilde{A}}(x) - v_{\tilde{A}}(x) = \left(1 - \mu_{\tilde{A}}^{+}(x) - v_{\tilde{A}}^{+}(x), 1 - \mu_{\tilde{A}}^{-}(x) - v_{\tilde{A}}^{-}(x)\right). \tag{14.51}$$

For convenience, let $\mu_{\tilde{A}}(\mathrm{x}) = \left[\mu_{\tilde{A}}^{-}(x),\ \mu_{\tilde{A}}^{+}(x)\right] = \left[\mu_{\tilde{A}}^{-},\ \mu_{\tilde{A}}^{+}\right]$, $v_{\tilde{A}}(x) = \left[\upsilon_{\tilde{A}}^{-}(x),\ \upsilon_{\tilde{A}}^{+}(x)\right] = \left[\upsilon_{\tilde{A}}^{-},\ \upsilon_{\tilde{A}}^{+}\right]$, so $\tilde{A} = \left(\left[\mu_{\tilde{A}}^{-}, \mu_{\tilde{A}}^{+}\right], \left[\upsilon_{\tilde{A}}^{-}, \upsilon_{\tilde{A}}^{+}\right]\right)$.

Figure 14.1 illustrates an interval-valued intuitionistic fuzzy set (Atanassova 2008).

Defuzzification of an IVIFN can be made as follows: Let $\tilde{\alpha}_j = \left(\left[\mu_j^{-}, \mu_j^{+}\right], \left[v_j^{-}, v_j^{+}\right]\right)$ be an interval-valued intutionistic fuzzy number. The following score function is proposed for defuzzifying $\tilde{\alpha}$:

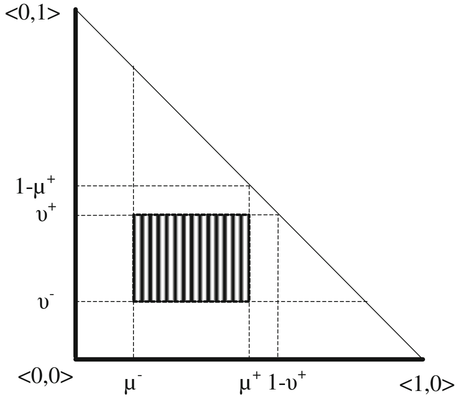

Fig. 14.1 Interval-valued intuitionistic fuzzy set

$$I(\tilde{\alpha}_j) = \frac{\mu_j^- + \mu_j^+ + \left(1 - v_j^-\right) + \left(1 - v_j^+\right) + \mu_j^- \times \mu_j^+ - \sqrt{\left(1 - v_j^-\right) \times (1 - v_j^+)}}{4} \tag{14.52}$$

In Eq. 14.52 the terms $(1 - v_j^-)$ and $(1 - v_j^+)$ convert non-membership degrees to membership degrees while the term $\sqrt{\left(1 - v_j^-\right) \times (1 - v_j^+)}$ decreases the defuzzified value.

Aggregation Operators for IVIFN have also been defined in the literature. Let $\tilde{\alpha}_j = \left(\left[\mu_j^-, \mu_j^+\right], \left[v_j^-, v_j^+\right]\right)$ $(j = 1, 2, \ldots, n)$ be a collection of interval-valued intuitionistic fuzzy numbers and let IIFWA: $Q^n \to Q$, if

$$IIFWA_w(\tilde{\alpha}_1, \tilde{\alpha}_2, \ldots, \tilde{\alpha}_n) = w_1\tilde{\alpha}_1 \oplus w_2\tilde{\alpha}_2 \oplus \cdots \oplus w_n\tilde{\alpha}_n \tag{14.53}$$

then IIFWA is called an interval-valued intuitionistic fuzzy weighted averaging (IIFWA) operator, where Q is the set of all IVIFNs, $w = (w_1, w_2, \ldots, w_n)$ is the weight vector of the IVIFNs $\tilde{\alpha}_j (j = 1, 2, \ldots, n)$, and $w_j > 0$, $\sum_{j=1}^n w_j = 1$. The IIFWA operator can be further transformed into the following form (Xu 2007):

$$IIFWA_w(\tilde{\alpha}_1, \tilde{\alpha}_2, \ldots, \tilde{\alpha}_n) = \left(\left[1 - \prod_{j=1}^n \left(1 - \mu_j^-\right)^{w_i}, 1 - \prod_{j=1}^n \left(1 - \mu_j^+\right)^{w_i}\right], \left[\prod_{j=1}^n \left(v_j^-\right)^{w_i}, \prod_{j=1}^n \left(v_j^+\right)^{w_i}\right]\right) \tag{14.54}$$

Especially if $w = (1/n, 1/n, \ldots, 1/n)$, then the IIFWA operator reduces to an interval-valued intuitionistic fuzzy averaging (IIFA) operator, where

$$IIFA(\tilde{\alpha}_1, \tilde{\alpha}_2, \ldots, \tilde{\alpha}_n) = \frac{1}{n}(\tilde{\alpha}_1 \oplus \tilde{\alpha}_2 \oplus \cdots \oplus \tilde{\alpha}_n)$$
$$= \left(\left[1 - \prod_{j=1}^{n} \left(1 - \mu_j^-\right)^{1/n}, 1 - \prod_{j=1}^{n} \left(1 - \mu_j^+\right)^{1/n} \right], \left[\prod_{j=1}^{n} \left(v_j^-\right)^{1/n}, \prod_{j=1}^{n} \left(v_j^+\right)^{1/n} \right] \right) \quad (14.55)$$

14.3.3.5 IVIF Net Present Worth Method

The intuitionistic fuzzy present worth $(\widetilde{PW}_I)$ is calculated by Eq. 14.56 and Eq. 14.57:

$$\widetilde{PW}_I = -\widetilde{FC}_I - \widetilde{UAC}_I\left(\frac{P}{A}, \tilde{i}_I, \tilde{n}_I\right) + \widetilde{UAB}_I\left(\frac{P}{A}, \tilde{i}_I, \tilde{n}_I\right) + \widetilde{SV}_I\left(\frac{P}{F}, \tilde{i}_I, \tilde{n}_I\right) \quad (14.56)$$

or

$$\widetilde{PW}_I = -\widetilde{FC}_I - \widetilde{UAC}_I\left[\frac{\left(1+\tilde{i}_I\right)^{\tilde{n}_I} - 1}{\tilde{i}_I\left(1+\tilde{i}_I\right)^{\tilde{n}_I}}\right] + \widetilde{UAB}_I\left[\frac{\left(1+\tilde{i}_I\right)^{\tilde{n}_I} - 1}{\tilde{i}_I\left(1+\tilde{i}_I\right)^{\tilde{n}_I}}\right] + \widetilde{SV}_I\left(1+\tilde{i}_I\right)^{-\tilde{n}_I} \quad (14.57)$$

14.3.3.6 IVIF Annual Worth Analysis

Fuzzy equivalent uniform annual worth is calculated by Eq. 14.58:

$$\widetilde{EUAW}_I = -\widetilde{FC}_I\left(\frac{A}{P}, \tilde{\mathrm{i}}_I, \tilde{n}_I\right) - \widetilde{UAC}_I + \widetilde{UAB}_I + \widetilde{SV}_I\left(\frac{A}{F}, \tilde{i}_I, \tilde{n}_I\right) \quad (14.58)$$

or

$$\widetilde{EUAW}_I = -\widetilde{FC}_I\left[\frac{\tilde{i}_I\left(1+\tilde{i}_I\right)^{\tilde{n}_I}}{\left(1+\tilde{i}_I\right)^{\tilde{n}_I} - 1}\right] - \widetilde{UAC}_I + \widetilde{UAB}_I + \widetilde{SV}_I\left[\frac{\tilde{i}_I}{\left(1+\tilde{i}_I\right)^{\tilde{n}_I} - 1}\right] \quad (14.59)$$

Interval-Valued Intuitionistic Fuzzy Annual Worth $\widetilde{\mathrm{EUAW}}_{\mathrm{Iv,I}}$ is calculated as in Eq. 14.60:

$$\widetilde{\mathrm{EUAW}}_{\mathrm{Iv,I}} = -\widetilde{FC}_{Iv,I}\left(\frac{A}{P}, \tilde{i}_{Iv,I}, \tilde{n}_{Iv,I}\right) - \widetilde{UAC}_{Iv,I} + \widetilde{UAB}_{Iv,I} + \widetilde{SV}_{Iv,I}\left(\frac{A}{F}, \tilde{i}_{Iv,I}, \tilde{n}_{Iv,I}\right) \tag{14.60}$$

or

$$\begin{aligned} \widetilde{EUAW}_{Iv,I} = {} & -\widetilde{FC}_{Iv,I}\left[\frac{\tilde{i}_{Iv,I}\left(1+\tilde{i}_{Iv,I}\right)^{\tilde{n}_{Iv,I}}}{\left(1+\tilde{i}_{Iv,I}\right)^{\tilde{n}_{Iv,I}}-1}\right] \\ & - \widetilde{UAC}_{Iv,I} + \widetilde{UAB}_{Iv,I} + \widetilde{SV}_{Iv,I}\left[\frac{\tilde{i}_{Iv,I}}{\left(1+\tilde{i}_{Iv,I}\right)^{\tilde{n}_{Iv,I}}-1}\right] \end{aligned} \tag{14.61}$$

14.3.4 Hesitant Fuzzy Environmental Economics Methods

Hesitant fuzzy engineering economics methods are first proposed by Kahraman et al. in 2015. They generated hesitant fuzzy net present worth and hesitant fuzzy annual worth formulas. In this section first a brief background information on triangular hesitant fuzzy numbers is given than two common engineering economics methods which are triangular hesitant fuzzy net present worth and triangular hesitant fuzzy annual worth methods are detailed.

14.3.4.1 Introduction to Hesitant Fuzzy Numbers

A hesitant fuzzy set (HFS) is a novel and recent extension of fuzzy sets that aims to model the uncertainty originated by the hesitation that might arise in the assignment of membership degrees of the elements to a fuzzy set. A HFS is defined in terms of a function that returns a set of membership values for each element in the domain (Torra 2010).

Yu (2013) introduced the concept of Triangular Fuzzy Hesitant Fuzzy Set (TFHFS), whose membership degrees of an element to a fuzzy set are expressed by several triangular fuzzy numbers.

Let X be a fixed set, a TFHFS $\tilde{E}$ on X is defined in terms of a function $\tilde{f}_{\tilde{E}}(x)$ that returns several triangular fuzzy values,

$$\tilde{E} = \left\{ < x, \tilde{f}_{\tilde{E}}(x) > \middle| x \in X \right\} \tag{14.62}$$

where $\tilde{f}_{\tilde{E}}(x)$ is a set of several triangular fuzzy numbers which express the possible membership degrees of an element $x \in X$ to a set $\tilde{E}$.

For a Triangular Fuzzy Hesitant Fuzzy Set (TFHFS), $\tilde{f}$, $s(\tilde{f}) = \frac{1}{l_{\tilde{f}}}\sum_{\widetilde{TFN} \in \tilde{f}} X\left(\widetilde{TFN}\right)$ is called the score function of $\tilde{f}$ with $l_{\tilde{f}}$ being the number of

TFNs in $\tilde{f}$ (Yu 2013). $h(\tilde{f}) = \frac{1}{l_{\tilde{f}}}\sum_{\widetilde{TFN}\in\tilde{f}} \sigma\left(\widetilde{TFN}\right)$ is called the deviation function of $\tilde{f}$. For $\tilde{f}_1$ *and* $\tilde{f}_2$,

$$\begin{aligned}
&\text{if } s(\tilde{f}_1) > s(\tilde{f}_2), \quad \text{then } \tilde{f}_1 \geq \tilde{f}_2 \\
&\text{if } s(\tilde{f}_1) = s(\tilde{f}_2),\ h(\tilde{f}_1) = h(\tilde{f}_2), \quad \text{then } \tilde{f}_1 = \tilde{f}_2 \\
&\text{if } s(\tilde{f}_1) = s(\tilde{f}_2),\ h(\tilde{f}_1) > h(\tilde{f}_2), \quad \text{then } \tilde{f}_1 < \tilde{f}_2 \\
&\text{if } s(\tilde{f}_1) = s(\tilde{f}_2),\ h(\tilde{f}_1) < h(\tilde{f}_2), \quad \text{then } \tilde{f}_1 > \tilde{f}_2
\end{aligned}$$

Let $\tilde{f}_1$ *and* $\tilde{f}_2$ be two THHFEs, then

$$\tilde{f}_1 \oplus \tilde{f}_2 = \left\{(l_1 + l_2 - l_1.l_2, m_1 + m_2 - m_1.m_2, u_1 + u_2 - u_1.u_2) | \widetilde{TFN}_1 \in \tilde{f}_1, \widetilde{TFN}_2 \in \tilde{f}_2\right\} \tag{14.63}$$

$$\tilde{f}_1 \otimes \tilde{f}_2 = \left\{l_1.l_2, m_1.m_2, u_1.u_2 | \widetilde{TFN}_1 \in \tilde{f}_1, \widetilde{TFN}_2 \in \tilde{f}_2\right\} \tag{14.64}$$

$$\tilde{f}^{\lambda} = \left\{(l)^{\lambda}, (m)^{\lambda}, (u)^{\lambda} \middle| \widetilde{TFN} \in \tilde{f}\right\}, \quad \lambda > 0 \tag{14.65}$$

$$\lambda\tilde{f} = \left\{1 - (1-l)^{\lambda}, 1 - (1-m)^{\lambda}, 1 - (1-u)^{\lambda} \middle| \widetilde{TFN} \in \tilde{f}\right\}, \quad \lambda > 0 \tag{14.66}$$

where $\widetilde{TFN}_1 = (l_1, m_1, u_1)$ and $\widetilde{TFN}_2 = (l_2, m_2, u_2)$.

Aggregation operators for triangular fuzzy hesitant fuzzy sets have been given for various means such as weighted average, geometric average etc. The aggregation problem consists of aggregating n-tuples of objects all belonging to a given set, into a single object of the same set. In other words, aggregation operations on fuzzy numbers are operations by which several fuzzy numbers are combined to produce a single fuzzy number.

Let $\tilde{f}_j (j = 1, 2, \ldots, n)$ be a collection of TFHFEs. $w = (w_1, w_2, \ldots, w_n)^{\mathrm{T}}$ is the weight vector of $\tilde{f}_j (j = 1, 2, \ldots, n)$ with $w_j \in [0, 1]$ and $\sum_{j=1}^{n} w_j = 1$, then a Triangular Fuzzy Hesitant Fuzzy Weighted Averaging (TFHFWA) operator is a mapping TFHFWA: $F^n \to \overline{F}$ such that (Xia and Xu 2011)

$$\begin{aligned}
TFHFWA(\tilde{f}_1, \tilde{f}_2, \ldots, \tilde{f}_n) = \oplus_{j=1}^{n}(w_j\tilde{f}_j) = \Bigg\{ & 1 - \prod_{j=1}^{n} (1 - L_j)^{w_j}, 1 - \prod_{j=1}^{n} (1 - M_j)^{w_j}, \\
& 1 - \prod_{j=1}^{n} (1 - U_j)^{w_j} \Bigg| \widetilde{TFN}_1 \in \tilde{f}_1, \widetilde{TFN}_2 \in \tilde{f}_2, \ldots, \widetilde{TFN}_n \in \tilde{f}_n \Bigg\}
\end{aligned} \tag{14.67}$$

Alternatively, a Triangular Fuzzy Hesitant Fuzzy Weighted Geometric (TFHFWG) operator is a mapping IVHFWG: $F^n \to \overline{F}$ such that

$$TFHFWG\left(\tilde{f}_1,\tilde{f}_2,\ldots,\tilde{f}_n\right) = \otimes_{j=1}^{n}\tilde{f}_j^{w_j} = \left\{\left(\prod_{j=1}^{n}\left(L_j\right)^{w_j},\prod_{j=1}^{n}\left(M_j\right)^{w_j},\prod_{j=1}^{n}\left(U_j\right)^{w_j}\right)\middle| \widetilde{TFN}_1 \in \tilde{f}_1, \widetilde{TFN}_2 \in \tilde{f}_2,\ldots, \widetilde{TFN}_n \in \tilde{f}_n\right\} \tag{14.68}$$

Defuzzification of triangular hesitant fuzzy sets can be made as follows: Let If $\widetilde{TFN} = (l, m, u)$ is a hesitant TFN, then the defuzzified value of $\widetilde{TFN}$ can be defined as follows:

$$Def\left(\widetilde{TFN}\right) = \frac{l + 2m + u}{4} \tag{14.69}$$

14.3.4.2 Triangular Hesitant Fuzzy Net Present Worth Method

In the hesitant fuzzy present worth analysis, triangular fuzzy hesitant fuzzy sets are used to express the investment parameters. The handled parameters are first cost (FC), uniform annual cost (UAC), uniform annual benefit (UAB), project life (n), interest rate (i), and salvage value (SV). These parameters are expressed by triangular fuzzy hesitant fuzzy sets as follows, assuming that m evaluations for each parameter are made:

$$\widetilde{FC}_{T,h} = \left\{ \begin{array}{c} \langle fc_1, TFN_1,\ldots, TFN_m\rangle, \langle fc_2, TFN_1,\ldots, TFN_m\rangle, \\ \ldots, \langle fc_k, TFN_1,\ldots, TFN_m\rangle \end{array} \right\} \tag{14.70}$$

$$\widetilde{UAC}_{T,h} = \left\{ \begin{array}{c} \langle uac_1, TFN_1,\ldots, TFN_m\rangle, \\ \langle uac_2, TFN_1,\ldots, TFN_m\rangle, \\ \ldots, \langle uac_k, TFN_1,\ldots, TFN_m\rangle \end{array} \right\} \tag{14.71}$$

$$\widetilde{UAB}_{T,h} = \left\{ \begin{array}{c} \langle uab_1, TFN_1,\ldots, TFN_m\rangle, \\ \langle uab_2, TFN_1,\ldots, TFN_m\rangle, \\ \ldots, \langle uab_k, TFN_1,\ldots, TFN_m\rangle \end{array} \right\} \tag{14.72}$$

$$\widetilde{SV}_{T,h} = \left\{ \begin{array}{c} \langle sv_1, TFN_1,\ldots, TFN_m\rangle, \langle sv_2, TFN_1,\ldots, TFN_m, \rangle \\ \ldots, \langle sv_k, TFN_1,\ldots, TFN_m\rangle \end{array} \right\} \tag{14.73}$$

$$\tilde{i}_{T,h} = \left\{ \begin{array}{c} \langle i_1, TFN_1,\ldots, TFN_m\rangle, \langle i_2, TFN_1,\ldots, TFN_m\rangle, \\ \ldots, \langle i_k, TFN_1,\ldots, TFN_m\rangle \end{array} \right\} \tag{14.74}$$

$$\tilde{n}_{T,h} = \left\{ \begin{array}{c} \langle n_1, TFN_1, \ldots, TFN_m \rangle, \langle n_2, TFN_1, \ldots, TFN_m \rangle, \\ \ldots, \langle n_k, TFN_1, \ldots, TFN_m \rangle \end{array} \right\} \quad (14.75)$$

Using the triangular hesitant fuzzy parameters above, the hesitant fuzzy present worth ($\widetilde{PW}_{T,h}$) of an investment alternative can be calculated using the following equations.

$$\begin{aligned} \widetilde{PW}_{T,h} = & -\widetilde{FC}_{T,h} \\ & - \widetilde{UAC}_{T,h}\left(\frac{P}{A}, \tilde{i}_{T,h}, \tilde{n}_{T,h}\right) + \widetilde{UAB}_h\left(\frac{P}{A}, \tilde{i}_{T,h}, \tilde{n}_{T,h}\right) + \widetilde{SV}_h\left(\frac{P}{F}, \tilde{i}_{T,h}, \tilde{n}_{T,h}\right) \end{aligned} \quad (14.76)$$

or

$$\widetilde{PW}_{T,h} = -\widetilde{FC}_{T,h} - \widetilde{UAC}_{T,h}\left[\frac{\left(1+\tilde{i}_{T,h}\right)^{\tilde{n}_{T,h}}-1}{\tilde{i}_{T,h}\left(1+\tilde{i}_{T,h}\right)^{\tilde{n}_{T,h}}}\right] + \widetilde{UAB}_{T,h}\left[\frac{\left(1+\tilde{i}_{T,h}\right)^{\tilde{n}_{T,h}}-1}{\tilde{i}_{T,h}\left(1+\tilde{i}_{T,h}\right)^{\tilde{n}_{T,h}}}\right] + \widetilde{SV}_{T,h}\left(1+\tilde{i}_{T,h}\right)^{-\tilde{n}_{T,h}} \quad (14.77)$$

where

$$\widetilde{FC}_{T,h} = \bigcup_{j=1}^{k} TFHFWA\left(\langle fc_j, TFN_1, \ldots, TFN_m \rangle\right)$$

$$\widetilde{UAC}_{T,h} = \bigcup_{j=1}^{k} TFHFWA\left(\langle uac_j, TFN_1, \ldots, TFN_m \rangle\right),$$

$$\widetilde{UAB}_{T,h} = \bigcup_{j=1}^{k} TFHFWA\left(\langle uab_j, TFN_1, \ldots, TFN_m \rangle\right),$$

$$\widetilde{SV}_{T,h} = \bigcup_{j=1}^{k} TFHFWA\left(\langle sv_j, TFN_1, \ldots, TFN_m \rangle\right),$$

$$\tilde{i}_{T,h} = \bigcup_{j=1}^{k} TFHFWA\left(\langle i_j, TFN_1, \ldots, TFN_m \rangle\right),$$

$$\tilde{n}_{T,h} = \bigcup_{j=1}^{k} TFHFWA\left(\langle n_j, TFN_1, \ldots, TFN_m \rangle\right).$$

The defuzzified values of these parameters are needed for further calculations. For instance, the defuzzified value of $\widetilde{FC}_{T,h}$ is obtained by the following process:

$$TFHFWA(\langle fc_j, TFN_1, \ldots, TFN_m \rangle) = \tilde{\mu}_{\mathrm{fc_j}} = \left(\mu_{fc_{jl}}, \mu_{fc_{jm}}, \mu_{fc_{ju}}\right), \quad j = 1, \ldots, k \tag{14.78}$$

The defuzzified value of $\widetilde{FC}_{T,h}$ is obtained by defuzzification. Defuzzified value of $(\mu_{\mathrm{fc_{jl}}}, \mu_{\mathrm{fc_{jm}}}, \mu_{\mathrm{fc_{ju}}})$ is $Def(\tilde{\mu}_{\mathrm{fc_j}})$ which is obtained by Eq. 14.69. The defuzzification of the other parameters is realized similar to the above calculations.

14.3.4.3 Triangular Hesitant Fuzzy Annual Worth Analysis

Triangular hesitant fuzzy annual worth $\widetilde{EUAW}_{T,h}$ is calculated as in Eq. 14.79:

$$\widetilde{EUAW}_{T,h} = -\widetilde{FC}_{T,h}\left(\frac{A}{P}, \tilde{i}_{T,h}, \tilde{n}_{T,h}\right) - \widetilde{UAC}_{T,h} + \widetilde{UAB}_{T,h} + \widetilde{SV}_{T,h}\left(\frac{A}{F}, \tilde{i}_{T,h}, \tilde{n}_{T,h}\right) \tag{14.79}$$

or

$$\begin{aligned}\widetilde{EUAW}_{T,h} = -\widetilde{FC}_{T,h}&\left[\frac{\tilde{i}_{T,h}\left(1+\tilde{i}_{T,h}\right)^{\tilde{n}_{T,h}}}{\left(1+\tilde{i}_{T,h}\right)^{\tilde{n}_{T,h}}-1}\right]\\ &- \widetilde{UAC}_{T,h} + \widetilde{UAB}_{T,h} + \widetilde{SV}_{T,h}\left[\frac{\tilde{i}_{T,h}}{\left(1+\tilde{i}_{T,h}\right)^{\tilde{n}_{T,h}}-1}\right]\end{aligned} \tag{14.80}$$

Aggregation of triangular intuitionistic fuzzy parameters is performed as in the previous sections and later the defuzzified values of the parameters are substituted into Eq. 14.80.

14.4 A Numerical Illustration

A chemical products company uses a thermoplastic polymer to enhance the appearance of its panels. Over a 3-year period, the costs and revenues associated with one product line are as in Table 14.1. The other possible parameter values are represented by ordinary fuzzy sets, intuitionistic fuzzy sets, and triangular hesitant fuzzy sets as given in Tables 14.1, 14.2, 14.3, 14.4 and 14.5.

Table 14.1 Experts' Compromised Membership Degrees based on OFS

Parameter	Possible values	Experts' compromised membership degree
FC	$10,000	0.7
	$12,000	0.7
	$14,000	0.9
UAC	$3,000	0.7
	$4000	0.9
	$5000	0.8
UAB	$8000	0.9
	$9000	0.9
	$10,000	0.9
SV	$5000	0.9
	$6000	0.9
	$7000	0.7
i	7 %	0.7
	8 %	0.8
	9 %	0.6

14.4.1 Solution Using Ordinary Fuzzy Annual Worth

Table 14.1 shows the possible values of parameters and their corresponding compromised membership degrees based on experts' evaluations using ordinary fuzzy sets.

In the following we calculate the annual worth in three different approaches. In the first approach, we calculate the expected value based on possibilities. This is similar to the expected value calculation in the probability theory. In the second approach, we apply possibility based max-max approach. In this approach, the annual worth is calculated by using the parameters with maximum membership degrees. The third approach is called possibility based min-min approach. In this approach, the annual worth is calculated by using the parameters with minimum membership degrees. At the end, we present all the results in a unique fuzzy set.

Possibility based expected value approach:

$$\begin{aligned}\widetilde{AW} &= -(12,173.91;0.767)\left(\frac{A}{P},(8.0\,\%;0.700),3\right) - (4,041.67;0.800)\\ &\quad + (9,000;0.900) + (5,920;0.833)\left(\frac{A}{F},(8.0\,\%;0.700),\ 3\right)\\ \widetilde{AW} &= (2,062.91;0.700)\end{aligned}$$

Table 14.2 Experts' compromised membership degrees based on IVIFS

		Experts' weights		
		E1	E2	E3
Parameter	Possible values	0.5	0.3	0.2
FC	\$15,000	([0.2,0.7] [0.1,0.2])	([0.1,0.4] [0.4,0.5])	([0.1,0.3] [0.45,0.6])
	\$16,000	([0.2,0.7] [0.2,0.3])	([0.1,0.6] [0.2,0.3])	([0.1,0.7][0.3,0.3])
	\$17,000	([0.4,0.9] [0.05,0.1])	([0.4,0.9] [0.1,0.1])	([0.1,0.5][0.5,0.4])
UAC	\$2000	([0.1,0.7] [0.05,0.2])	([0.2,0.5] [0.25,0.4])	([0.2,0.4][0.4,0.5])
	\$3000	([0.3,0.7] [0.05,0.3])	([0.1,0.4] [0.35,0.5])	([0.3,0.9][0.1,0.1])
	\$4000	([0.4,0.8] [0.1,0.2])	([0.1,0.3] [0.45,0.6])	([0.4,0.8][0.1,0.2])
UAB	\$7000	([0.1,0.7] [0.05,0.3])	([0.3,0.5] [0.25,0.5])	([0.2,0.9][0.1,0.1])
	\$8000	([0.5,0.9] [0.1,0.1])	([0.4,0.9] [0.1,0.1])	([0.1,0.8][0.1,0.2])
	\$9000	([0.4,0.8] [0.2,0.2])	([0.4,0.8] [0.2,0.2])	([0.2,0.9][0.1,0.1])
SV	\$4000	([0.5,0.9] [0.1,0.1])	([0.3,0.8] [0.1,0.2])	([0.1,0.4] [0.35,0.5])
	\$5000	([0.2,0.7] [0.3,0.3])	([0.2,0.4] [0.6,0.6])	([0.1,0.9][0.1,0.1])
	\$6000	([0.2,0.5] [0.3,0.4])	([0.1,0.3] [0.7,0.7])	([0.3,0.7][0.1,0.2])
i	6 %	([0.1,0.4] [0.4,0.5])	([0.1,0.7] [0.1,0.2])	([0.1,0.3] [0.45,0.6])
	7 %	([0.1,0.5] [0.5,0.5])	([0.3,0.8] [0.2,0.2])	([0.2,0.5] [0.35,0.45])
	8 %	([0.2,0.7] [0.2,0.25])	([0.2,0.4] [0.35,0.5])	([0.1,0.4] [0.35,0.5])

Possibility based max-max approach:

$$\widetilde{AW} = -(14,000;0.9)\left(\frac{A}{P}, (8.0\,\%;0.800), 3\right) - (4,000;0.900) + (9,000;0.900) + (5,500;0.900)\left(\frac{A}{F}, (8.0\,\%;0.800),\ 3\right)$$

$$\widetilde{AW} = (1,261.72;0.900)$$

Table 14.3 Aggregated and defuzzified matrix for IVIFS

Parameter	Possible values	Aggregated value	Defuzzified Value
FC	$15,000	([0.141,0.524][0.238,0.366])	0.360
	$16,000	([0.141,0.673][0.226,0.3])	0.412
	$17,000	([0.322,0.838][0.123,0.152])	0.573
UAC	$2000	([0.161,0.569][0.151,0.324])	0.398
	$3000	([0.245,0.734][0.11,0.252])	0.495
	$4000	([0.322,0.709][0.157,0.278])	0.511
UAB	$7000	([0.194,0.748][0.1,0.252])	0.479
	$8000	([0.37,0.877][0.1,0.123])	0.615
	$9000	([0.346,0.838][0.162,0.162])	0.578
SV	$4000	([0.34,0.789][0.146,0.2])	0.556
	$5000	([0.171,0.734][0.266,0.266])	0.441
	$6000	([0.204,0.525][0.278,0.384])	0.377
i	6 %	([0.1,0.49][0.273,0.401])	0.326
	7 %	([0.194,0.62][0.341,0.368])	0.395
	8 %	([0.171,0.545][0.28,0.379])	0.371

Table 14.4 Experts' compromised membership degrees based on triangular HFS

		Experts' weights		
		E1	E2	E3
Parameter	Possible values	0.4	0.3	0.3
FC	$10,000	(0.2,0.4,0.7)	(0.1,0.3,0.4)	(0.1,0.2,0.3)
	$12,000	(0.2,0.6,0.7)	(0.1,0.3,0.6)	(0.1,0.5,0.7)
	$14,000	(0.4,0.6,0.9)	(0.4,0.8,0.9)	(0.1,0.5,0.5)
UAC	$3000	(0.1,0.5,0.7)	(0.2,0.3,0.5)	(0.2,0.3,0.4)
	$4000	(0.3,0.6,0.7)	(0.1,0.3,0.4)	(0.3,0.6,0.9)
	$5000	(0.4,0.4,0.8)	(0.1,0.2,0.3)	(0.4,0.5,0.8)
UAB	$8000	(0.1,0.3,0.7)	(0.3,0.4,0.5)	(0.2,0.8,0.9)
	$9000	(0.5,0.7,0.9)	(0.4,0.5,0.9)	(0.1,0.4,0.8)
	$10,000	(0.4,0.6,0.8)	(0.4,0.6,0.8)	(0.2,0.5,0.9)
SV	$5000	(0.5,0.9,0.9)	(0.3,0.7,0.8)	(0.1,0.2,0.4)
	$6000	(0.2,0.4,0.7)	(0.2,0.3,0.4)	(0.1,0.4,0.9)
	$7000	(0.2,0.3,0.5)	(0.1,0.2,0.3)	(0.3,0.5,0.7)
i	7 %	(0.1,0.3,0.4)	(0.1,0.2,0.7)	(0.1,0.2,0.3)
	8 %	(0.1,0.3,0.5)	(0.3,0.4,0.8)	(0.2,0.4,0.5)
	9 %	(0.2,0.6,0.7)	(0.2,0.3,0.4)	(0.1,0.3,0.4)

Table 14.5 Aggregated and defuzzified values of triangular HFS

Parameter	Possible values	Aggregated value	Defuzzified value
FC	$15,000	(0.141,0.315,0.524)	0.324
	$16,000	(0.141,0.494,0.673)	0.451
	$17,000	(0.322,0.653,0.838)	0.616
UAC	$2000	(0.161,0.388,0.569)	0.377
	$3000	(0.245,0.527,0.734)	0.508
	$4000	(0.322,0.381,0.709)	0.448
UAB	$7000	(0.194,0.541,0.748)	0.506
	$8000	(0.37,0.569,0.877)	0.596
	$9000	(0.346,0.572,0.838)	0.582
SV	$4000	(0.34,0.741,0.789)	0.653
	$5000	(0.171,0.372,0.734)	0.412
	$6000	(0.204,0.341,0.525)	0.353
i	6 %	(0.1,0.242,0.49)	0.268
	7 %	(0.194,0.362,0.62)	0.385
	8 %	(0.171,0.44,0.49)	0.385

Possibility based min-min approach:

$$\widetilde{AW} = -(11{,}000; 0.7)\left(\frac{A}{P}, (9.0\,\%; 0.600), 3\right) - (3{,}000; 0.700) + (9{,}000; 0.900) + (7{,}000; 0.700)\left(\frac{A}{F}, (9.0\,\%; 0.600),\ 3\right)$$

$$\widetilde{AW} = (3{,}789.78; 0.600)$$

The union operation for the above results gives the following set. The most possible annual worth is $1261.72 with a membership degree of 0.900.

$$\cup\left(\widetilde{AW}\right) = \{(3{,}789.78; 0.600), (2{,}062.91; 0.700), (1{,}261.72; 0.900)\}$$

14.4.2 Solution Using Intuitionistic Fuzzy Annual Worth

Table 14.2 shows the possible values of parameters and their corresponding compromised membership degrees based on experts' evaluations using IVIFS.

Table 14.3 presents the aggregated and defuzzified values for IVIFS based on Eqs. 14.42 and 14.44.

Possibility based expected value approach:

$$\widetilde{AW} = -(12,317.12; 0.448)\left(\frac{A}{P}, (7.98\,\%; 0.364), 3\right) - (3,946.05; 0.468)$$
$$+ (8,834.19; 0.557) + (6,217.51; 0.458)\left(\frac{A}{F}, (7.98\,\%; 0.364),\ 3\right)$$
$$\widetilde{AW} = (2,025.91; 0.364)$$

Possibility based max-max approach:

$$\widetilde{AW} = -(14,000; 0.573)\left(\frac{A}{P}, (8.0\,\%; 0.395), 3\right) - (5,000; 0.511)$$
$$+ (9,000; 0.615) + (5,000; 0.556)\left(\frac{A}{F}, (8.0\,\%; 0.395),\ 3\right)$$
$$\widetilde{AW} = (107.69; 0.615)$$

Possibility based min-min approach:

$$\widetilde{AW} = -(10,000; 0.360)\left(\frac{A}{P}, (7.0\,\%; 0.326), 3\right) - (3,000; 0.398)$$
$$+ (8,000; 0.479) + (7,000; 0.377)\left(\frac{A}{F}, (7.0\,\%; 0.326),\ 3\right)$$
$$\widetilde{AW} = (3,366.85; 0.479)$$

The union operation for the above results gives the following set. The most possible annual worth is \$107.69 with a membership degree of 0.615.

$$\cup(\widetilde{AW}) = \{(3,366.85; 0.479), (107.69; 0.615), (2,025.91; 0.364)\}$$

14.4.3 Solution Hesitant Fuzzy Annual Worth

Table 14.4 shows the possible values of parameters and their corresponding compromised membership degrees based on experts' evaluations using triangular HFS.

Table 14.5 presents the aggregated and defuzzified values for Triangular HFS based on Eqs. 14.57 and 14.59.

Possibility based expected value approach:

$$\widetilde{AW} = -(12{,}420.77; 0.464)\left(\frac{A}{P}, (8.1\,\%; 0.346), 3\right) - (4{,}053.52; 0.444) + (9{,}044.99; 0.562) + (5{,}788.65; 0.473)\left(\frac{A}{F}, (8.1\,\%; 0.346),\ 3\right)$$

$$\widetilde{AW} = (1{,}943.11; 0.346)$$

Possibility based max-max approach:

$$\widetilde{AW} = -(14{,}000; 0.616)\left(\frac{A}{P}, (8.5\,\%; 0.385), 3\right) - (4{,}000; 0.508) + (9{,}000; 0.596) + (5{,}000; 0653)\left(\frac{A}{F}, (8.5\,\%; 0.385),\ 3\right)$$

$$\widetilde{AW} = (1{,}051.15; 0.653)$$

Possibility based min-min approach:

$$\widetilde{AW} = -(10{,}000; 0.324)\left(\frac{A}{P}, (7.0\,\%; 0.268), 3\right) - (3{,}000; 0.377) + (8{,}000; 0.506) + (7{,}000; 0.353)\left(\frac{A}{F}, (7.0\,\%; 0.268),\ 3\right)$$

$$\widetilde{AW} = (3{,}366.85; 0.506)$$

The union operation for the above results gives the following set. The most possible annual worth is \$1,051.15 with a membership degree of 0.653.

$$\cup(\widetilde{AW}) = \{(3{,}366.85; 0.4506), (1{,}051.15; 0.653), (1{,}943.11; 0.346)\}$$

14.5 Conclusion

Environmental economics is the application of the principles of economics to the study of how environmental and natural resources are developed and managed. Uncertainty conditions exist in almost all kinds of decision making problems. Incomplete and vague data cause the fuzzy set theory to be used in the solution of these problems. Engineering economy based fuzzy analyses of environmental economics have been proposed in this chapter. New extensions of fuzzy sets such as intuitionistic, hesitant and type-2 fuzzy sets have been employed while proposing these analyses. Illustrative examples showed that these analyses are very successful in handling the uncertainty and vagueness in the data.

For further research we suggest other extensions of fuzzy sets such as nonstationary fuzzy sets, fuzzy multisets, or interval-valued fuzzy sets to be employed in the environmental economic analyses for comparative purposes.

References

Ahman, M., & Holmgren, K. (2006). New entrant allocation in the Nordic energy sectors: Incentives and options in the EU ETS. *Climate Policy, 6*(4), 423–440.

Atanassov, K. (2012). *On intuitionistic fuzzy sets theory*. Berlin: Springer.

Atanassov, K. T. (1986). Intuitionistic fuzzy sets. *Fuzzy Sets and Systems, 20*, 87–96.

Atanassova, L. (2008). On interval-valued intuitionistic fuzzy versions of L. Zadeh's extension principle. *Issues in Intuitionistic Fuzzy Sets and Generalized Nets, 7*, 13–19.

Azeez, K., Zayed, T., & Ammar, M. (2013). Fuzzy-versus simulation-based life-cycle cost for sewer rehabilitation alternatives. *Journal of Performance of Constructed Facilities, 27*(5), 656–665.

Baral, H., Keenan, R. J., Sharma, S. K., Stork, N. E., & Kasel, S. (2014). Economic evaluation of ecosystem goods and services under different landscape management scenarios. *Land Use Policy, 39*, 54–64.

Becker, N., Helgeson, J., & Katz, D. (2014). Once there was a river: A benefit-cost analysis of rehabilitation of the Jordan River. *Regional Environmental Change, 14*(4), 1303–1314.

Carrasco, L. R., & Papworth, S. K. (2014). A ranking of net national contributions to climate change mitigation through tropical forest conservation. *Journal of Environmental Management, 146*, 575–581.

Chen, D., Zhang, L., & Jiao, J. (2010). Triangle fuzzy number intuitionistic fuzzy aggregation operators and their application to group decision making. In F. L. Wang et al., (Eds.), *AICI 2010, Part II, LNAI* (Vol. 6320, pp. 350–357).

Chen, S. J., Hwang, C. L., & Hwang, F. P. (1992). *Fuzzy multiple attribute decision making: Methods and applications*. Berlin: Springer.

Chinowsky, P. S., Price, J. C., & Neumann, J. E. (2013). Assessment of climate change adaptation costs for the U.S. road network. *Global Environmental Change, 23*(4), 764–773.

Chiu, C. Y., & Park, C. S. (1994). Fuzzy cash flow analysis using present worth criterion. *The Engineering Economist, 39*(2), 113–138.

Cooke, R., Wielicki, B. A., Young, D. F., & Mlynczak, M. G. (2014). Value of information for climate observing systems. *Environment Systems and Decisions, 34*(1), 98–109.

Dai, H., Sun, T., & Guo, W. (2016). Brownfield redevelopment evaluation based on fuzzy real options. *Sustainability (Switzerland), 8*(2), 170.

Duke, J. M., Dundas, S. J., Johnston, R. J., & Messer, K. D. (2014). Prioritizing payment for environmental services: Using nonmarket benefits and costs for optimal selection. *Ecological Economics, 105*, 319–329.

Espinoza, R. D., & Rojo, J. (2015). Using DNPV for valuing investments in the energy sector: A solar project case study. *Renewable Energy, 75*, 44–49.

Hanss, M. (2005). *Applied fuzzy arithmetic: An introduction with engineering applications*. Berlin: Springer.

Hardisty, P. E., Sivapalan, M., & Humphries, R. (2013). Determining a sustainable and economically optimal wastewater treatment and discharge strategy. *Journal of Environmental Management, 114*, 285–292.

Jiang, L., Kronbak, J., & Christensen, L. P. (2014). The costs and benefits of sulphur reduction measures: Sulphur scrubbers versus marine gas oil. *Transportation Research Part D: Transport and Environment, 28*, 19–27.

Kahraman, C., Çevik Onar, S., & Öztayşi, B. (2015). Engineering economic analyses using intuitionistic and hesitant fuzzy sets. *Journal of Intelligent & Fuzzy Systems, 29*(3), 1151–1168.

Kahraman, C., Onar, S. C., & Oztaysi, B. (2016). A comparison of wind energy investment alternatives using interval-valued intuitionistic fuzzy benefit/cost analysis. *Sustainability (Switzerland), 8*(2), 118.

Kahraman, C., Ruan, D., & Tolga, E. (2002). Capital budgeting techniques using discounted fuzzy versus probabilistic cash flows. *Information Sciences, 142*(1–4), 57–76.

Karnik, N. N., & Mendel, J. M. (2001). Centroid of a type-2 fuzzy set. *Information Sciences, 132* (1–4), 195–220.

Kaufmann, A., & Gupta, M. M. (1988). *Fuzzy mathematical models in engineering and management science*. Amsterdam: Elsevier.

Kumar, P. S., & Hussain, R. J. (2014). A method for solving balanced intuitionistic fuzzy assignment problem. *International Journal of Engineering Research and Applications, 4*(3), 897–903.

Kunsch, P. L., & Vander Straeten, M. (2015). The cost of a nuclear-fuel repository: A criterion valuation by means of fuzzy logic. In *Evaluation and decision models with multiple criteria: Case studies* (p. 311). Berlin: Springer.

Kuo-Ping, C. (2011). Multiple criteria group decision making with triangular interval type-2 fuzzy sets. In *Proceedings of 2011 IEEE International Conference on Fuzzy Systems (FUZZ)* (pp. 1098–7584) June 27–30, Taipei.

Lia, C., Zhong, S., Duan, L., & Song, Y. (2011). Evaluation of petrochemical wastewater treatment technologies in Liaoning Province of China. *Procedia Environmental Sciences, 10*, 2798–2802.

Mahapatra, G. S., & Roy, T. K. (2009). Reliability evaluation using triangular intuitionistic fuzzy numbers arithmetic operations. *World Academy of Science, Engineering and Technology, 3*(2), 422–429.

Milanesi, G. S., Broz, D., Tohmé, F., & Rossit, D. (2014). Strategic analysis of forest investments using real option: The fuzzy pay-off model (FPOM). *Fuzzy Economic Review, 19*(1), 33–44.

Nepal, P., Ince, P. J., Skog, K. E., & Chang, S. J. (2013). Forest carbon benefits, costs and leakage effects of carbon reserve scenarios in the United States. *Journal of Forest Economics, 19*(3), 286–306.

Niewiadomski, A., Ochelska, J., & Szczepaniak, P. S. (2006). Interval-valued linguistic summaries of databases. *Control and Cybernetics, 35*(2), 415–443.

Petković, D., Shamshirband, S., Kamsin, A., Lee, M., Anicic, O., & Nikolić, V. (2016). Survey of the most influential parameters on the wind farm net present value (NPV) by adaptive neuro-fuzzy approach. *Renewable and Sustainable Energy Reviews, 57*, 1270–1278.

Quintero, A., Konare, D., & Pierre, S. (2005). Prototyping an intelligent decision support system for improving urban infrastructures management. *European Journal of Operational Research, 162*(3), 654–672.

Ross, T. J. (1995). *Fuzzy logic with engineering applications*. USA: McGraw-Hill.

Shamshirband, S., Petković, D., Ćojbašić, Ž., Nikolić, V., Anuar, N. B., Mohd Shuib, N. L., et al. (2014). Adaptive neuro-fuzzy optimization of wind farm project net profit. *Energy Conversion and Management, 80*, 229–237.

Sharda, V. N., Dogra, P., & Sena, D. R. (2015). Comparative economic analysis of inter-crop based conservation bench terrace and conventional systems in a sub-humid climate of India. *Resources, Conservation and Recycling, 98*, 30–40.

Sheen, J. N. (2009). Applying fuzzy engineering economics to evaluate project investment feasibility of wind generation. *WSEAS Transactions on Systems, 8*(4), 501–510.

Sheen, J. N. (2014a). Valuing wind power project on renewable electricity whole-sale tariff in power market. *Applied Mechanics and Materials, 483*, 664–667.

Sheen, J. N. (2014b). Real option analysis for renewable energy investment under uncertainty. *Lecture Notes in Electrical Engineering, 293*, 283–289.

Sheley, R., Sheley, J., & Smith, B. (2014). Cost/benefit analysis of managing invasive annual grasses in partially invaded sagebrush steppe ecosystems. *Weed Science, 62*(1), 38–44.

Singh, S., & Mishra, A. (2014). Deforestation-induced costs on the drinking water supplies of the Mumbai metropolitan. *India Global Environmental Change, 27*(1), 73–83.

Tim Chamen, W. C., Moxey, A. P., Towers, W., Balana, B., & Hallett, P. D. (2015). Mitigating arable soil compaction: A review and analysis of available cost and benefit data. *Soil and Tillage Research, 146*, 10–25.

Torra, V. (2010). Hesitant fuzzy sets. *International Journal of Intelligent Systems, 25*(6), 529–539.

Uçal Sarı, I., & Kahraman, C. (2015). Interval type-2 fuzzy capital budgeting. *International Journal of Fuzzy Systems, 17*(4), 635–646.

Vahdat-Aboueshagh, H., Nazif, S., & Shahghasemi, E. (2014). Development of an algorithm for sustainability based assessment of reservoir life cycle cost using fuzzy theory. *Water Resources Management, 28*(15), 5389–5409.

Wicke, B., Smeets, E. M. W., Akanda, R., Stille, L., Singh, R. K., Awan, A. R., et al. (2013). Biomass production in agroforestry and forestry systems on salt-affected soils in South Asia: Exploration of the GHG balance and economic performance of three case studies. *Journal of Environmental Management, 127*, 324–334.

Winans, K. S., Tardif, A.-S., Lteif, A. E., & Whalen, J. K. (2015). Carbon sequestration potential and cost-benefit analysis of hybrid poplar, grain corn and hay cultivation in southern Quebec, Canada. *Agroforestry Systems, 89*(3), 421–433.

Wolf, K. L., Measells, M. K., Grado, S. C., & Robbins, A. S. T. (2015). Economic values of metro nature health benefits: A life course approach. *Urban Forestry and Urban Greening, 14*(3), 694–701.

Xia, M. M., & Xu, Z. S. (2011). Hesitant fuzzy information aggregation in decision making. *International Journal Approximate Reasoning, 52*, 395–407.

Xu, Z.-S. (2007). Methods for aggregating interval-valued intuitionistic fuzzy information and their application to decision making. *Control and Decision, 22*(2), 215–219.

You, L., Li, Y. P., Huang, G. H., & Zhang, J. L. (2014). Modeling regional ecosystem development under uncertainty—A case study for New Binhai District of Tianjin. *Ecological Modelling, 288*, 127–142.

Yu, D. (2013). Triangular hesitant fuzzy set and its application to teaching quality evaluation. *Journal of Information & Computational Science, 10*(7), 1925–1934.

Zadeh, L. A. (1965). Fuzzy sets. *Information and Control, 8*(3), 338–353.

Zadeh, L. A. (1974). Fuzzy logic and its application to approximate reasoning. *Information Processing, 74*, 591–594.

Zadeh, L. A. (1975). The concept of a linguistic variable and its application to approximate reasoning—I. *Information Sciences, 8*(3), 199–249.

Zhang, Y., White, M. A., & Colosi, L. M. (2013). Environmental and economic assessment of integrated systems for dairy manure treatment coupled with algae bioenergy production. *Bioresource technology, 130*, 486–494.

Zhao, H., & Guo, S. (2015). External benefit evaluation of renewable energy power in China for sustainability. *Sustainability (Switzerland), 7*(5), 4783–4805.

Chapter 15
Economic Analysis of Municipal Solid Waste Collection Systems Using Type-2 Fuzzy Net Present Worth Analysis

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Abstract Solid waste management is one of the most important concepts of environmental management due to its direct effect on citizens' life standards and public health. In this chapter it is aimed to compare underground waste bins and roadside waste bins in a solid waste collection system from economic perspective using type-2 fuzzy net present worth analysis. Results show that underground waste bins should be preferred instead of roadside bins even if they have higher initial investment costs.

15.1 Introduction

Solid waste management is one of the most important issues in environmental management, especially for the developing countries. In a developing country, the increase on industrial activities mostly occurs an increase on the volume of the generated solid wastes and it changes their composition. Municipalities of the developing countries should pay more attention on the solid waste management to aware the penalties in the form of resources needlessly lost and a staggering adverse impact on the environment and on public health and safety (UNEP 2005).

In developed countries mostly separated collection is preferred for the municipal solid waste collection whereas in the developing countries wastes are mostly collected mixed. For both of the collection types a solid waste collection systems require an effective planning which includes determination of the collection points, the container capacities in that points, the route of the collection process and the transportation of the solid wastes to the disposal areas. To construct an efficient solid waste collection system, there is one more important point which could affect

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all of the system requirements, is the determination of the container that which will be used in the system. There are several types of containers which are suitable for different purposes such as separate collection or underground collection of the solid wastes and each of them has different properties such as resistance, capacity, sealing, odor tightness, volume etc. Determination of the waste bins will also determine the trucks used for the collection and the schedule of the transportation. For example, if wastes are collected with roadside bins rather than underground bins, the collection should be scheduled more often to avoid the odor and the visual pollution. The labor requirements, type of the trucks are also affected by this choice.

There are several criteria which will lead the determination process of a solid waste collection system. The habits of the population, especially for the separate collection, types of the solid wastes generated by the citizens, location limitations and the costs of the system are some of them. Total cost of a solid waste collection system is an important criterion which is used to determine the best appropriate alternative collection system could be calculated by environmental economic techniques. The economic evaluation of the alternative systems could be complex. The reason is that a particular container type could change the schedule and the route of the transportation of the solid wastes. In the evaluation process all system should be considered at once including the labor costs, transportation costs, investment costs of the trucks and containers, fuel consumption of the trucks and the maintenance costs. Some of these parameters could be uncertain in the evaluation period. Therefore, the usage of intelligent techniques in the evaluation process will result in more accurate evaluations of the alternatives.

Fuzzy logic is one of the most used intelligent technique in the environmental economics to handle the uncertainty. Definition of the parameters in terms of fuzzy numbers enables the analysts to consider the effect of uncertainty of the unknown or unpredictable parameters and by this way the vagueness on the parameters for the future such as the capacity requirement or the fuel costs could be included in the evaluation process. There are several fuzzy environmental analysis techniques used in the literature. Most of the studies used discounted cash flow analysis techniques such as present worth, equivalent annual worth, benefit cost ratio analysis and internal rate of return analysis using different types of fuzzy numbers such as type-1 fuzzy numbers, type-2 fuzzy numbers, intuitionistic fuzzy numbers and hesitant fuzzy numbers. Each method is suitable for different situations. For example, present worth is better for the alternatives which has equal useful lives where equivalent annual worth analysis is better for the alternatives which have different useful lives. It is same for the fuzzification process. The amount of the uncertainty derives the type of the fuzzy number which should be preferred during the analysis. For example, type-1 fuzzy numbers use crisp numbers in the determination of the membership functions of a fuzzy number whereas type-2 fuzzy numbers use type-1 fuzzy numbers in the determination of the fuzzy membership function. Intuitionistic fuzzy numbers take into account the membership value as well as the non-membership value whereas hesitant fuzzy numbers defined in terms of a function that returns a set of membership values for each element in the domain.

In this chapter, it is aimed to evaluate different solid waste collection systems in terms of environmental economics using interval type-2 fuzzy net present value analysis. For this purpose, a pilot region is selected in Istanbul which is the most developed city in Turkey, and two collection system alternatives are evaluated by solid waste managers and the economy department to determine the best solid waste collection system.

The chapter is organized as follows. In the next section, a detailed literature review is given on solid waste management systems. Then the main concepts of solid waste management are determined. After introducing the basics of interval type-2 fuzzy sets, the interval type-2 fuzzy net present value method is determined. In the application section two solid waste collection systems are compared due to their economic evaluations. Finally, the chapter is concluded with interpretation of the results.

15.2 Literature Review

When the literature on solid waste management is examined, it is seen that most of the studies are focused on the optimization and the transportation of the solid waste collection systems. Xue et al. (2015) review the current municipal solid waste collection and disposal systems in Singapore and propose a spatial allocation model which is especially for the problematic allocation of incineration resources. Lopez et al. (2015) generate an approach for a multi-depot vehicle routing problem. In this paper, alternative scenarios are studied where two different locations for one or two additional depots for a recyclable waste collection system, in order to increase efficiency in their operations. Kinobe et al. (2015) use geographic information system tools to optimize travel distances, trips and collection time, which leads to maximizing total waste collection, yielding large savings and keeping the environment clean. Alshraideh and Abu Qdais (2016) propose a route scheduling model to minimize the total travel distance which in turn minimizes transportation cost and reduces emissions for the medical waste collection. Rabbani et al. (2016) propose a multimodal transportation system to minimize total cost of waste collection routing problem by using tabu search and genetic algorithm. Xue and Cao (2016) propose a hybrid model which combines the ant colony optimization based multi-objective routing model with min-max model and Dijkstra's algorithm to address the question of which route to take from waste-generating points to the target incineration plants considering travel time, accident probability, and population exposure. Willemse and Joubert (2016) evaluate four constructive heuristics capable of computing feasible solutions for mixed capacity arc routing problem under time restrictions with intermediate facilities with a primary objective to either minimize total cost or to minimize the fleet size with an application in municipal waste collection. Oliveira et al. (2015) analyze the impact of using vehicles with multiple compartments in a recyclable waste collection system with a heuristic approach. Maimoun et al. (2016) use TOPSIS and simple additive weighting methods, to rank fuel alternatives for the U.S. waste collection industry with respect to a multi-level environmental and financial decision matrix. Mamun et al. (2016) propose a novel model, architecture and intelligent sensing algorithm for real time solid waste bin monitoring system that would contribute to the solid waste collection optimization. Huang and Lin (2015) propose a bi-level optimization formulation to model the split delivery vehicle routing problem with multiple trips to determine the minimum-distance route. In this formulation the first stage optimally plans the collection points that cover all residential blocks and the second stage applies a heuristics method to solve the minimum vehicles used and minimum distance traveled for collecting residential waste.

Although economic perspective is one of the most determining criteria for the solid waste collection and transportation systems, just a few of the articles are focused on the economic perspectives of these systems. Franchetti and Dellinger (2014) analyze the economic prospects for the utilization of food waste collected from different sources as feedstock for a standalone waste-to-energy business model in Toledo. In this study internal rate of return method and present worth methods are used to examine two scenarios. Kadama (2013) investigate and evaluate the alternative methods for implementing proposed changes at communal waste collection points in Mafikeng city by using internal rate of return, net present worth and payback period methods. Regué and Bristow (2013) analyze the waste trams in Barcelona to explore the costs and benefits, by means of a cost benefit analysis and to identify the factors that critically influence the potential success or failure of schemes and to examine through sensitivity testing ways of improving performance. Cost benefit analysis is carried out based on the best available public domain information and with clearly specified assumptions. Ninni (2011) investigates the existence of economies of scale and other economic parameters influencing the rate of return of the domestic solid waste collection process. The investigating approach is performed via the transcendental logarithmic cost function, a member of the family of flexible functions, which was selected as the most suitable for a particular application. Wang et al. (2014) use internal rate of return method to valuate an improved solid waste collection and disposal service for a poor country in China. Kerstens et al. (2015) analyze solid waste systems according to land requirement, compost and energy production and recovery of plastic and paper. They compared investments, operational costs and benefits and total lifecycle costs of all investigated options.

As it is seen from the literature review the solid waste collection and transportation systems are very popular. To the best of our knowledge, there is no study which compares the usage of different solid waste bins. Therefore, in this chapter, the effect of using different kinds of solid waste bins in a solid waste collection system are evaluated in terms of environmental economics.

15.3 Solid Waste Collection Systems

Economic and rapid urbanization growth has led to over exploitation of natural resources which indirectly has also increased waste quantity production especially in the urban area (Anand 2010). The increase waste quantity imposes the obligation of having an efficient solid waste management system to avoid disease and to have an aesthetic environment in the urban areas. In solid waste management there are four main phases which should be under consideration.

The first phase is waste generation. In this phase appropriate strategies should be taken to minimize the amount of generated waste on source. One of the most popular and most effective waste minimization strategy is recycling. To have an effective recycling process for the municipal wastes, it is suggested to collect wastes separately on sources. This strategy could increase the load of the solid waste collection phase whereas it reduces the amount of the wastes which will be transported to the disposal areas. The second phase is solid waste collection. In this phase the waste load of the region, the required collection points and their locations, the type and the number of the waste bins and the waste trucks and the schedule of the collection process are determined. Third phase is transportation of the wastes. It includes the collection of the wastes from waste bins to with a suitable waste truck and transport the wastes to the disposal areas or temporary disposal points. The most important part of this phase is the scheduling of the transportation process. It requires an efficient schedule which will minimize the costs by providing an aesthetic environment. The fourth and the last phase is disposal. It includes the selection of the suitable disposal area and transfer stations and the management of the disposed wastes.

Management requires safe collection, transportation and disposal, but sustainable management requires an integrated system. This includes large increase in efficiency investment economically feasible recycling with a stable market for end products and shouldering of responsibility by government industry and individual (Harris 2004).

In this chapter we will focus on the solid waste collection and transportation phases from an economic perspective. Therefore, these two phases will be examined in detail at rest of this section. The steps of the solid waste collection and transportation phases are explained below:

- Determination of the waste load of the region: There are several steps involved in calculating reasonable and usable set of waste quantity projections which are establishment of unit waste factors, establishment of waste generation districts, obtaining transportation data, employment projections and population projections, calculation of future waste quantities and estimation of future composition shifts. The analyst should keep in mind that the analysis should be done for long term periods, average over 10–20 years. (Russell et al. 1986).

- Determination of the required collection points and their locations, the type and the number of the waste bins and the waste trucks: The design of an efficient collection system needs careful selection of type and size and location for the containers. Appropriate storage containers are required to save energy and labor and increase the speed of collection and reduce the crew size. It is important that the containers should be functional to the type of materials and the collection vehicles used. Containers should also be durable, easy to handle, economical as well as resistant to corrosion, weather conditions and metals, glass tips etc. Usually these are made up of thick plastics. When mechanized collection system is used the containers are specially designed to fit the truck mounted loading mechanisms. (Hosetti 2006). After determination of the waste bins and appropriate waste trucks that will be used in the solid waste collection system, the number of the collection points is determined using the capacity of the bins and the predictions on the waste generation of the region. The locations of the collection points should be determined considering several factors such as the traffic density, accessibility, aesthetic concerns and the distance to the main transportation route.
- Determination of the collection schedule and the route: Efficient routing of solid waste collection vehicles can help decrease costs by reducing labor expended for collection. Routing procedures usually consists of two separate components which are macro routing and micro routing. Macro routing consists of dividing the total collection area into routes, sized in such a way as to represent a day's collection for each crew. The size of each route depends on the amount of waste collected per stop, distance between stops, loading time and traffic conditions. Micro-routing can define the specific path that each crew and collection vehicle will take each collection day using the results of the macro routing analysis. It should also include input and review from experienced collection drivers. In the determination of the routes, it is suggested to pay attention to avoid from overlapping routes (Ramachandra 2006).
- Determination of the transfer stations: Transfer station is a centralized facility, where waste is unloaded from smaller collection vehicles and re-loaded into large vehicles for transport to a disposal or processing site. Types of waste received, processes required in recovering material from wastes, required capacity and amount of waste storage desired, types of collection vehicles using the facility, types of transfer vehicles that can be accommodated at the disposal facilities and site topography are the main factors that affect the selection of a transfer station (Ramachandra 2006).

To design and operate an efficient solid waste collection system, it is important to analyze the options of all the components both in economic and social perspectives. In the next section one of the intelligent economic analysis techniques is introduced which could be suitable for the economic analysis of solid waste collection systems.

15.4 Interval Type-2 Fuzzy Net Present Value Analysis

In this section, at first the basic information on interval type-2 fuzzy sets is given then the formulas needed for fuzzy net present value analysis are determined as follows.

15.4.1 Type-2 Fuzzy Sets

The concept of a type-2 fuzzy set was introduced by Zadeh as an extension of the concept of an ordinary fuzzy set called a type-1 fuzzy set (Zadeh 1974). Such sets are fuzzy sets whose membership grades themselves are type-1 fuzzy sets; they are very useful in circumstances where it is difficult to determine an exact membership function for a fuzzy set; hence, they are useful for incorporating linguistic uncertainties, e.g., the words that are used in linguistic knowledge can mean different things to different people (Karnik and Mendel 2001).

A type-2 fuzzy sets $\tilde{\tilde{A}}$ in the universe of discourse X can be represented by a type-2 membership function $\mu_{\tilde{\tilde{A}}}$, shown as follows (Zadeh 1975):

$$\tilde{\tilde{A}} = \{((x,u), \mu_{\tilde{\tilde{A}}}(x,u) | \forall x \in X, \forall u \in J_x \subseteq [0,1], 0 \le \mu_{\tilde{\tilde{A}}}(x,u) \le 1\} \tag{15.1}$$

where J_x denotes an interval [0,1].

Triangular interval type-2 fuzzy sets are the most used interval type-2 fuzzy sets in the literature. A triangular interval type-2 fuzzy set is illustrated as $\tilde{\tilde{A}}_i = ((a_{il}^U, a_{im}^U, a_{ir}^U; H(\tilde{A}_i^U)), (a_{il}^L, a_{im}^L, a_{ir}^L; H(\tilde{A}_i^L)))$ where $\tilde{A}_i^L$ and $\tilde{A}_i^U$ are type-1 fuzzy sets, $a_{il}^U, a_{im}^U, a_{ir}^U, a_{il}^L, a_{im}^L$ and a_{ir}^L are the references points of the interval type-2 fuzzy set $\tilde{\tilde{A}}_i$, $H(\tilde{A}_i^U)$ denotes the membership value of the element a_i^U in the upper triangular membership function $\tilde{A}_i^U$, $H(\tilde{A}_i^L)$ denotes the membership value of the element a_i^L in the lower triangular membership function $\tilde{A}_i^L$, $H(\tilde{A}_i^U) \in [0,1], H(\tilde{A}_i^L) \in [0,1]$ and $1 \le i \le 2$.

The basic algebraic operations which are addition, subtraction, multiplication, multiplication with a scalar $k > 0$, division, inverse and root operations of type-2 fuzzy sets $\tilde{\tilde{A}}_1 = ((a_{1l}^U, a_{1m}^U, a_{1r}^U; H(\tilde{A}_1^U)), (a_{1l}^L, a_{1m}^L, a_{1r}^L; H(\tilde{A}_1^L)))$ and $\tilde{\tilde{A}}_2 = ((a_{2l}^U, a_{2m}^U, a_{2r}^U; H(\tilde{A}_2^U)), (a_{2l}^L, a_{2m}^L, a_{2r}^L; H(\tilde{A}_2^L)))$ are given in Eqs. 15.2–15.5 respectively (Kuo-Ping 2011):

$$\begin{aligned} \tilde{\tilde{A}}_1 \oplus \tilde{\tilde{A}}_2 = ((&a_{1l}^U + a_{2l}^U; a_{1m}^U + a_{2m}^U; a_{1r}^U + a_{2r}^U; \min(H(\tilde{A}_1^U); H(\tilde{A}_2^U))), \\ &(a_{1l}^L + a_{2l}^L; a_{1m}^L + a_{2m}^L; a_{1r}^L + a_{2r}^L; \min(H(\tilde{A}_1^L); H(\tilde{A}_2^L))) \end{aligned} \tag{15.2}$$

$$\tilde{\tilde{A}}_1 - \tilde{\tilde{A}}_2 = ((a_{1l}^U - a_{2r}^U; a_{1m}^U - a_{2m}^U; a_{1r}^U - a_{2l}^U; \min(H(\tilde{A}_1^U); H(\tilde{A}_2^U))), \\ (a_{1l}^L - a_{2r}^L; a_{1m}^L - a_{2m}^L; a_{1r}^L - a_{2l}^L; \min(H(\tilde{A}_1^L); H(\tilde{A}_2^L))) \tag{15.3}$$

$$\tilde{\tilde{A}}_1 \otimes \tilde{\tilde{A}}_2 = ((a_{1l}^U \times a_{2l}^U; a_{1m}^U \times a_{2m}^U; a_{1r}^U \times a_{2r}^U; \min(H(\tilde{A}_1^U); H(\tilde{A}_2^U))), \\ (a_{1l}^L \times a_{2l}^L; a_{1m}^L \times a_{2m}^L; a_{1r}^L \times a_{2r}^L; \min(H(\tilde{A}_1^L); H(\tilde{A}_2^L))) \tag{15.4}$$

$$k\tilde{\tilde{A}}_1 = ((k \times a_{1l}^U; k \times a_{1m}^U; k \times a_{1r}^U; H(\tilde{A}_1^U)), (k \times a_{1l}^L; k \times a_{1m}^L; k \times a_{1r}^L; H(\tilde{A}_1^L)) \tag{15.5}$$

$$\frac{\tilde{\tilde{A}}_1}{\tilde{\tilde{A}}_2} \cong ((\frac{a_{1l}^U}{a_{2r}^U}, \frac{a_{1m}^U}{a_{2m}^U}, \frac{a_{1r}^U}{a_{2l}^U}; \min(H(\tilde{A}_1^U), H(\tilde{A}_1^U))), (\frac{a_{1l}^L}{a_{2r}^L}, \frac{a_{1m}^L}{a_{2m}^L}, \frac{a_{1r}^L}{a_{2l}^L}; \min(H(\tilde{A}_1^L); H(\tilde{A}_2^L))) \tag{15.6}$$

$$\frac{1}{\tilde{\tilde{A}}_1} \cong ((\frac{1}{a_{1r}^U}, \frac{1}{a_{1m}^U}, \frac{1}{a_{1l}^U}; H(\tilde{A}_1^U)), (\frac{1}{a_{1r}^L}, \frac{1}{a_{1m}^L}, \frac{1}{a_{1l}^L}; H(\tilde{A}_1^L))) \tag{15.7}$$

$$\sqrt[n]{\tilde{\tilde{A}}_1} = ((\sqrt[n]{a_{1l}^U}, \sqrt[n]{a_{1m}^U}, \sqrt[n]{a_{1r}^U}; H(\tilde{A}_1^U)), \ (\sqrt[n]{a_{1l}^L}, \sqrt[n]{a_{1m}^L}, \sqrt[n]{a_{1r}^L}; H(\tilde{A}_1^L))) \tag{15.8}$$

15.4.2 Defuzzification of Type-2 Fuzzy Numbers

Defuzzification of a type-2 fuzzy set consists of two steps. In the first step, a type-2 fuzzy set is determined as a type-1 fuzzy set by using type reduction process. Then one of the defuzzification methods for ordinary (type-1) fuzzy sets is used to find the equivalence of the type-2 fuzzy set (Karnik and Mendel 2001). There is a lot of type reduction methods proposed in the literature. In this chapter type reduction indices which are proposed by Niewiadomski et al. (2006) are used to determine a type-2 fuzzy set as a type-1 fuzzy set and then mode of the ordinary fuzzy set is taken to determine the crisp equivalent of the type-2 fuzzy set.

Type reduction indices method: Niewiadomski et al. (2006) proposed optimistic, pessimistic, realistic and weighted average indices which determine different points of view for the type reduction of interval type-2 fuzzy sets. If $\tilde{\tilde{A}}$ is an interval-valued fuzzy set in the universe X, and $\underline{\mu}_{\tilde{A}}(x), \overline{\mu}_{\tilde{A}}(x)$ are its lower and upper membership functions, Eqs. 15.9–15.12 which transform $\tilde{\tilde{A}}$ into an ordinary fuzzy set are type-reductions.$TR_{opt}(\tilde{\tilde{A}})$ determines optimistic type reduction of $\tilde{\tilde{A}}$, $TR_{pess}(\tilde{\tilde{A}})$ determines pessimistic type reduction of $\tilde{\tilde{A}}$, $TR_{re}(\tilde{\tilde{A}})$ determines realistic type reduction of $\tilde{\tilde{A}}$ and $TR_{wa}(\tilde{\tilde{A}})$ determines weighted average type reduction of $\tilde{\tilde{A}}$.

$$TR_{opt}(\tilde{\tilde{A}}) = \overline{\mu}_{\tilde{A}}(x), \quad x \in X \tag{15.9}$$

$$TR_{pess}(\tilde{\tilde{A}}) = \underline{\mu}_{\tilde{A}}(x), \quad x \in X \tag{15.10}$$

$$TR_{re}(\tilde{\tilde{A}}) = \frac{\underline{\mu}_{\tilde{A}}(x) + \overline{\mu}_{\tilde{A}}(x)}{2}, \quad x \in X \tag{15.11}$$

$$TR_{wa}(\tilde{\tilde{A}}) = w_1\underline{\mu}_{\tilde{A}}(x) + w_2\overline{\mu}_{\tilde{A}}(x), \quad x \in X \tag{15.12}$$

where w_1, w_2 are coefficients which satisfy the equation "$w_1 + w_2 = 1$".

The type reduction indices method allows us to determine an interval type-2 fuzzy set in the terms of an ordinary fuzzy set. To rank the ordinary fuzzy sets there are lots of defuzzification methods in the literature. In this chapter, mode of an ordinary fuzzy set which is one of the easiest defuzzification method for an interval ordinary fuzzy set is used. The purpose of this method is to find the value which divides the area below the membership function into two equal areas. In Eq. 15.13 mode of an interval fuzzy set $\tilde{M} = [M_L; M_R]$ is determined:

$$\text{Mode}_{\tilde{M}} = \frac{M_L + M_R}{2} \tag{15.13}$$

15.4.3 Type-2 Fuzzy Net Present Worth Method

Type-2 fuzzy net present worth method has been proposed by Uçal Sarı and Kahraman (2015) for the first time. Triangular interval type-2 fuzzy net present value $(N\tilde{\tilde{P}}V)$ is formulized in Eq. 15.14 where $\tilde{\tilde{F}}_t = (f_{tl}^U, f_{tm}^U, f_{tr}^U; H(\tilde{f}_t^U)), (f_{tl}^L, f_{tm}^L, f_{tr}^L; H(\tilde{f}_t^L))$ denotes the cash flow occurred at time t, $\tilde{\tilde{i}}_t = (i_{tl}^U, i_{tm}^U, i_{tr}^U; H(\tilde{i}_t^U)), (i_{tl}^L, i_{tm}^L, i_{tr}^L; H(\tilde{i}_t^L))$, $\forall \tilde{i} > 0$ denotes the discount rate at time t and n represents useful life of the investment:

$$\begin{aligned}
N\tilde{\tilde{P}}V = &((\sum_{t=0}^{n}(\frac{\max(f_{tl}^U,0)}{\prod_{t'=0}^{t}(1+i_{t'r}^U)} + \frac{\min(f_{tl}^U,0)}{\prod_{t'=0}^{t}(1+i_{t'l}^U)}), \sum_{t=0}^{n}\frac{f_{tm}^U}{\prod_{t'=0}^{t}(1+i_{t'm}^U)}, \\
&+ \sum_{t=0}^{n}(\frac{\max(f_{tr}^U,0)}{\prod_{t'=0}^{t}(1+i_{t'l}^U)} + \frac{\min(f_{tr}^U,0)}{\prod_{t'=0}^{t}(1+i_{t'r}^U)}); \min(H(\tilde{f}_t^U), H(\tilde{i}_t^U))), \\
&(\sum_{t=0}^{n}(\frac{\max(f_{tl}^L,0)}{\prod_{t'=0}^{t}(1+i_{t'r}^L)} + \frac{\min(f_{tl}^L,0)}{\prod_{t'=0}^{t}(1+i_{t'l}^L)}), \sum_{t=0}^{n}\frac{f_{tm}^L}{\prod_{t'=0}^{t}(1+i_{t'm}^L)}, \\
&\sum_{t=0}^{n}(\frac{\max(f_{tr}^L,0)}{\prod_{t'=0}^{t}(1+i_{t'l}^L)} + \frac{\min(f_{tr}^L,0)}{\prod_{t'=0}^{t}(1+i_{t'r}^L)}); \min(H(\tilde{f}_t^L), H(\tilde{i}_t^L))))
\end{aligned} \tag{15.14}$$

When the cash flows of the investment alternative are same during its useful life triangular type-2 fuzzy net present value formula can be rewritten as in Eq. 15.15.

$$\begin{aligned}
N\tilde{\tilde{P}}V = & ((I_l^U + \frac{\max(A_l^U,0)\times((1+i_r^U)^n-1)}{i_r^U(1+i_r^U)^n} + \frac{\min(A_l^U,0)\times((1+i_l^U)^n-1)}{i_l^U(1+i_l^U)^n} + \frac{S_l^U}{(1+i_r^U)^n}),\\
& (I_m^U + \frac{A_m^U\times((1+i_m^U)^n-1)}{i_m^U(1+i_m^U)^n} + \frac{S_m^U}{(1+i_m^U)^n}),\\
& (I_r^U + \frac{\max(A_r^U,0)\times((1+i_l^U)^n-1)}{i_l^U(1+i_l^U)^n} + \frac{\min(A_r^U,0)\times((1+i_r^U)^n-1)}{i_l^U(1+i_r^U)^n} + \frac{S_r^U}{(1+i_l^U)^n});\\
& \min(H(\tilde{A}^U),H(\tilde{i}^U),H(\tilde{I}^U),H(\tilde{S}^U)),\\
& (I_l^L + \frac{\max(A_l^L,0)\times((1+i_r^L)^n-1)}{i_r^L(1+i_r^L)^n} + \frac{\min(A_l^L,0)\times((1+i_l^L)^n-1)}{i_l^L(1+i_l^L)^n} + \frac{S_l^L}{(1+i_r^L)^n}),\\
& (I_m^L + \frac{A_m^L\times((1+i_m^L)^n-1)}{i_m^L(1+i_m^L)^n} + \frac{S_m^L}{(1+i_m^L)^n}),\\
& (I_r^L + \frac{\max(A_r^L,0)\times((1+i_l^L)^n-1)}{i_l^L(1+i_l^L)^n} + \frac{\min(A_r^L,0)\times((1+i_r^L)^n-1)}{i_l^L(1+i_r^L)^n} + \frac{S_r^L}{(1+i_l^L)^n});\\
& \min(H(\tilde{A}^L),H(\tilde{i}^L),H(\tilde{I}^L),H(\tilde{S}^L)))
\end{aligned} \tag{15.15}$$

where $\tilde{\tilde{I}} = ((I_l^U, I_m^U, I_r^U; H(\tilde{I}^U)),(I_l^L, I_m^L, I_r^L; H(\tilde{I}^L)))$ is the initial investment cost, $\tilde{\tilde{A}} = ((A_l^U, A_m^U, A_r^U; H(\tilde{A}^U)),(A_l^L, A_m^L, A_r^L; H(\tilde{A}_t^L)))$ denotes the annual cash flow, $\tilde{\tilde{I}} = ((I_l^U, I_m^U, I_r^U; H(\tilde{I}^U)),(I_l^L, I_m^L, I_r^L; H(\tilde{I}^L)))$ is the salvage value, $\tilde{\tilde{i}} = ((i_l^U, i_m^U, i_r^U; H(\tilde{i}^U)), (i_l^L, i_m^L, i_r^L; H(\tilde{i}^L))), \forall \tilde{i} > 0$ denotes the discount rate during the investment period and n represents useful life of the investment.

An important point in net present worth analysis is that when the alternatives which have different useful lives are compared, the analysis period should be extended to the least common multiplies of these different useful lives. In that kind of analysis, alternatives are assumed to be reinvested at the end of their useful lives again with the same cash flows till the end of the analysis period. Then the fuzzy net present values obtained by using either Eq. 15.14 or Eq. 15.15 could be used to determine the best investment alternative.

15.5 An Application

Fatih is one of the biggest districts of Istanbul. Solid waste collection of the district consists of three main regions. One of them which has 5, 95 km^2 area and approximately 200,000 population is selected for the application. Total waste amount of Fatih is 700 tons per day and the total wastes generated in the selected region is approximately 230 tons a day. In the selected region there are 166 underground waste bins and 1007 roadside waste bins. The daily waste load of an underground waste bin and a roadside waste bin is determined as approximately 0.7 and 0.1 ton, respectively. For the roadside waste bins there are 4 high-capacity (7 tons) trucks are operating for 7 shifts and 8 small-capacity (4 tons) trucks are operating for 15 shifts. For the underground waste bins there are 3 techno-trucks with the capacity of 13 tons are operating for 3 shifts. There are three kinds of workers in solid waste collection system. Drivers and the qualified workers has a salary of 2400 TL where the normal worker has a salary of 2190 TL. One driver and one normal worker work at each techno-truck and one driver and two normal workers work at each small-capacity and high-capacity trucks. There is also one truck for the maintenance of both kinds of the waste bins. In this truck one driver and two qualified workers are working.

It is considered to renew 20 of the existing underground waste bins which were built 10 years ago and have lower capacity (2500 L). The municipality wants to add 10 more underground waste bins on the same route and discard all of the roadside bins at this route which counts 110. The waste load of this new 10 underground waste bins and the load comes from the increased capacity of the renewed 20 underground waste bins could be collected and transferred by existing trucks by adding one more shift. And by discarding 110 roadside bins, 2 shifts of one small capacity truck will be unnecessary and one small capacity truck could be removed from the system. The locations of existing underground waste bins are pointed with squares and the ones which should be renewed are pointed with circles in Fig. 15.1.

Table 15.1 shows the data required for the calculations. The number of the workers used in the solid waste collection system of this region is uncertain due to the need of utility men in the vacations and illnesses of the existing workers. Therefore, the salaries are also determined using fuzzy numbers.

The economic life of the underground waste bins and roadside waste bins are determined as 10 and 2 years, respectively. There are two scenarios for the analysis. The first scenario is replacing the old underground waste bins with new high capacity underground waste bins by discarding 55 roadside waste bins. This scenario will decrease the usage of one small-capacity truck by one shift which will remove one small-capacity truck from the system. In the economic analysis the workers need for the collection of this route is taken as 1 shift in a techno-truck and 1 shift in a small-capacity truck. The remaining useful lives of trucks are both 15 years.

The second scenario is replacing the old underground waste bins with new high capacity underground waste bins and purchasing 10 more new high capacity underground waste bins by discarding 110 roadside bins. This scenario will decrease the usage of one small-capacity truck by two shifts which will remove one small-capacity truck from the system. In the economic analysis the workers need for the collection of this route is taken as 1 shift in a techno-truck. In both scenarios the techno-truck will be operated one more shift. The truck operated for the maintenance of the waste bins will be operated same as current system in both scenarios. Therefore, the costs of maintenance will be ignored in the analysis. The interest rate is determined as ((0.04, 0.06, 0.08; 1), (0.05, 0.06, 0.07; 0.9)).

Fig. 15.1 Locations of the underground waste bins

15.5.1 Economic Analysis of Option 1

The cash flows of option 1 are calculated and given in Table 15.2 as follows.

Interval type-2 fuzzy net present value of the cash flows shown in Table 15.3 is calculated as ((−2,289,365, −1,746,856, −1,298,718; 1), (−2,032,280, −1,746,856, −1,485,696; 0.9)) using Eq. 15.14.

Table 15.1 Required cost information of the solid waste collection system

Initial investment cost of underground waste bins	Purchasing cost	(11,000, 13,000, 15,000; 1), (11,500, 13,000, 14,500; 0.9)
	Construction cost	(3000, 4000, 5000; 1), (3250, 4000, 4750; 0.9)
	Labor cost of the construction	(2500, 3000, 3500; 1), (2700, 3000, 3300; 0.9)
Purchasing cost of a roadside waste bin		(400, 500, 600; 1), (450, 500, 550; 0.9)
Salary of a qualified worker (or driver)		(2400, 2500, 2600; 1), (2420, 2500, 2580; 0.9)
Salary of a normal worker in a truck		(2100, 2200, 2300; 1), (2120, 2200, 2280; 0.9)
Salvage value of the small capacity underground waste bins		(2000, 2500, 3000; 1), (2100, 2500, 2900; 0.9)
Salvage value of the high capacity underground waste bins		(3000, 3500, 4000; 1), (3250, 3500, 3750; 0.9)
Salvage value of a roadside bin		(30, 40, 50; 1), (35, 40, 45; 0.9)
Salvage value of a small-capacity truck		(35,000, 40,000, 45,000; 1), (37,000, 40,000, 43,000; 0.9)
Cost of the fuel consumption of a techno-truck used (per a ton waste)		(12, 13, 14; 1), (12.5, 13, 13.5; 0.9)
Cost of the fuel consumption of a small-capacity truck (per a ton waste)		(17, 18, 19; 1), (17.5, 18, 18.5; 0.9)
Daily waste load of a high capacity underground waste bin (ton)		(0.6, 0.7, 0.8; 1), (0.65, 0.7, 0.75; 0.9)
Daily waste load of a roadside waste bin (ton)		(0.06, 0.1, 0.14; 1), (0.08, 0.1, 0.1.2; 0.9)

Pessimistic type reduction of the interval type-2 fuzzy net present value of option 1 is calculated as (−2,289,365, −1,746,856, −1,298,718) using Eq. 15.10. Optimistic type reduction of the interval type-2 fuzzy net present value of option 1 is calculated as (2,032,280, −1,746,856, −1,485,696) using Eq. 15.11. Defuzzified values of net present value of option 1 are calculated as −1,794,042 and −1,758,988 TL for the pessimistic and optimistic type reductions respectively.

15.5.2 Economic Analysis of Option 2

The cash flows of option 2 are calculated and given in Table 15.4 as follows.

Interval type-2 fuzzy net present value of the cash flows shown in Table 15.5 is calculated as ((−2,037,540, −1,595,473, −1,220,284; 1), (−1,840,224, −1,595,473, −1,367,385; 0.9)) using Eq. 15.14.

Pessimistic type reduction of the interval type-2 fuzzy net present value of option 1 is calculated as (−2,037,540, −1,595,473, −1,220,284) using Eq. 15.10. Optimistic type reduction of the interval type-2 fuzzy net present value of option 1 is calculated as (−1,840,224, −1,595,473, −1,367,385) using Eq. 15.11.

Table 15.2 Cash flows of option 1

	Year	Calculation formula	Cash flow
Initial investment of underground waste bins	0	20 × [((11,000, 13,000, 15,000; 1), (11,500, 13,000, 14,500; 0.9)) + ((3000, 4000, 5000; 1), (3250, 4000, 4750; 0.9)) + ((2500, 3000, 3500; 1), (2700, 3000, 3300; 0.9))]	((330,000, 400,000, 470,000; 1), (349,000, 400,000, 451,000; 0.9))
Replacement of roadside bins with the new ones	0	55 × ((400, 500, 600; 1), (450, 500, 550; 0.9))	((22,000, 27,500, 33,000; 1), (24,750, 27,500, 30,250; 0.9))
Salvage value of roadside bins	0	110 × ((30, 40, 50; 1), (35, 40, 45; 0.9))	((3300, 4400, 5500; 1), (3850, 4400, 4950; 0.9))
Salvage value of the small capacity underground waste bins	0	20 × ((2000, 2500, 3000; 1), (2100, 2500, 2900; 0.9))	((40,000, 50,000, 60,000; 1), (42,000, 50,000, 58,000; 0.9))
Salaries of the workers	1–10	12 × [2 × ((2400, 2500, 2600; 1), (2420, 2500, 2580; 0.9)) +3 × ((2100, 2200, 2300; 1), (2120, 2200, 2280; 0.9))]	((75,600, 79,200, 82,800; 1), (76,320, 79,200, 82,080; 0.9))
Fuel consumption	1–10	365 × [20 × ((0.6, 0.7, 0.8; 1), (0.65, 0.7, 0.75; 0.9)) × ((12, 13, 14; 1), (12.5, 13, 13.5; 0.9)) + 55 × ((0.06, 0.1, 0.14; 1), (0.08, 0.1, 0.12; 0.9)) × ((17, 18,19; 1), (17.5, 18, 18.5; 0.9))]	((73,036.5, 102,565, 135,159.5; 1), (87,417.5, 102,565, 118,479; 0.9))
Purchasing cost of roadside waste bin	2, 4, 6, 8	55 × ((400, 500, 600; 1), (450, 500, 550; 0.9))	((22,000, 27,500, 33,000; 1), (24,750, 27,500, 30,250; 0.9))
Salvage values of roadside waste bin	2, 4, 6, 8, 10	55 × ((30, 40, 50; 1), (35, 40, 45; 0.9))	((1650, 2200, 2750; 1), (1925, 2200, 2475; 0.9))
Salvage values of underground waste bins	10	20 × ((3000, 3500, 4000; 1), (3250, 3500, 3750; 0.9))	((60,000, 70,000, 80,000; 1), (65,000, 70,000, 75,000; 0.9))

Defuzzified values of net present value of option 1 are calculated as −1,628,912 and −1,603,805 TL for the pessimistic and optimistic type reductions, respectively.

15.5.3 Comparison of the Options

Both of the defuzzfied net present values of the options in pessimistic and optimistic point of view, shows that option 2 will result in less costs which makes Option 2 the selected alternative for the solid waste collection system. Therefore, municipality

Table 15.3 Netcash flows of option 1

Year	Net cash flow
0	((−459,700, −373,100, −286,500; 1), (−435,400, −373,100, −310,800; 0.9))
1	((−217,959.5, −181,765, −148,636.5; 1), (−200,559, −181,765, −163,737.5; 0.9))
2	((−249,309.5, −207,065, −167,886.5; 1), (−228,884, −207,065, −186,012.5; 0.9))
3	((−217,959.5, −181,765, −148,636.5; 1), (−200,559, −181,765, −163,737.5; 0.9))
4	((−249,309.5, −207,065, −167,886.5; 1), (−228,884, −207,065, −186,012.5; 0.9))
5	((−217,959.5, −181,765, −148,636.5; 1), (−200,559, −181,765, −163,737.5; 0.9))
6	((−249,309.5, −207,065, −167,886.5; 1), (−228,884, −207,065, −186,012.5; 0.9))
7	((−217,959.5, −181,765, −148,636.5; 1), (−200,559, −181,765, −163,737.5; 0.9))
8	((−249,309.5, −207,065, −167,886.5; 1), (−228,884, −207,065, −186,012.5; 0.9))
9	((−217,959.5, −181,765, −148,636.5; 1), (−200,559, −181,765, −163,737.5; 0.9))
10	((−156,309.5, −109,565, −65,886.5; 1), (−133,634, −109,565, −86,262.5; 0.9))

Table 15.4 Cash flows of option 2

	Year	Calculation formula	Cash flow
Initial investment of underground waste bins	0	30 × [((11,000, 13,000, 15,000; 1), (11,500, 13,000, 14,500; 0.9)) + ((3000, 4000, 5000; 1), (3250, 4000, 4750; 0.9)) + ((2500, 3000, 3500; 1), (2700, 3000, 3300; 0.9))]	((495,000, 600,000, 705,000; 1), (523,000, 600,000, 676,500; 0.9))
Salvage value of the discarded roadside bins	0	110 × ((30, 40, 50; 1), (35, 40, 45; 0.9))	((3300, 4400, 5500; 1), (3850, 4400, 4950; 0.9))
Salvage value of the small capacity underground waste bins	0	20 × ((2000, 2500, 3000; 1), (2100, 2500, 2900; 0.9))	((40,000, 50,000, 60,000; 1), (42,000, 50,000, 58,000; 0.9))
Salvage value of a small-capacity truck	0	((35,000, 40,000, 45,000; 1), (37,000, 40,000, 43,000; 0.9))	((35,000, 40,000, 45,000; 1), (37,000, 40,000, 43,000; 0.9))
Salaries of the workers	1–10	((2400, 2500, 2600; 1), (2420, 2500, 2580; 0.9)) + ((2100, 2200, 2300; 1), (2120, 2200, 2280; 0.9))	((54,000, 56,400, 58,800; 1), (54,480, 56,400, 58,320; 0.9))
Fuel consumption	1–10	365 × [30 × ((0.6, 0.7, 0.8; 1), (0.65, 0.7, 0.75; 0.9))]	((78,840, 99,645, 122,640; 1), (88,968.75, 99,645, 110,868.75; 0.9))
Salvage values of underground waste bins	10	30 × ((3000, 3500, 4000; 1), (3250, 3500, 3750; 0.9))	((90,000, 105,000, 120,000; 1), (97,500, 105,000, 112,500; 0.9))

Table 15.5 Net cash flows of option 2

Year	Net cash flow
0	((−626,700, −505,600, −384,500; 1), (−593,650, −505,600, −417,050; 0.9)
1–9	((−181,440, −156,045, −132,840; 1), (−169,188.75, −156,045, −143,448.75; 0.9))
10	((−91,440, −51,045, −12,840; 1), (−71,688.75, −51,045, −30,948.75; 0.9))

should discard all of the roadside waste bins in the selected route, renew 20 small-capacity underground waste bins with the high capacity underground waste bins and purchase 10 more high capacity underground waste bins. This result proves that even if an alternative has really high initial cost than the others, the cash flows of the future time could increase its net present worth and make it the best alternative for the system. Therefore, in a selection process among alternative scenarios, analysts should make a detailed economic analysis to find the real value of an alternative.

15.6 Conclusion

Solid waste collection systems have a critical importance for municipalities because of their high costs and direct effect on the citizens' life standards. To construct a solid waste collection system which satisfies the citizens' expectations, municipalities have to manage and renew the collection system in a continuous way to overcome the increasing waste generations by time. In this chapter, two different alternative solid waste bins are compared for a region in Istanbul including the collection and transportation phases using type-2 fuzzy net present worth analysis method. The results show that the underground waste bins which are preferable due to their odor consumption and aesthetic advantages are also preferable due to their economic values. The method used in the evaluation is type-2 fuzzy net present worth analysis which enables us to gather the uncertain information into the analysis. By applying this intelligent technique, we can say that the obtained results will be affected by the uncertain parameters less.

For further research, it is suggested to extend the analysis to the whole district to find out the best scheduling for the solid waste collection system. Also different brands of the selected bins could be evaluated.

References

Alshraideh, H., & Abu Qdais, H. (2016). Stochastic modeling and optimization of medical waste collection in Northern Jordan. *Journal of Material Cycles and Waste Management*, 1–11. (Article in Press).

Anand, S. (2010). *Solid waste management*. India: Mittal Publications.

Franchetti, M., & Dellinger, A. (2014). Economic feasibility analysis of a municipal food waste collection and energy generation model. In *Proceedings of the Air and Waste Management Association's Annual Conference and Exhibition, AWMA* (Vol. 1, pp. 471–484).

Harris, F. (Ed.). (2004). *Global environmental issues* (pp. 246–276). England: Wiley.

Hosetti, B. B. (2006). *Prospects and perspective of solid waste management*. New Age International.

Huang, S.-H., & Lin, P.-C. (2015). Vehicle routing-scheduling for municipal waste collection system under the "keep trash off the ground" policy. *Omega (United Kingdom), 55*, 24–37.

Kadama, F. R. K. (2013). Crafting a strategy for improved communal waste management in Mafikeng. *International Journal of Sustainable Development and Planning, 8*(1), 20–35.

Karnik, N. N., & Mendel, J. M. (2001). Centroid of a type-2 fuzzy set. *Information Sciences, 132* (1–4), 195–220.

Kerstens, S. M., Leusbrock, I., & Zeeman, G. (2015). Feasibility analysis of wastewater and solid waste systems for application in Indonesia. *Science of the Total Environment, 530–531*, 53–65.

Kinobe, J. R., Bosona, T., Gebresenbet, G., Niwagaba, C. B., & Vinnerås, B. (2015). Optimization of waste collection and disposal in Kampala city. *Habitat International, 49*, 126–137.

Kuo-Ping, C. (2011). Multiple criteria group decision making with triangular interval type-2 fuzzy sets. In *Proceedings of 2011 IEEE International Conference on Fuzzy Systems (FUZZ)* (pp. 1098–7584), June 27–30. Taipei.

Lopes, D., Ramos, T. R. P., & Barbosa-Póvoa, A. P. (2015). Optimization of a recyclable waste collection system-the valorsul case study. *Operations Research and Big Data: IO2015-XVII Congress of Portuguese Association of Operational Research (APDIO)* (Vol. 15, pp. 97–105).

Maimoun, M., Madani, K., & Reinhart, D. (2016). Multi-level multi-criteria analysis of alternative fuels for waste collection vehicles in the United States. *Science of the Total Environment, 550*, 349–361.

Mamun, M. A. A., Hannan, M. A., Hussain, A., & Basri, H. (2016). Theoretical model and implementation of a real time intelligent bin status monitoring system using rule based decision algorithms. *Expert Systems with Applications, 48*, 76–88.

Niewiadomski, A., Ochelska, J., & Szczepaniak, P. S. (2006). Interval-valued linguistic summaries of databases. *Control and Cybernetics, 35*(2), 415–443.

Ninni, V. (2011). Estimating flexible cost functions on refuse collection in Attica region, Greece. *Neural, Parallel and Scientific Computations, 19*(1–2), 165–180.

Oliveira, A. D., Ramos, T. R. P., & Martins, A. L. (2015). Planning collection routes with multi-compartment vehicles. *Operations Research and Big Data: IO2015-XVII Congress of Portuguese Association of Operational Research (APDIO)* (Vol. 15, pp. 131–138).

Rabbani, M., Sadri, S., & Rafiei, H. (2016). A multimodal transportation system routing implemented in waste collection. *Decision Science Letters, 5*(1), 61–80.

Ramachandra, T. V. (2006). *Management of municipal solid waste*. India: The Energy and Resources Institute (TERI Press).

Regué, R., & Bristow, A. L. (2013). Appraising freight tram schemes: A case study of Barcelona. *European Journal of Transport and Infrastructure Research, 13*(1), 56–78.

Russell, S. H., Brickner, R., & Peterson, C. (1986). The feasibility study, procurement, and construction management. In W. D. Robinson (Ed.), *The solid waste handbook a practical guide*. New York: Wiley.

Uçal Sarı, I., & Kahraman, C. (2015). Interval type-2 fuzzy capital budgeting. *International Journal of Fuzzy Systems, 17*(4), 635–646.

UNEP-United Nations Environment Programme.(2005). Solid waste management—Chapter I. In *Introduction.* ISBN 92-807-2676-5.

Wang, H., He, J., Kim, Y., & Kamata, T. (2014). Municipal solid waste management in rural areas and small counties: An economic analysis using contingent valuation to estimate willingness to pay for Yunnan, China. *Waste Management and Research, 32*(8), 695–706.

Willemse, E. J., & Joubert, J. W. (2016). Constructive heuristics for the mixed capacity arc routing problem under time restrictions with intermediate facilities. *Computers & Operations Research, 68*, 30–62.

Xue, W., & Cao, K. (2016). Optimal routing for waste collection: A case study in Singapore. *International Journal of Geographical Information Science, 30*(3), 554–572.

Xue, W., Cao, K., & Li, W. (2015). Municipal solid waste collection optimization in Singapore. *Applied Geography, 62*, 182–190.

Zadeh, L. A. (1974). Fuzzy logic and its application to approximate reasoning. *Information Processing, 74*, 591–594.

Zadeh, L. A. (1975). The concept of a linguistic variable and its application to approximate reasoning—I. *Information Sciences, 8*(3), 199–249.

Part VII
Land Use Planning

Chapter 16
Applications of Multicriteria Techniques to Plan the Harvest of a Forest Taken into Account Different Kinds of Objectives

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Abstract This chapter addresses the operational planning of a forest bearing in mind that forest management involves a multiplicity of goods and services. The proposed model not only includes economic and sustainable development objectives but also takes into account the key role trees play in counteracting the greenhouse effect. In addition, we add adjacency constraints to limit the maximum contiguous area where clear-cutting can be carried out. The solution to the proposed model provides a set of efficient management plans that are of assistance in analyzing the tradeoffs between the economic and ecological objectives. The model is first applied to a plantation owned by a Cuban company, and then to randomly generated simulated forests to compare its performance in other contexts. As the problem is a multiobjective integer nonlinear model, metaheuristic procedures are used to solve it since exact methods would be very expensive.

16.1 Introduction

Traditionally, forests fulfil a threefold role: production, protection, and recreation. Field (1973) was pioneer in analyzing a forest management problem in a multicriteria context, considering timber production, familiar incomes and recreation. Since then, multiobjective programming has been often applied to this kind of

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problems. Field et al. (1980), Hotvedt (1983), Kao and Brodie (1979) are examples of authors that have applied goal programming to timber production management. Other authors have used interactive multiobjective models (Steuer and Schuler 1978; De Kluyver et al. 1980; Hallefjord et al. 1986; Bare and Mendoza 1988; Kazana et al. 2003). Also, compromise programming, which is another multiobjective technique, is used in a recent work of De Sousa Xavier et al. (2015) to solve a forest management problem in southern Portugal involving multiple objectives as well as multiple stakeholders. Furthermore, several articles, books, and book chapters have been devoted exclusively to this topic (see Weintraub et al. 2007; Mendoza and Martins 2006; Buongiorno and Gilless 2003; Pukkala 2002). The use of multiple techniques is due to the different information available and the specific characteristics of each problem (Gómez et al. 2006). According to Diaz-Balteiro and Romero (2007, 2008), forest systems aim to obtain a balanced forest, taking into account several economic, environmental and social criteria to solve complex decision-making problems. Therefore, to consider all of the mentioned criteria, multicriteria techniques are needed. Recently, in Mönkkönen et al. (2014) multiple optimization tools are used in order to solve the problem of simultaneously address with habitat availability and timber production in a boreal forest.

In this work, we use a multiobjective programming model to solve a forest management problem that focuses on two of the three traditional roles forests previously mentioned. In this sense, the paper of Triviño et al. (2015) examine the trade-offs between a provisioning and regulating ecosystem services in a large boreal forest landscape. We take into account the economic factors of timber production, but also considering environmental protection and other aspects related to. We aim to fulfil the wishes of the planner, according to the volume of timber harvested, the net present value (NPV) obtained, the age of trees targeted for clear-cutting, and the regulation of the forest. We follow the lines of finding the efficient set of the multiobjective problem like the works of Tóth et al. (2006), Tóth and McDill (2008). These authors tested different methods of generating the efficient frontier for harvest schedule problems that included timber criteria plus other criteria related to wildlife management. Their models included, among others, harvest flow constraints, maximum harvest opening size constraints and an average ending age constraints. They used a hypothetical forest planning problem to evaluate the procedures and pointed out that the exact procedures used can be computationally expensive when the problems are large. Also, our model includes ecological objectives regarding carbon sequestration. In this regard, the Kyoto Protocol was a significant step forward that recommended forestry as a means to offset industrial carbon dioxide emissions (Platinga et al. 1999). In this sense, Bateman and Lovett (2000) developed methodologies for the modelling and mapping of the value of net carbon flow produced by afforestation. Couture and Reynaud (2011) proposed a stochastic dynamic model to maximize the expected utility of the forest owner under fire risk with both timber and carbon benefits. Some studies have included carbon sequestration as an additional objective when planning forest harvesting like Hoen and Solberg (1994) who studied the trade-off between net present value of timber and net carbon flow, using a linear model for the county of Buskerud (Norway). In this line, the present study includes maximizing net carbon sequestration and the net present value (NPV) as objectives, in conjunction with other ones of the planner, such as minimizing the area covered by trees older than the rotation age and obtaining an even-age distributed forest.

Spatial constraints are also incorporated, aimed at limiting the maximum adjacent area to which clear-cutting can be applied. Known in the literature as adjacency constraints, such restrictions assist in preserving visual beauty and biodiversity, and prevent erosion. Currently, the use of adjacency constraints is standard practice in the management of public and private forests (Murray and Weintraub 2002). As said in Bachmatiuk et al. (2015) harvest scheduling problems taking into account spatial constraints are "a challenge as these models represent complex combinatorial problems". Two different models have been mainly used to address adjacency issues. In the URM (Unit Restriction Model), two or more neighbouring basic units cannot be felled at the same time. In the ARM (Area Restriction Model), the area adjacent to clear-cutting cannot exceed a certain size (maximum opening size). In other words, two adjacent basic units could be felled at the same time as long as they do not exceed a certain maximum area (Murray 1999). The present work applies the ARM, which is much more powerful and complex than the URM, as indicated in the references (Murray and Weintraub 2002; McDill et al. 2002; Goycoolea et al. 2005; Weintraub and Murray 2006). In order to incorporate these spatial constraints, binary variables must be used in the model.

We applied the proposed method to a timber production plantation in Cuba. Currently, Cuba is making great efforts to reduce the pressure its natural forests are under by increasing the number of productive plantations to meet the country's timber requirements. One factor to be taken into account in Cuban plantations is that the forest has a highly unbalanced age distribution. Therefore, in addition to the classical objectives of forest planning, these plantations have the extra goal of rebalancing age distribution by the end of the planning horizon, thereby obtaining a final constant flow of timber. In the literature, usually, rebalancing the forest area by areas is modelled as constraints that must be satisfied (Kao and Brodie 1979; Buongiorno and Gilles 2003; Tóth et al. 2006; Tóth and McDill 2008). But when the forest is organized by units, if the forest is not initially age balanced, to impose these constraints might lead to unfeasible solutions. In this work, the proposed model incorporates this age balance requirement in a more flexible way, as an objective instead of a set of constraints. This objective has been incorporated by following the fractional formulation of Gómez et al. (2006, 2011), Hernández et al. (2014) which models the relative difference between age-classes via a fractional function.

Taking the foregoing into account, the model presented in this study incorporates the following key points: it does not demand too much information from the decision-makers; it helps them to choose the most preferred solution by analysing the tradeoffs between the different objectives (net present value, the carbon capture as well as the regulation of the forest) along the efficient set; and also it addresses the regulation requirement using a relative way instead of the usual formulation, in order to avoid infeasible solutions that might appear when spatial constraints are introduced.

The model does not have a linear formulation and this, together with its other characteristics, make it a highly complex problem necessitating the use of metaheuristic procedures to solve it. These kinds of methods are being increasingly used to solve forest planning problems because exact methods are not powerful enough (Pukkala and Heinonen 2006). Some metaheuristic methods to solve forest planning problems found in the literature are simulated annealing (Bachmatiuk et al. 2015), tabu search, and genetic algorithms, among others (see Borges et al. 2002; Falcão and Borges 2002; Caro et al. 2003; Liu et al. 2006). The metaheuristic algorithm used to solve the present problem is an adaptation of the evolutionary method SSPMO (Scatter Search Procedure for Multiobjective Optimization, Molina et al. 2007).

The model was applied to a 3347.7 ha Cuban plantation (Pinus Caribaea) belonging to the forestry company "Empresa Forestal Integral (E.F.I.) Macurije" in Pinar del Río, Cuba, which covers the municipalities of Guane and Mantua. This plantation forms 30.5 % of the "Minadora" management unit which is part the E.F.I "Macurije." The "Minadora" covers 12 % of the total surface area belonging to the company and is distributed over 35 woodlots of different sizes. All the woodlots are classified in compliance with Cuban forestry law, and their main purpose is timber production. The woodlots are made up of smaller sections that we call basic units, having different sizes but similar mass characteristics. The elements taken into account to differentiate basic units within the woodlot are: age, average tree diameter, height, basal area, and forest density and composition. According to Bobko and Aldana (1981), basic units form the core of forestry management. This means that each one represents a nearly even unit regarding behaviour, typology, and dasometric measurements. The area studied is made up of 305 such units assigned to producing small-sized timber used by the Cuban tobacco industry.

Finally, we investigated to what extent the model is applicable to other contexts and different starting conditions by planning the harvest in a series of randomly generated simulated forests that had characteristics similar to the Cuban plantation.

The structure of this work is as follows: Sect. 16.2 describes the theoretical basis and introduces the model proposed; Sect. 16.3 illustrates the application to the Cuban forest and the obtained results are discussed; Sect. 16.4 presents the conclusions followed by References.

16.2 A Multiobjective Harvest Scheduling Model

In this section we develop a model to plan the harvest schedule of a plantation over a planning horizon of T years. We assume that the plantation is divided into U different basic units according to its physical characteristics, e.g. slopes, altitude, accessibility, etc. The aim is to determine the optimum treatment (first thinning, second thinning, clear-cut, etc.) for each entire unit in a specific year of the planning horizon in such a way that the decision-makers objectives are fulfilled while taking into account technical, physical and environmental constraints.

Each basic unit is characterized by three magnitudes:

- S_u is the surface area measured in hectares, which we assume is constant over the entire planning horizon because it is assumed that for every tree felled a new one is planted.
- $A_{u,t}$ is the age, expressed in years, of the basic unit u in year t of the planning horizon, and $A_{u,0}$ is the starting age of this basic unit.
- SI_u is the site index which is a productivity indicator. Suppose $SI_u = 1, 2,\ldots H$.

Let us assume that J different silvicultural intermediate treatments can be applied to the basic units, apart from clear-cutting. These intermediate treatments depend on the age of the unit. Thus, we assume that it is possible to apply treatment j ($j = 1, 2, \ldots, J$) to unit u ($u = 1, 2,\ldots, U$) in year t if $A_{u,t-1}$ belongs to the interval $[Lb_j, Ub_j]$. All of these age intervals are disjoint sets, so it is not possible to apply more than one intermediate treatment to the same unit in the same year.

In the model, we use two different types of decision variables: binary variables $x_{u,t}$ which represent whether clear-cutting is applied ($x_{u,t} = 1$) or not ($x_{u,t} = 0$) to basic unit u ($u = 1, 2,\ldots, U$) in year t ($t = 1, 2,\ldots, T$); and binary variables $y_{u,t}$ which show whether a basic unit u ($u = 1, 2,\ldots, U$) receives an intermediate treatment in year t ($t = 1, 2,\ldots, T$) ($y_{u,t} = 1$) or not ($y_{u,t} = 0$). Obviously, if $y_{u,t} = 1$, then unit u will receive the corresponding treatment j ($j = 1, 2,\ldots, J$) such that $A_{u,t-1} \in [Lb_j, Ub_j]$.

The following criteria are considered relevant to strategic management: (a) *obtaining an even-age distributed forest,* i.e., the area covered by each age-class should be roughly the same by the end of the planning horizon; (b) *minimizing the area covered by trees older than the rotation age*; (c) *maximizing the NPV of the forest over the planning horizon*; and (d) *maximizing total carbon sequestration over the whole planning horizon.*

Feasible harvesting schedules are limited by different constraints, as described below.

Firstly, the age of each unit is changing during the planning horizon. Thus, this age increases by 1 in relation to the previous year, or, if the basic unit has been clear-cut, its age becomes 1. That is:

$$A_{u,t} = (A_{u,t-1} + 1)(1 - x_{u,t}) + x_{u,t} \quad u = 1, 2, \ldots, U; \quad t = 1, 2, \ldots T \tag{16.1}$$

On other hand, it is obvious that clear-cutting and an intermediate treatment cannot be applied at the same period to a basic unit:

$$x_{u,t} + y_{u,t} \leq 1 \quad u = 1, 2, \ldots, U; \quad t = 1, 2, \ldots, T \tag{16.2}$$

An intermediate treatment can also be applied at most once during the period associated with the treatment, that is:

$$\sum_{t/A_{u,t-1}\in[Lb_j\ \ Ub_j]} y_{u,t} \leq 1 \quad u = 1,2,\ldots U; \quad j = 1,2,\ldots,J \tag{16.3}$$

As described in the introduction, we address the problem of adjacency constraints within the framework of the ARM, whereby the areas adjacent to clear-cutting cannot exceed a certain size. Thus, we assume that the units are grouped depending on adjacency, such that there are K adjacency groups $G_1, G_2,\ldots, G_K$. These groups are calculated in such a way that each G_k is made up of two or more adjacent units, whose joint surface area exceeds a permitted threshold (i.e., maximum opening size) (Murray and Weintraub 2002). Thus, all the units belonging to the same adjacency group cannot be clear-cut at the same time during the same planning period. However, groups are calculated in such a way that the joint surface area of all units but one does not exceed the permitted threshold S^*. Thus, if the combined surface area of neighbouring basic units (within a particular group, G_k) does not exceed the threshold S^*, then the decision on whether or not to clear-cut these units in the same period is determined by the model's solution.

Furthermore, given that this model deals with yearly periods, when dealing with adjacencies we take into account *green-up requirements* that prevent clear-cutting basic units belonging to the same adjacency group until g years or planning periods have passed. Consequently:

$$\sum_{u\in G_k}\sum_{s=t}^{t+g-1} x_{u,s} \leq |G_k| - 1 \quad k = 1,2,\ldots,K; \quad t = 1,2,\ldots T-g \tag{16.4}$$

Sustainability constraints are also included. On the one hand, young units cannot be clear-cut, that is, units with trees younger than n^*:

$$\sum_{t=1}^{T}\left(\sum_{u/A_{u,t-1}<n*} x_{u,t}\right) = 0 \tag{16.5}$$

On the other hand, the area to which clear-cutting is applied during each period is constrained. Firstly, it cannot exceed the surface area that ensures the sustainability of the forest (Se) which is given by the total surface area in the plantation divided by the rotation age. Second, we have to establish minimum bounds for the area felled as a whole in each period (thus guaranteeing regeneration of the forest) which is a percentage of the area Se. Thus, the constraint that formalizes this requirement is as follows:

$$\tau\, Se \leq \sum_{u=1}^{U} S_u x_{u,t} \leq Se \quad 0 \leq \tau \leq 1, \quad t = 1,2,\ldots,T \tag{16.6}$$

In addition, we endeavour to maintain harvest levels at the maximum sustainable yield. Thus, if V^t represents the maximum sustainable volume in year t, $v^{cc}_{A_{u,t-1}}$ is the volume obtained by clear-cutting basic unit u in year t, and $v^{ha}_{A_{u,t-1}}$ is the volume obtained from the corresponding intermediate treatment of unit u, in year t, then this constraint can be expressed by the following equation:

$$\sum_{u=1}^{U} v^{cc}_{A_{u,t-1}} x_{u,t} + v^{ha}_{A_{u,t-1}} y_{u,t} \leq V^t, \quad t = 1, 2, \ldots, T \tag{16.7}$$

Let's now see the objectives set in the plan.

As mentioned, one of the objectives of the decision-makers is to reorganize the plantation structure by age during the planning horizon. To do this, we use the fractional formulation developed by Gómez et al. (2006), where this aspect is modelled using a ratio that shows the relative difference between the surface area covered by trees in a first age-class and the area covered by a last age-class. Thus, age-classes have been defined in the following way: the first age-class is comprised of basic units with ages ranging between *1* and *m* years (*m* being a constant divisor of *N**), the second age-class includes basic units with ages between *m* + *1* and *2 m* years, and so on until the last age-class, which is comprised by units older than *N** − *m* years. Note that there will be *I* = *N*/m* age-classes in total. The constant *m* has to be set by the decision-makers.

Bearing this in mind, let S_i^t denote the total surface area available of age-class i at period t, which is expressed as:

$$S_i^t = \sum_{u/A_{u,t}=(i-1)m+1}^{A_{u,t}=im} S_u \quad i = 1, 2, \ldots, I-1$$

and:

$$S_I^t = \sum_{u/A_{u,t} > N*-m} S_u$$

Let $\frac{S_1^T}{S_I^T}$ be the ratio. Bearing in mind constraint (16.6) (with $Se = \frac{S}{T}$), this ratio is lower than or equal to 1. If we assume $T \geq N^* - m$, then we can generalize the result presented in Gómez et al. (2006) to this context and ensure that if this ratio reaches value 1 then a total even-aged distributed forest is obtained. Thus, the first objective is to maximize this ratio:

$$\max \quad f^1 = \frac{S_1^T}{S_I^T} \tag{16.8}$$

A further objective is to reduce the surface area of units with trees over the rotation age (*old trees*), that is:

$$\min \quad f^2 = \sum_{t=1}^{T} \sum_{u/A_{u,t} > N*} S_u \tag{16.9}$$

We also define the economic objective of the plan; that is, the NPV obtained through the planning horizon has to be maximized.

$$\text{Max} \quad f^3 = \sum_{t=1}^{T} \sum_{u=1}^{U} \left(NPV^{cc}_{A_{u,t-1}} x_{u,t} + NPV^{ha}_{A_{u,t-1}} y_{u,t}\right) \tag{16.10}$$

where $NPV^{cc}_{A_{u,t-1}}$ represents NPV obtained after clear-cutting unit u in year t, and $NPV^{ha}_{A_{u,t-1}}$ represent the NPV obtained after applying the corresponding treatment to unit u in year t.

Regarding the last objective, the total carbon sequestered by the plantation over the planning horizon should be maximized. The carbon sequestered during each period is expressed as the difference between the carbon sequestered due to the growth of the timber biomass plus the harvest and the carbon emissions due to the harvest for each period. Let γ represent the proportion of carbon contained in timber biomass (tons carbon/m^3 timber), and let β^{cc}_{ut}, β^{ha}_{ut} denote, respectively, the proportion of fixed carbon released during clear-cutting and the corresponding treatment of unit u in year t. The equation that measures the balance of net carbon in a generic t period is:

$$C^t = \gamma \sum_{u=1}^{U} \left(\left(v^{cc}_{A_{u,t}} - v^{cc}_{A_{u,t-1}}\right) + x_{u,t} v^{cc}_{A_{u,t-1}} \left(1 - \beta^{cc}_{u,t}\right) + y_{u,t} v^{ha}_{A_{u,t-1}} \left(1 - \beta^{ha}_{u,t}\right) \right)$$

Finally, the fourth objective, i.e. maximizing the total net carbon sequestered, by the plantation is formulated as follows:

$$\max \quad f^4 = \sum_{t=1}^{T} C^t \tag{16.11}$$

Thus, the model can be expressed as:

$$Opt\left(f^1, f^2, f^3, f^4\right)$$

Subject to: *Constraints* (16.1)–(16.7)

$$x_{ut}, y_{ut} \in \{0, 1\} \quad u = 1, \ldots, U; \quad t = 1, \ldots, T \tag{16.12}$$

This is a multiobjective non-linear programming problem with binary variables, and once solved provides a set of efficient forest management plans that combine technical as well as economic and environmental factors.

16.3 Application

The industrial use of forest resources is one of the pillars of the Cuban economy. However, the severe environmental impact of deficiencies in age-distribution and exploitation of the forest have led to serious imbalances in the operational planning process and the expected returns not being achieved. Thus, one of the main objectives of the Cuban Forestry Law (published July 1998) is to *regulate the sustainable and multiple use of forests as well as to promote the rational use of forestry products.*

The province of Pinar del Rio in Cuba contains the largest forests in the country. The *Forestal Integral Macurije* company manages one of the largest forested surface areas in the sector (91,036.2 ha) located in the west of the province in the municipalities of Guane and Mantua. The main production activities of the company are silviculture, sawn timber production, and pine charcoal and resin.

The model described in Sect. 16.2 has been applied to a plantation owned by Forestal Integral Macurije that has 3347.7 ha of *Pinus Caribea*. This surface area was divided into 305 basic units with ages ranging from 3 to 41 years. All the basic units were relatively homogenous in relation to each other regarding behaviour, typology, and dasometric measurements.

Figure 16.1 shows the initial distribution of the plantation's surface area, where basic units with 1 to 5-year-old trees (m = 5) are the first age-class, and units with trees over 25 years old are the last age-class.

The plantation has a rather uneven age distribution. A surface area of 2451.6 ha contained trees older than 25 years, and the relative difference between the surface area of basic units less than 5 years old and those older than 25 was 2.58 %.

Fig. 16.1 Surface area covered by each age-class at baseline

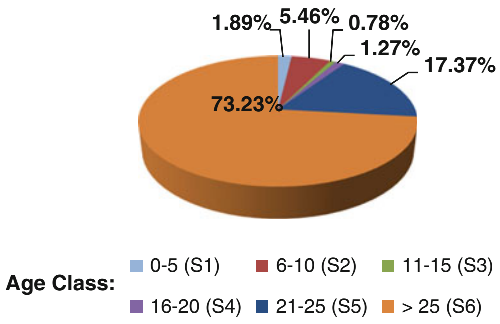

Table 16.1 Model parameters

Parameter value
T = 30
N* = 30
K = 103
j = 3
$[Lb_1, Ub_1] = [11, 15]$
$[Lb_2, Ub_2] = [16, 25]$
$[Lb_3, Ub_3] = [25, 100]$
g = 1
n* = 15
$Se = \frac{1}{30} 3347.7 = 111.6$ ha.
τ = 0.75
$V^t = 34{,}869\ m^3, \forall t$

The values of the model parameters for this application are shown in Table 16.1.

The atmospheric/biomass carbon conversion rate is 47.54 %, i.e. $\gamma = 0.4753$, (Alvarez et al. 2005). The β values were taken from Table 7 of the Forest Research Institute (1990) publication "*Tablas de Volumen Surtido y Densidad del Pinus Caribaea en plantaciones puras de Cuba*" (Density and Volume Tables for *Pinus Caribaea* in Cuba) where the different uses of logging activities, by percentages, are described.

As mentioned in the introduction, we applied an SSPMO method adapted to the forestry context since it has demonstrated competitive problem-solving abilities (Gómez et al. 2011). The problem was resolved by this procedure using a Pentium IV processor (3.2 GHz) computer with a resolution time of 33,472 s.

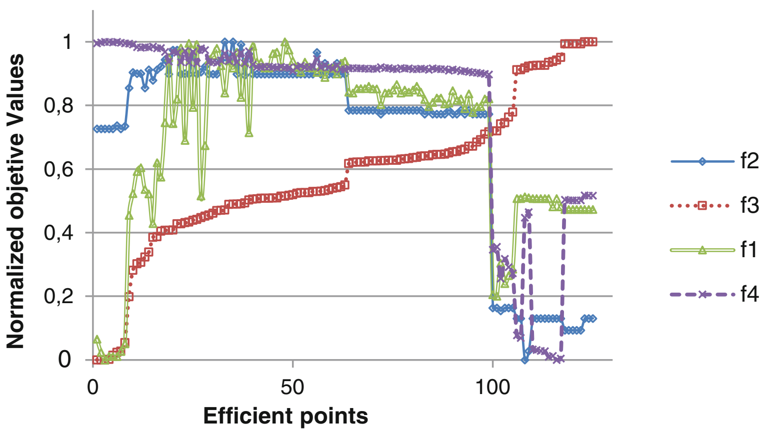

Fig. 16.2 Distribution of the efficient points for the objectives

Solving the problem provided a set of 125 efficient management plans over 30 years. Data output was in the form of a user-friendly spreadsheet. To analyze this efficient set, we show all the efficient points in a single graph.

In order to do that, we have normalized all the functions. In this way, and regardless of the measuring unit used for each objective, all values were between 0 and 1. In addition, all normalized functions have been set to be maximized.

The results are shown in Fig. 16.2. It should be noted that the best values for the economic objective are obtained at the expense of worse values for the remaining objectives.

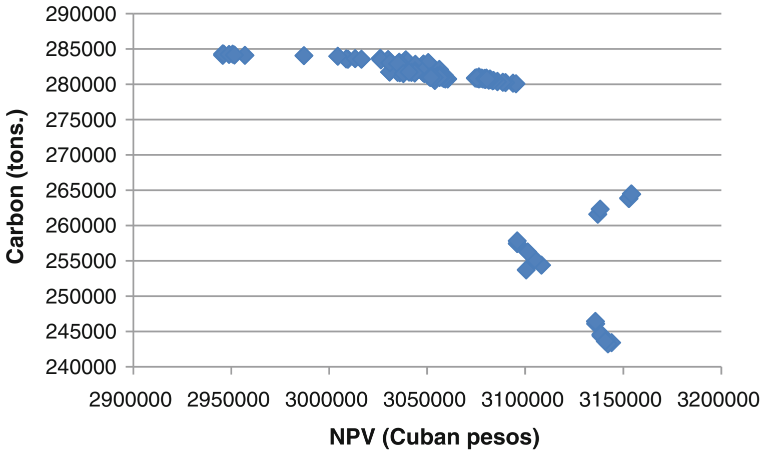

Fig. 16.3 Trade-off between NPVand sequestered carbon

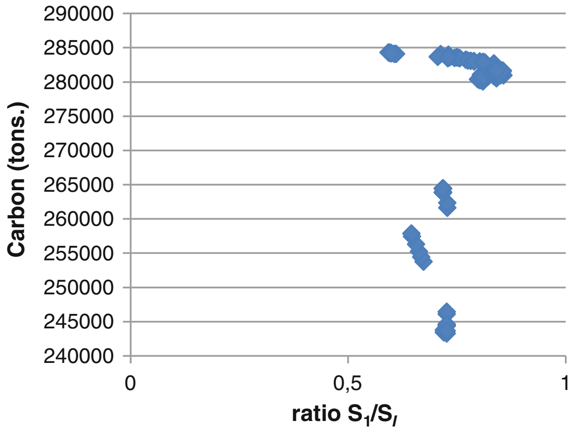

Fig. 16.4 Trade-off between age-distribution and sequestered carbon

In fact, the trade-off between the economic objective and carbon sequestration is noteworthy. In fact, the best carbon sequestration corresponds to the solution where the NPV has the smallest value, and vice versa. This trade-off is confirmed in Fig. 16.3, which shows the value at each efficient point in these two objectives.

Moreover, the solution that maximizes carbon sequestration also yields the best balance regarding age distribution within the plantation. However, when the efficient points for carbon sequestration and even age-distribution objectives are graphically represented, it cannot be concluded that the trade-off is substantial (see Fig. 16.4).

Regarding the solution that maximizes an even age-distribution (Solution 48 in Fig. 16.2), the relative difference between the area covered by first age-class units and last age-class units increases each year from 2.58 to 85.7 %. Although a fully even age-distribution is not achieved by the end of the planning horizon, there has been a striking improvement compared to baseline, as shown in Fig. 16.5 (also see Fig. 16.1). In the final plan, the number of hectares occupied by trees older than 25 years is 18.9 % of the total plantation area, compared to 73.23 % at baseline.

This solution shows that by the end of the planning horizon, there were 145.7 ha of basic units with trees more than 30 years old comprising 4.35 % of the total surface area as compared to 66 % at baseline.

To test whether these results were due to the features of the case studied, we randomly generated simulated plantations with characteristics similar to the real case.

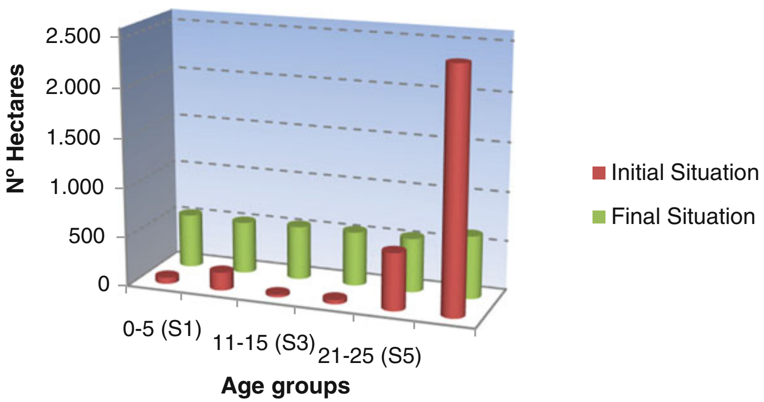

Fig. 16.5 Comparing initial situation with final situation in solution 48

Table 16.2 Mean values for the randomly generated forests

No. units	100	200	300	400
Size (ha.)	1105.93	2073.98	3133.97	4085.21
K	10	20	30	40
Initial age distr.	0.203	0.398	0.488	0.483

Table 16.3 Mean values for the simulated forests

No. units	100	200	300	400
f^1	0.7174	0.7844	0.8439	0.9029
f^2	109.73	154.98	162.37	188.014
f^3	878,112	1870,021	2435,306	3,622,241
f^4	119,268	234,200	316,767	479,711
Efficient points	126	120	136	126
Solving time (s)	86,348.93	72,443.86	54,950.29	56,356.00

Software was used that generated forests similar to the real plantation (in terms of soil type and species) but with different sizes, initial age distributions and site indexes. We generated seven plantations with 100, 200, 300 and 400 basic units. In each simulated forest, the program randomly assigned to each one a given age and surface area, with an average of 10 ha. The clustering of units into adjacency groups was also randomized, but with the restriction that those in the same adjacency group had to belong to the same site index. Table 16.2 shows the mean size (in hectares), the number of adjacency groups, and the initial age distribution (i.e. the ratio between the number of hectares of first age-class trees and last age-class at baseline) for each simulated plantation group.

Each simulated forest problem was solved by applying the model proposed in this paper. The results are summarized in Table 16.3 which shows the mean values for each objective function in every simulated situation. The last two rows of Table 16.3 show the average number of efficient points and the runtime to find the solution.

The results obtained for the simulations confirm the good performance of the model because it is not influenced by the baseline conditions of the real plantation. In fact, the problem solved for the real case could be included in the data shown in column 300 in Tables 16.2 and 16.3, and if these data are compared to those obtained in our specific Cuban case it can be seen that the results are similar. The number of basic units has an effect on the values of some objectives. Thus, in all cases, a more even age-distribution is achieved for the plantation, as shown by the fact that the mean values of objective f^1 are higher than those shown in the row "*Initial Age Distr*" (age distribution at baseline). This objective improves as the number of basic units increases, which indicates that the greater the number of units, the better the distribution of hectares by age group achieved by the model. On the other hand, by the end of the planning horizon, the number of hectares of old trees (f^2) did not exceed 10 % of the total plantation in any instance, although by the end of planning horizon a completely even age-distribution was not achieved in any simulation. Finally, note that f^3 (NPV) and f^4 (carbon) are two objectives which are in conflict in all the simulations generated because as one objective improves the other deteriorates.

16.4 Conclusions

This work proposes a model for forest planning which includes different constraints and objectives. The aims were to optimize the objectives without degrading the ecosystem; obtain a balanced age class distribution by the end of the planning period without having to sacrifice young basic units in the process; meet the economic objectives; and take into account adjacency constraints. So, the constructed model gives us efficient treatments schedules such that all spatial and technical constraints are met and the objectives of the decision-makers are taken into account to the greatest extent possible.

We focus on harvest planning which involves identifying the stands to be treated, the kind of treatment to be applied, and the schedule. The approach selected does not demand too much information from the decision-makers, and the analysis of the efficient set allows us to compare tradeoffs between different objectives to gain greater understanding of the situation being addressed. After studied the trade-offs between NPV objective and carbon sequestration, it is concluded that when one is optimized, the other reaches its worst value. Furthermore, the optimal economic value is reached at the expense of the worst values in the other objectives. Our results show that management planners should take into consideration not only economic objectives when planning a harvest, and that the use of multiobjective models should be an imperative in this context.

Other important key point in this work has been the formulation of rebalancing the age distribution of the stands as an objective with a fractional formulation instead of treating this as a constraint. So, the unfeasibility problems are eliminated but also the model tries to achieve at the end of the horizon a balanced age distribution as much as possible.

The model proposed is highly complex due to its fundamental characteristics so a metaheuristic method for its resolution is needed. The SSPMO evolutionary method was adapted to our situation, due to its highly competitive problem-solving capacity for multiobjective problems.

The model was resolved in order to planning a real plantation located in Pinar del Río (Cuba). Although the final balanced age class distribution was not reached in the efficient solutions, the final distribution by age classes had improved very much compared with the initial situation. Finally, we investigated to what extent the model is valid to other contexts and different starting conditions by planning the harvest in a series of randomly generated simulated forests. The conclusion is that the model could be applied to other single-species plantations where the aim is timber production, regardless of the number of hectares and baseline ages, because in all the situations similar results have been obtained.

So, the model proposed has demonstrated its practical value in the operational planning of the cutting of a forest when the DM not only has the objective of maximizing the NPV. This model would be mostly recommended in those situations where the initial distribution of the forest is not age-balanced.

In this sense, the development of a DSS tool that includes the present model to help management planners to take into account the mentioned objectives can be considered as a future line of this work. Segura et al. (2014) analyse and evaluate different models and methods that have been used in developing of DSS for forest management. The main conclusion is that the most of DSS systems analysed focus only on market economic value. They strong recommend the development and application of MCDM models and incorporating them in the design of new DSS for forest management.

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References

Alvarez, A., Mercadet, A., & Escarré, A. (2005). El papel de los coeficientes de carbono de la madera en la certificación del efecto sumidero de los bosques cubanos (Spanish). In DEFORS, Sept 20–23, 2005 (pp. 1–13).

Bachmatiuk, J., García-Gonzalo, J., & Borges, J. G. (2015). Analysis of the performance of different implementations of a heuristic method to optimize forest harvest scheduling. *Silva Fennica, 49*(4), Article ID 1326.

Bare, B., & Mendoza, G. (1988). Multiple objective forest land and management planning: An illustration. *European Journal of Operational Research, 34*, 44–55.

Bateman, I. J., & Lovett, A. A. (2000). Estimating and valuing the carbon sequestered in softwood and hardwood trees, timber products and forest soils in Wales. *Journal of Environmental Management, 60*, 301–323.

Bobko, A., & Aldana, E. (1981). Ordenación de montes (Spanish). Cuba: Centro Universitario de Pinar del Río.

Borges, J. G., Hoganson, H. M., & Falcão, A. O. (2002). Heuristics in multi-objective forest planning. In T. Pukkala (Ed.), *Multi-objective forest planning* (pp. 119–151). Boston: Kluwer Academic Publishers.

Buongiorno, J., & Gilless, J. K. (2003). *Decision methods for forest resource management*. Boston: Academic Press.

Caro, F., Constantino, M., Martins, I., & Weintraub, A. (2003). A 2-opt tabu search procedure for the multiperiod forest harvesting problem with adjacency, green-up, old growth, and even flow constraints. *Forest Science, 49*, 738–751.

Couture, S., & Reynaud, A. (2011). Forest management under fire risk when forest carbon sequestration has value. *Ecological Economics, 70*, 2002–2011.

De Kluyver, C. A., Daellenbach, H. G., & Whyte, A. G. D. (1980). A two-stage, multiple objective mathematical programming approach to optimal thinning and harvesting. *Forest Science, 26*, 674–686.

De Sousa Xavier, A. M., Costa Freitas, M. B., & de Sousa Fragoso, R. M. (2015). Management of Mediterranean forests—A compromise programming approach considering different stakeholders and different objectives. *Forest Policy Economy, 57*, 38–46.

Diaz-Balteiro, L., & Romero, C. (2007). Multiple criteria decision-making in forest planning: Recent results and current challenges. In A. Weintraub, C. Romero, T. Bjørndal, & R. Epstein (Eds.), *Handbook of operations research in natural resources* (Vol. 99). International Series in Operations Research and Management Science. New York: Springer.

Diaz-Balteiro, L., & Romero, C. (2008). Making forestry decisions with multiple criteria: A review and an assessment. *Forest Ecology and Management, 225*, 3222–3241.

Falcão, A., & Borges, J. (2002). Combining random and systematic search heuristic procedures for solving spatially constrained forest management scheduling models. *Forest Science, 48*, 608–621.

Field, D. B. (1973). Goal programming for forest management. *Forest Science, 19*, 125–135.

Field, R., Dress, P. E., & Fortson, J. C. (1980). Complementary linear and goal programming procedures for timber harvest scheduling. *Forest Science, 26*(1), 121–133.

Gómez, T., Hernández, M., León, M. A., Aldana, E., & Caballero, R. (2011). A multiobjective model for forest planning with adjacency constraints. *Annals of Operations Research, 190*(1), 75–92.

Gómez, T., Hernández, M., León, M. A., & Caballero, R. (2006). A forest planning problem solved via a linear fractional goal programming model. *Forest Ecology and Management, 227*, 79–88.

Goycoolea, M., Murray, A. T., Barahona, F., Epstein, R., & Weintraub, A. (2005). Harvest scheduling subject to maximum area restrictions: Exploring exact approaches. *Operations Research, 53*, 490–500.

Hallefjord, A., Jörnsten, K., & Eriksson, O. (1986). A long range forestry planning problem with multiple objectives. *European Journal of Operational Research, 26*, 123–133.

Hernández, M., Gómez, T., Molina, J., León, M. A., & Caballero, R. (2014). Efficiency in forest management: A multiobjective harvest scheduling model. *Journal of Forest Economy, 20*(3), 236–251.

Hoen, H. F., & Solberg, B. (1994). Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management. *Forest Science, 40*, 429–451.

Hotvedt, J. E. (1983). Application of linear goal programming to forest harvest scheduling. *Southern Journal of Agricultural Economics, 15*, 103–108.

Kao, C., & Brodie, J. D. (1979). Goal programming for reconciling economic, even flow, and regulation objectives in forest harvest scheduling. *Canadian Journal of Forest Research, 9*, 525–531.

Kazana, V., Fawcett, R. H., & Mutch, W. E. S. (2003). A decision support modelling framework for multiple use forest management: The Queen Elizabeth Forest case study in Scotland. *European Journal of Operational Research, 148*, 102–115.

Liu, G., Han, S., Zhao, X., Nelson, J. D., Wang, H., & Wang, W. (2006). Optimisation algorithms for spatially constrained forest planning. *Ecological Modelling, 194*, 421–428.

McDill, M. E., Rebain, S. A., & Braze, J. (2002). Harvest scheduling with area-based adjacency constraints. *Forest Science, 48*, 631–642.

Mendoza, G. A., & Martins, H. (2006). Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms. *Forest Ecology and Management, 230*, 1–22.

Molina, J., Laguna, M., Marti, R., & Caballero, R. (2007). SSPMO: A scatter tabu search procedure for non-linear multiobjective optimization. *Journal of Computing, 19*(1), 91–100.

Mönkkönen, M., Juutinen, A., Mazziotta, A., Miettinen, K., Podkopaev, D., Reunanen, P., et al. (2014). Spatially dynamic forest management to sustain biodiversity and economic returns. *Journal of Environmental Management, 134*, 80–89.

Murray, A. T. (1999). Spatial restrictions in harvest scheduling. *Forest Science, 45*, 1–8.

Murray, A. T., & Weintraub, A. (2002). Scale and unit specification influences in harvest scheduling with maximum area restrictions. *Forest Science, 48*, 779–789.

Platinga, A. J., Mauldin, T., & Miller, J. (1999). An econometric analysis of the costs of sequestering carbon in forests. *American Journal of Agricultural Economics, 81*, 812–824.

Pukkala, T. (2002). *Multi-objective forest planning*. Boston: Kluwer Academic Publishers.

Pukkala, T., & Heinonen, T. (2006). Optimizing heuristic search in forest planning. *Nonlinear Analysis, 7*, 1284–1297.

Segura, M., Ray, D., & Maroto, C. (2014). Decision support systems for forest management: A comparative analysis and assessment. *Computers and Electronics in Agriculture, 101*, 55–67.

Steuer, R. E., & Schuler, A. T. (1978). An interactive multiple objective linear programming approach to a problem in forest management. *Operations Research, 26*, 254–269.

Tóth, S. F., & McDill, M. E. (2008). Finding efficient harvest schedules under three conflicting objectives. *Forest Science, 55*, 117–131.

Tóth, S. F., McDill, M. E., & Rebain, S. (2006). Finding the efficient frontier of a bi-criteria, spatially explicit, harvest scheduling problem. *Forest Science, 52*, 93–107.

Triviño, M., Juutinen, A., Mazziotta, A., Mietinnen, K., Podkopaev, D., Reunanen, P., et al. (2015). Managing a boreal forest landscape for providing timber, storing and sequestering carbon. *Ecosystem Service, 14*, 179–189.

Weintraub, A., & Murray, A. T. (2006). Review of combinatorial problems induced by spatial forest harvesting planning. *Discrete Applied and Mathematics, 154*, 867–879.

Weintraub, A., Romero, C., Bjørndal, T., & Epstein, R. (Eds.) (2007). *Handbook of operations research in natural resources*. *Series: International Series in Operations Research and Management Science* (Vol. 99). New York: Springer.

Chapter 17
Analytic Hierarchy Process and Fuzzy Rule Based System-Integrated Methodology for Urban Land Use Planning

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Abstract While the specific constraints may vary over time and by location, urban planners essentially execute the same function, namely to create effective urban areas subject to the constraints of land, resources, finance and time. Thereby, it should be emphasized that planned urban forms cannot be excluded from organic growth processes. Land-use planning is regarded as a branch of urban planning including various disciplines which aims at providing land-use in an efficient and ethical way, thus preventing land-use conflicts. A crucial stage in land-use planning is the suitability analysis, which is the central part of land-use evaluation. Modern planning theories lead to approaches that consider all stakeholders with a variety of discourse values to avoid political and manipulative decisions. In recent years, application of quantitative approaches such as multi-criteria decision making techniques (MCDM) in land suitability procedures has increased. However, it is generally impossible to provide a land-use allocation satisfying each land-use goal simultaneously. Among MCDM techniques, Analytic Hierarchy Process (AHP), allowing subjective judgments in a consistent way, has the ability of including the criteria of land-use planning in a structured way. In addition, fuzzy rule based systems (FRBS) can be regarded as an appropriate method to capture and represent vague, imprecise and uncertain data in urban land-use planning. In this context, this chapter proposes an AHP-FRBS integrated methodology with the aim of assessing urban land-use suitability. The proposed methodology is applied on a selected area in Turkey. Finally, scenario analysis is performed so as to evaluate different scenarios.

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17.1 Introduction

Recently, the urban world is changing in a rapid manner. It becomes vitally important to look at how cities develop and how they are planned (Duhl and Sanchez 1999). The character of a city is greatly affected by the organization of space and activities within its boundaries. This sense of place is partly an aesthetic attribute; by invoking the name of major world cities, it is possible to picture their structure and form such as the grid-iron streets and high-rises of New York or the hillside favelas of Rio de Janeiro. However, the city's social, economic and environmental performance is arguably a consequence of urban form Keirstead and Shah (2013). Through the deliberate positioning of activity and transportation facilities, urban authorities hope to ensure the success of their cities in economic, social and environmental terms. Urban planning models are important tools to help them in this task (Keirstead and Shah 2013).

Today, urban planning can be described as a technical and political concept related with the welfare of people, control of the use of land, design of the urban environment including transportation and communication networks, and protection and enhancement of the natural environment. Urban planning guides and ensures the orderly development of settlements and satellite communities, which commute into and out of urban areas or share resources with it. The interdisciplinary working environment of urban planners include the fields of architecture, landscape architecture, civil engineering and public administration to achieve strategic, policy related and sustainability goals. Urban planners have always been involved in designing and maintaining cities and counties through land-use regulation and infrastructure support. The existence of several professional associations (American Planning Association (APA), European Council of Town Planners (ECTP), International Federation of Urban Planning Associations (FNAU), European Council of Town Planners (ECTP), International Federation of Urban Planning Associations (FNAU), International Society of City and Regional Planners (ISoCaRP), Pacific Rim Council on Urban Development (PRCUD), Town and Country Planning Association (TCPA), Urban and Regional Information Systems Association (URISA), Commonwealth Association of Planners (CAP), Royal Town Planning Institute (RTPI), etc.) and national planning and research institutes (Canadian Institute of Planners (CIP), Arab Planning Institute-Kuwait (API), German Institute for Urbanism (difu), City Planning Institute of Japan (CPIJ), New Zealand Planning Institute (NZPI), Nordic Institute for Studies in Urban and Regional Planning (NORDPLAN), Italian National Town Planning Institute (INU), South African Planners (SAP), etc.) can be regarded as an indicator of importance of urban planning.

As an important branch of urban planning, land-use planning may be expressed as the process of allocating different activities or uses (such as agriculture, manufacturing, industries, recreational activities or conservation) to specific units of area within a region and this planning process is a priority for city communities throughout the world (Zhou 2015). Generally, land-use, which is determined by the human activities on land, can be defined by two interrelated phenomena, namely land cover and land utilization. Land cover describes both the natural and human altered land surface where human actions take place, while human actions determine the land utilization (Ullah and Mansourian 2016). Land-use planning can play an important role in sustainable development as well as for sustainable urban development (Shen et al. 2011).

Urban planning analysis involves the consideration of a number of factors, including natural system constraints, compatibility with existing land-uses, existing land-use policies, and the availability of community facilities. The suitability techniques analyze the interaction between location, development actions, and environmental elements to classify the units of observation according to their suitability for a particular use (Mosadeghi et al. 2015). As one of the core research aspect in land-use planning, the optimal allocation of land-use is soon becoming the key measure for sustainable land utilization. It is generally impossible for an allocation to achieve a maximum benefit with respect to each land-use goal simultaneously (Zhou 2015). Therefore, quantitative approaches such as multi-criteria decision making (MCDM) techniques in land suitability procedures can be used in an appropriate manner. Since, MCDM is often supported by a set of techniques to help decision makers who are faced with such decision situations of making numerous and sometimes, conflicting evaluations. There are many MCDM methods in use today, the main one of which is Analytic Hierarchy Process (AHP). AHP is a mathematical technique used for multi-criteria decision-making. In a way it is better than other multi-criteria techniques, as it is designed to incorporate tangible as well as non-tangible factors especially where the subjective judgments of different individuals constitute an important part of decision making (Saaty 1986). Furthermore, AHP considers the assessment of consistency among decision maker(s). It is used for making selection, evaluation, cost and benefit analysis, resource allocations, planning and development, priority and ranking, and forecasting (Vaidya and Kumar 2006).

The input data may contain inaccuracies, imprecision, and ambiguity in land-use planning. In this context, modeling of imprecise and qualitative knowledge, as well as the transmission and handling of uncertainty at various stages are possible through the use of fuzzy sets. Fuzzy logic is capable of supporting to a reasonable extent, human type reasoning in natural form. Especially, fuzzy rule based systems have been the most popular and easiest way to capture and represent fuzzy, vague, imprecise, and uncertain domain knowledge. The fuzzy rule based systems (FRBS) uses fuzzy IF-THEN rules to determine a mapping from fuzzy sets in the input universe of discourse to fuzzy sets in the output universe of discourse based on fuzzy logic principles (Ross 2010; Ustundag et al. 2010).

Taking into account the above-mentioned manners, this chapter presents a novel urban land-use planning methodology via the integration of AHP and FRBS in order to represent the uncertainty in the system in a certain level. In the proposed methodology, FRBS determines urban land-use suitability by means of using AHP rating model to obtain rating for each factor. The remainder of this chapter is organized as follows. In Sect. 17.2, the relevant literature is reviewed. Proposed methodology and background information are presented in Sect. 17.3. Application of the proposed urban land-use planning methodology and scenario analysis are included in Sect. 17.4. Finally, conclusions are given in Sect. 17.5.

17.2 Literature Review

The related literature provides a clear development of the urban land-use discipline, which becomes an important point with the environmental, social and engineering progress. According to the Scopus database, urban land-use planning concept is a highly researched area. The research is conducted by searching “urban land-use planning” concept in the fields of keyword, title, and the abstract. Especially in the early 2000s, in the early 2000s, there is an obvious trend and the researches on this area lead to the highest level with thousands of papers in 2013. The researchers of the urban land-use planning field are mostly from USA and China. Furthermore, more than the halves of these documents are found as articles of international journals such as Landscape and Urban Planning, Land Use Planning and Transportation Research Record. Respectively, environmental science, social science, engineering, earth and planetary sciences, agricultural and biological sciences and computer science are the most studied subjects of the urban land-use planning. In a similar manner, the urban land-use suitability concept follows the same trend for the researchers and article characteristics but reaches just eighty papers in 2013, sixty papers in 2014 and, forty-five papers in 2015. Additionally, land-use planning, land-use, urban planning, urban area, urban growth, urban development, land-use change, urbanization, and decision making are the most used concepts for literature review.

Geographical Information System (GIS) is the main technique for urban land-use planning studies to evaluate any type of land’s suitability. There are plenty of frameworks, support systems and case studies of GIS-based urban land-use planning papers. Moreover, literature review highlights that land-use assessment, suitability analysis, multi-criteria land suitability decision making, the comparison of land-use plans and strategies, and data mining applications are the various subjects of the field. Particularly, GIS and AHP techniques are commonly examined together within these papers, and they all have applications/case studies for a specific region.

While some of the studies discuss only the geomorphological/physical factors like slope, elevation, and vegetation, some of them examine the social, economic and environmental attributes in addition to these physical factors. For instance, a GIS-based land-use suitability analysis model including physical, locational, social, economic, and environmental factors for five types of land-use is suggested for land-use suitability grading (Wang et al. 2015). Similarly, geomorphological, geological, natural hazards and social-economic factors are discussed by using AHP and GIS (Bathrellos et al. 2013). Another research performs a multi-criteria evaluation within GIS to derive a suitability map with the factors such as current land-use, slope, distance to river, density of green surface, distribution of pollutant sources, distance to road network, distance to residential areas (Dai et al. 2008). Additionally, population density, accessibility to main roads, proximity to public health concern, proximity to beach, proximity to schools, life-support system, high-value area, geo-hazard risk area, proximity to different industries, existing plan are taken into consideration and ANP and scenario analysis are performed sequentially in the literature (Pourebrahim et al. 2011). The optimum suitability for coastal land-uses is proposed for a sustainable development by evaluating various scenarios, existing plans and guidelines, land availability (Pourebrahim et al. 2011). Besides, the population of the city is discussed in addition to the all above factors (Khalili-Damghani et al. 2014).

Table 17.1 presents a summary of a detailed literature review of urban land-use planning. Most of the papers address the physical, social and locational attributes of the particular land together. Although the case studies, AHP and GIS are the common techniques for these studies, linear programming, simulated annealing, Bayesian network, genetic algorithm, hierarchical assessment, digital elevation models (DEM), simulation and other multi criteria evaluation methods like DEMATEL, ELECTRE and ANP are applied in the existing literature.

In the early times of urban land-use planning, studies were basically about to create the maps. For example, Hofmann classifies the land according to its suitability based on capability ratings (foundation potential and suitability for septic systems) by using the parameters like natural slope, drainage conditions, slope stability and ease of excavation. As a consequence of this evaluation, six maps containing geology, geomorphology, natural hazards, extractive materials, hydrogeology and potential urban land capability are generated (Hofmann 1976).

In a detailed review, the evolution and development of the urban land-use planning with human action theory, which means provision of incentives for individuals who constitute government, is analyzed (Baffour Awuah et al. 2014). The study examines the UK, Japan and sub-Saharan Africa for the case studies. Accordingly, the historical progress of the urban land-use planning is illustrated in detailed, and the researchers reached the result emphasizing on the evolution of the planning over time is rooted in human action (Baffour Awuah et al. 2014). Also, another research examines the economic benefits of a country’s land-use planning and finds out that this planning contributes considerably in residential areas (Baffour Awuah et al. 2014). The benefits arise from tarred roads, concrete drains, electricity, formalized titles and pipe-borne water, while worship centers create no benefits. The developed methodology conducts a contingent survey to real estate agents and asks a bid on how much they are willing to pay for a specific region, and paired t-tests are assessed to this data to reach mentioned results (Baffour Awuah et al. 2014).

In one of the most cited papers, the researchers conduct a geo-environmental evaluation for urban land-use planning by applying GIS and AHP (Dai et al. 2001). They examine the study area, collect and process the data for urban land-use category generation, determine the factors for suitability as topography, ground condition and water, and geologic hazard. After standardization of factor measurements and weight developments by AHP, the geo-environmental evaluations of

Table 17.1 Literature review details

		Document type			Application	Techniques/methodology								
									Multi criteria evaluation					
		Journal	Book	Conference paper		Linear programming	Simulated annealing	GIS	AHP	DEMATEL	ELECTRE	ANP	Ranking method	Case study
1	Zhang and Chen (2011)			x	x				x				x	
2	Bathrellos et al. (2013)	x			x			x	x					
3	Baffour Awuah et al. (2014)	x			x									x
4	Yu et al. (2011)	x			x				x					
5	Meyer et al. (2014)	x			x									
6	Wang et al. (2015)	x			x			x						x
7	Santé-Riveira et al. (2008)	x			x	x	x							
8	Kang et al. (2013)	x			x									
9	Porta et al. (2013)	x			x									
10	Pourebrahim et al. (2011)	x			x							x		
11	Chandio et al. (2011)	x			x			x	x					
12	Ziadat (2007)	x			x									
13	Anagnostopoulos and Vavatsikos (2012)	x			x				x					
14	Cengiz and Akbulak (2009)	x			x			x	x					
15	Kergosien et al. (2014)	x			x									
16	Booth and Muir (2011)	x			x									
17	Dai et al. (2008)	x			x			x	x					
18	Kaffashi and Yavari (2011)	x			x	x		x						

(continued)

Table 17.1 (continued)

		Document type			Application	Techniques/methodology								
									Multi criteria evaluation					
		Journal	Book	Conference paper		Linear programming	Simulated annealing	GIS	AHP	DEMATEL	ELECTRE	ANP	Ranking method	Case study
19	Junker (2013)	x			x									
20	Busscher et al. (2013)	x			x									x
21	Khalili-Damghani et al. (2014)	x			x				x	x				
22	Akimoto (2009)	x												
23	Huang et al. (2012)	x			x			x						
24	Joerin et al. (2001)	x			x			x			x			
25	Keirstead and Shah 2013)		x		x	x								
26	Mosadeghi et al. (2015)	x			x			x	x					x
27	Sakieh et al. (2015)	x			x				x					
28	Ullah and Mansourian (2016)	x			x			x	x					
29	Zhou (2015)	x			x	x		x						x
30	La Rosa and Privitera (2013)	x			x			x						
31	Uy and Nakagoshi (2008)	x			x			x	x					x
32	Dou et al. (2016)	x			x									x
33	He et al. (2016)	x												
34	Dai et al. (2001)	x			x			x	x					
		32	1	1	32	4	1	14	13	1	1	1	1	7

(continued)

Table 17.1 (continued)

		Techniques/methodology									Type		
		Bayesian network	Genetic algorithm	Hierarchical assessment	Digital elevation models	Scenario analysis	Data mining	Literature review	Conceptual model	Simulation	Urban	Rural	Agricultural
1	Zhang and Chen (2011)										x		
2	Bathrellos et al. (2013)											x	x
3	Baffour Awuah et al. (2014)							x					
4	Yu et al. (2011)									x			x
5	Meyer et al. (2014)	x									x	x	
6	Wang et al. (2015)										x		
7	Santé-Riveira et al. (2008)											x	
8	Kang et al. (2013)			x							x		
9	Porta et al. (2013)		x								x	x	
10	Pourebrahim et al. (2011)					x					x		
11	Chandio et al. (2011)										x		
12	Ziadat (2007)				x								
13	Anagnostopoulos and Vavatsikos (2012)											x	
14	Cengiz and Akbulak (2009)											x	x
15	Kergosien et al. (2014)						x				x	x	
16	Booth and Muir (2011)							x					
17	Dai et al. (2008)										x		
18	Kaffashi and Yavari (2011)										x		

(continued)

Table 17.1 (continued)

		Techniques/methodology									Type		
		Bayesian network	Genetic algorithm	Hierarchical assessment	Digital elevation models	Scenario analysis	Data mining	Literature review	Conceptual model	Simulation	Urban	Rural	Agricultural
19	Junker (2013)							x			x		
20	Busscher et al. (2013)							x			x		
21	Khalili-Damghani et al. (2014)		x								x		
22	Akimoto (2009)							x			x		
23	Huang et al.,2012				x						x		
24	Joerin et al. (2001)									x		x	
25	Keirstead and Shah (2013)							x			x		
26	Mosadeghi et al. (2015)					x					x		
27	Sakieh et al. (2015)				x						x		x
28	Ullah and Mansourian (2016)										x		
29	Zhou (2015)												
30	La Rosa and Privitera (2013)											x	x
31	Uy and Nakagoshi (2008)										x		x
32	Dou et al. (2016)										x		
33	He et al. (2016)								x		x		
34	Dai et al. (2001)										x		
		1	2	1	3	2	1	6	1	2	23	9	6

specific land categories (high-rise building category, multi-storey building category, low-rise building category, waste disposal category and natural conservation category) are prioritized for suitability potential maps. It is mentioned that geo-environmental evaluation results assist planners in land-use decision making processes (Dai et al. 2001). As a basic methodology for this evaluation, GIS provides a degree of accuracy for assessing the potential suitability of land parcels. Additionally, accessibility at low cost, ease of use, short time requirement for data manipulation and creating various scenarios are some advantages of GIS. A GIS software utilization makes easier to store, analyze, and display the given data. Moreover, the study emphasizes that the reliability of the assessment results highly depends on multitude of the factors and evaluator perception. Some errors due to wrong data entry, manipulation and analysis within GIS range the multitude of the factors. Also, knowledge and perception of the decision makers give a form to priorities of the weighting method. Hence, the evaluation models are highly sensitive to determined weights in making decisions. Moreover, in a recent study, Dou et al. (2016) aims to conduct an empirical and quantitative study on the applications of TOD strategy in Shanghai based on Exploratory Spatial Data Analysis (ESDA) and the updating data. He et al. (2016) offers a conceptual model of UGS recreational service that follows the logical flow of ecosystem service generation, supplementing the knowledge gap and supporting the use of ecosystem base management in urban land use planning.

Another most cited study covers the comparison of two quantitative alternatives AHP and fuzzy AHP in spatial multi criteria decision making (MCDM) model for urban land-use planning (Mosadeghi et al. 2015). The study includes a case study utilizing definition and ranking land suitability criteria, GIS analysis, land suitability maps, and comparative analysis (Mosadeghi et al. 2015). Within the scope of the study, four land-use categories (residential, extractive industry, marine industry, and recreation) and criteria like proximity to places, compatibility with surrounding land-uses, and existence of infrastructure are examined and compared for two MCDM techniques. According to the results, these two models do not point different options for selection. When the aim is to identify priority areas as a focal point, simpler MCDM techniques like AHP is sufficient. However, when a more detailed plan is the aim, which is requiring identification of spatial boundaries, a hybrid or integrated method (two or more MCDM techniques) would be ideal. The study indicates that greatest confidence can be ensured by focusing on the intersection area between two outcomes of these two methods.

17.3 The Proposed Methodology

The methodology, which attempts to assess urban land-use suitability, comprises of four main modules, namely preliminary study, AHP rating model, Fuzzy Rule Based System and application as shown in Fig. 17.1. As the first main module of the methodology, preliminary study is conducted such that it includes literature

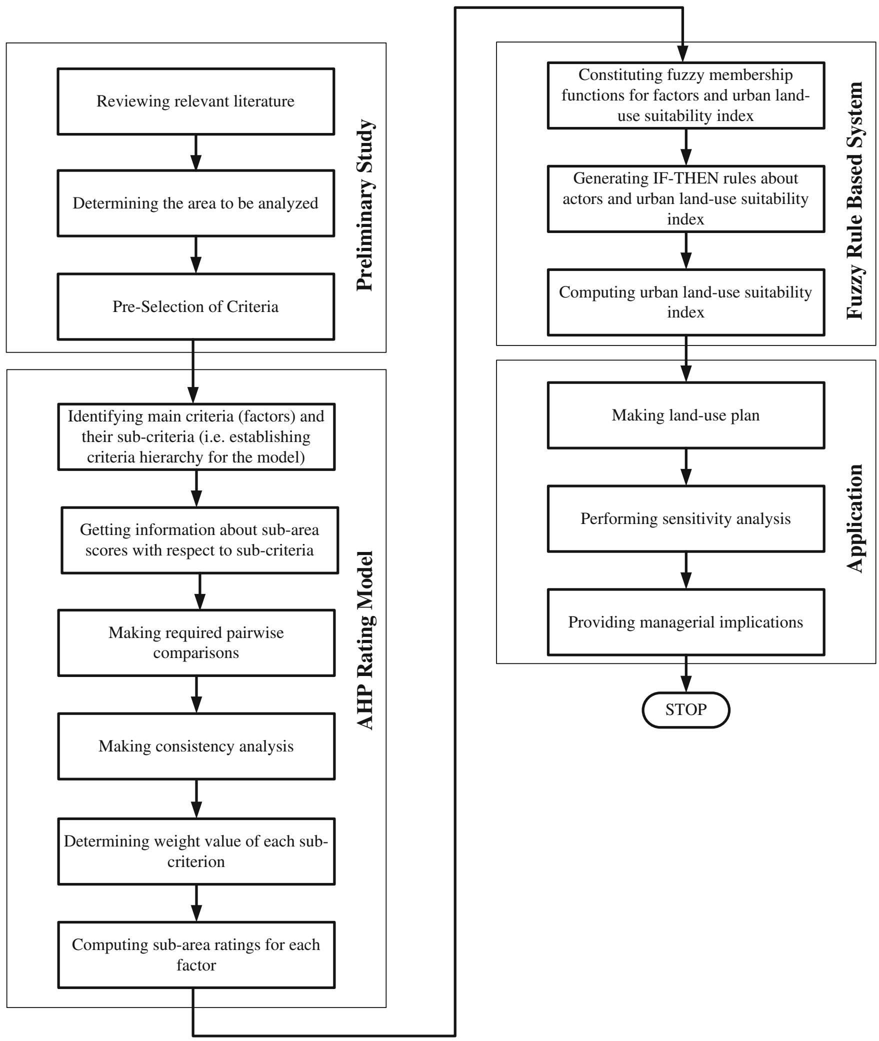

Fig. 17.1 Flowchart for the proposed methodology

review, focused area as well as pre-consideration of criteria. Then, AHP rating model is established in the second module of the methodology. Criteria hierarchy structuring, the calculation of sub-criteria and consistency analysis can be considered as the most crucial sub-steps of the module. The proposed AHP rating model provides factor ratings for each sub-area. Subsequently, the third module, namely FRBS, uses the output of the preceding module as input and gives urban land-use suitability indices of sub-areas. Being the last main module, application module involves land-use plan, which is made with respect to FRBS outputs. Then, scenario analysis is executed so as to provide insight for different scenarios. The methodology ends with the consideration of managerial implications.

17.3.1 Analytic Hierarchy Process

AHP, introduced by Saaty (1988), is a multi-criteria decision making technique for modeling unstructured problems. It provides a comprehensive framework to overcome the basic problem of decision making which is to choose the best in a set of competing alternatives under conflicting criteria (Saaty 1986).

When people try to make decisions on something, it is difficult to manage the evaluation process of even few ideas; thus structuring the complex real world problems enables the decision maker to consider these ideas one or two at a time and to do so, provides simplicity and complexity at the same time (Saaty 1986). The AHP assures these two concepts by allowing handling with the real world problems, which corresponds to the complexity, and by maintaining conceptually simple approach for ease of use, which corresponds to simplicity (Saaty 1986).

The AHP, assumed to be a psychophysical theory of measurement, has an assumption that the judgments about subjective feelings and understandings are similar to and also depend on the judgments about physical expressions of experiences and understanding (Saaty 2008). According to the traditional measurement definition, assigning only values based on the physical scales to the things is acceptable, so the main principle is to assign a single value to a single element (Saaty 2006).

In decision-making problems, generally there is a trade-off between elements (Saaty 2008) and the decision makers need to compare the elements relative to the others, which means by comparing an element with others, it will have a different value for each comparison (Saaty 2006). This comparison is called as pairwise comparison in AHP and as an outcome of the methodology; the priorities of the alternatives are obtained. Priorities have to be unique and they must capture the dominance of the judgments (Saaty 2003).

To structure a decision problem as a hierarchy, the upper-level elements have to be independent from the lower-level elements and it does not involve interaction (Saaty 2008). When there is an interaction and feedback, the structure becomes network and Analytic Network Process (ANP) is a suitable tool to model such problems (Saaty 2006).

A decision problem involves three main stages: Structuring the problem, constructing the decision model, and analyzing the problem. Structuring includes the definition of the problems with the required elements and the visualization (Saaty and Shih 2009). The elements are designed in the hierarchic structure descending from the goal to a set of criteria, sub-criteria, and a set of alternatives (Saaty 1990). Hierarchic structure shows the effects of changes in priorities of upper level on priorities of lower levels (Saaty 1988).

The steps of the classical AHP method can be explained as follows (Saaty 2008):

- Defining the decision problem and determining the evaluation criteria
- Structuring the hierarchy starting from the goal (top of the hierarchy) through the mid-levels (criteria, sub-criteria) to the set of alternatives
- Constructing the pairwise comparison matrices for comparison the criteria with respect to the parent criteria
- Doing the calculations for each level with respect to the upper levels, and calculating the overall and global priorities until the final priorities of the alternatives obtained.

In AHP, there are two different kinds of measurements: relative and absolute (Saaty 2006). In relative measurement, each alternative is compared with others and in absolute measurement; each alternative is compared with one ideal alternative, which is called as rating alternatives (Saaty 2006). In other words, the global scores of alternatives are revealed by using AHP Rating, which is a well-known scoring method (Topcu 2004).

To use AHP Rating Method, the hierarchical representation of the model is built. Then the pairwise comparisons of each element with respect to the upper-level elements are performed. Then, for each element, intensity levels (or degrees) are determined (Saaty 2008). After the pairwise comparisons are performed for these determined levels, each alternative is evaluated based on these levels. The score of each alternative can be calculated by the multiplication of the priority of the intensity by the priority of the related criterion and summing up these products of the related alternative (Saaty 2008; Topcu 2004).

17.3.2 Fuzzy Rule-Based Systems

A Fuzzy Rule-Based System (FRBS) is one of the most important application areas of the fuzzy set theory introduced by Zadeh in 1965. FRBS, a systematic inference method (Ross 2010), is used to model the interaction and relationship between variables and can be utilized for the problems involving uncertainty and vagueness (Cordon et al. 2001). These systems are presented with IF-THEN rules as an extension of classical rule-based systems, but in FRBS, both the antecedents and the consequents are fuzzy sets (Cordon et al. 2001; Riza et al. 2015). To clarify the fuzzy rules, assume that there are two antecedents, a consequent and their linguistic values as fuzzy sets are defined (adapted from Riza et al. 2015).

The number of the vehicles = {Low, Medium, High}

The width of the street = {Narrow, Medium, Wide}

The speed of a car = {Slow, Medium, Fast}

Based on these conditions, a sample IF-THEN rule can be defined as "IF the number of vehicles is LOW and the width of the street is MEDIUM, THEN the speed of the car is FAST".

Mamdani FRBS (Mamdani and Assilian 1975) and Takagi-Sugeno FRBS (Takagi and Sugeno 1985) are two types of Fuzzy rule-based systems (Cordon et al.

2001). Both of the models are similar and consider fuzzy inputs, but Mamdani produces fuzzy outputs whereas Takagi–Sugeno produces crisp outputs (Mamdani and Assilian 1975; Takagi and Sugeno 1985). In this study, the Mamdani type FRBS is used to examine the suitability index of the determined alternatives. There are four major components in the Mamdani FRBS: a knowledge base, an inference system, fuzzification and defuzzification interfaces (Requena et al. 2003). Here, the knowledge base represents the inputs and outputs, which are given to the system by the analysts based on their experiences, literature review, and several required analyses (Cordon et al. 2001). The inference system runs the IF-THEN rules where the fuzzification and defuzzification interfaces act as the reciprocal of each other (Requena et al. 2003).

The structure of Mamdani FRBS is given as follows (Cordon et al. 2001):

IF x_1 is A_1 AND x_2 is A_2 AND … AND x_n is A_n THEN y is B where x_i (i = 1, 2, …, n) are input variables and y is the output variable. A_1, A_2, …, A_n and B are the linguistic terms used for the corresponding input and output variables, respectively.

When centroid method is considered for defuzzification, the output of a fuzzy rule based model constructed using Mamdani-type fuzzy logic rules is obtained as follows (Ustundag et al. 2011):

$$Y = \frac{\sum_{r=1}^{R_1} A^{\alpha_r} C_{A^{\alpha_r}}}{\sum_{r}^{R_1} A^{\alpha_r}} \tag{17.1}$$

where $A^{\alpha r}$ represents the fuzzy subset area which is formed by regarding the membership values of input values in a fired rule with respect to Mamdani-type fuzzy inference method. Depending on the fired number of rules, each area is obtained and similar to the logic of center of gravity, area is multiplied by the distance which is represented by $C_{A^{\alpha_r}}$. Then, the sum of multiplications is divided by the total area to obtain the output value of Y (Ustundag et al. 2011).

$$\alpha = \underset{v=1}{\overset{n}{\mathrm{Min}}}\, \mu_v(\chi_v) \tag{17.2}$$

where $1 \leq v \leq n$ is the number of input variables that occur in the rule premise, n is the total number of inputs. Depending on the values of inputs, different rules can be fired out and R_l ($R_l \subseteq R$) is the number of rules fired out of a total of R rules present in the rule base for a set of input values $\mu_v(\chi_v)$ is the membership function value for the x_v input variable. Within each fired rule, the minimum value of the membership functions considering all inputs is determined as α value.

17.4 Application

The decision problem was structured, constructed and analyzed based on the iterative stages of the decision making process. First, the criteria related to the land-use planning problem were determined based on a literature review and experts who are familiar with the area considered in the case study.

The proposed model was applied to Didim, which is a popular seaside town of Aydın, lies on the Aegean cost of Turkey. Didim is the site of the antique city of Didyma with its ruined Temple of Apollo. Didim is located on the north shore of the gulf of Güllük, opposite Bodrum peninsula. The total population of Didim based on Address Based Population Registration System (ABPRS) Database in 2014 is 73.385 (TUİK).

The criteria set have been determined based on the literature review and the interviews with experts. "Land" represents the suitability of land characteristics of the evaluated area for land-use planning. While "Location" criteria set covers the position of the evaluated area in the form of distance to the some important buildings and places, the "Transportation Convenience" criteria set covers the distances to the alternative transportation systems.

After the decision model (Fig. 17.2) has prepared, a survey consists of the pairwise comparison questions was prepared in 1-9 ratio scale and was sent to the experts. Experts were asked to perform pairwise comparisons in linguistic scales, and then comparisons were converted into the corresponding number (see Saaty 2008). The underlying meaning of pairwise comparison is to enable comparison of criteria with respect to the goal and sub-criteria with respect to the related parent criteria. In survey, a brief explanation about criteria has been given in order to prevent misunderstandings.

The Super Decisions software was used to make all necessary calculations related to the AHP model (www.superdecisions.com). The judgments of all experts were entered into the software and the consistency of judgments has been checked. If there was an inconsistency for an expert, the related expert were asked for perform the pairwise comparisons again to reduce the inconsistency. The AHP allows inconsistency to a reasonable degree because people are more likely to be inconsistent when they are making judgments on their thoughts, feelings and preferences (Saaty 2003). Thus, inconsistency becomes a tolerable measurement error up to an acceptable level (10 % as suggested by Saaty) because greater consistency does not indicate greater accuracy (Saaty 1999). In Table 17.2, the inconsistency values of aggregated results are given.

After the consistency of the expert evaluations were checked, the geometric means (see Saaty 1986) of all paired comparison judgments were computed in order to reveal the aggregated group judgments. The relative priorities of the criteria and sub-criteria are given in Table 17.2 including the inconsistency values.

The priority values in Table 17.2 indicate the weight of the sub-criteria and they are used to evaluate rating scores of the determined areas. To evaluate the rating scores of these areas, first evaluation scales need to be determined for each

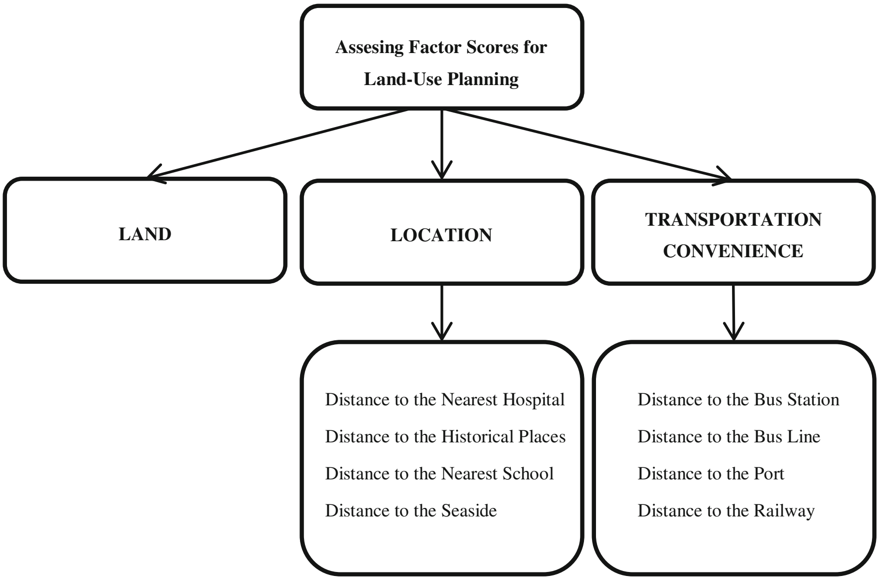

Fig. 17.2 The AHP model

Table 17.2 The relative priorities of the criteria set

	Priorities	Inconsistency (%)
w.r.t. goal		
Land	0.717	1.76
Location	0.205	
Transportation	0.078	
w.r.t. location		
Distance to the historical places	0.706	12.46
Distance to the nearest hospital	0.144	
Distance to the nearest school	0.093	
Distance to the seaside/view	0.057	
w.r.t. transportation		
Distance to the bus station	0.244	10.04
Distance to the bus line	0.654	
Distance to the port	0.062	
Distance to the railway	0.040	

sub-criterion. For the “Location” and “Transportation Convenience” criteria sets, a 1-5 ratio scale was determined, and similar to the criteria and sub-criteria comparison scales, it was again prepared as a linguistic scale. Here, 1 indicates the

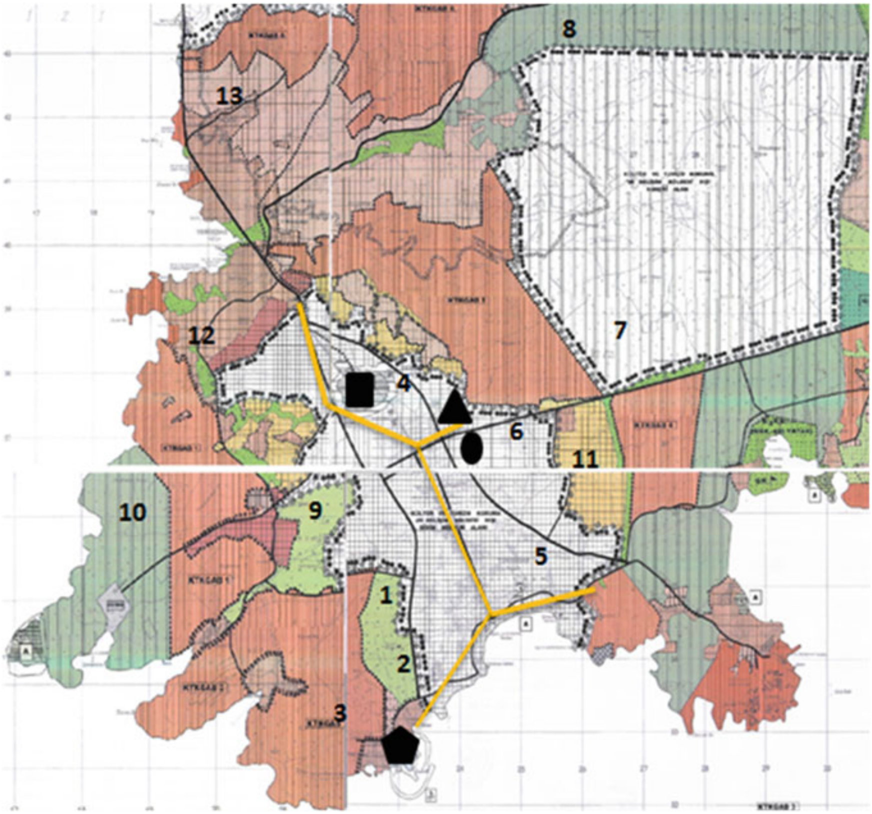

Fig. 17.3 The city map of Didim

"Very Short Distance", and 5 indicates "Very Long Distance". Due to the existence of cost and benefit attributes in the model, while making pairwise comparisons, very short distance is assumed to be an undesirable condition for cost attributes. While the distance to the historical places is a cost attribute, the other sub-criteria in the "Location" and "Transportation Convenience" criteria sets are benefit attributes. For the "Land" criterion, the main indicator is the suitability of the land to use as a residential zone. Thus, a 1-3 ratio scale was determined representing not suitable, average, and suitable, respectively.

After the pairwise comparison of the sub-criteria scales was performed, the rating scores of the areas were evaluated. In Fig. 17.3, there is a map of Didim including the detailed information about the land characteristics, the important buildings such as hospital, bus station, the city center, etc., and there are 13 determined areas which were planned to evaluate as candidates for being a residential zone. On the map, the square represents the ruined Temple of Apollo, which is the most important historical place of Didim. The circle, triangle, and the pentagon represent the only hospital in Didim, the bus station, and the port, respectively.

The white area, which involves the circle, square, and triangle, is the residential zone, in other words the center of Didim. The line across the residential zone is the current bus line. The areas, which include alternative areas 8 and 10, are forestland, the white area with straight lines is the closed military area and it is not allowed to be a residential zone. The areas around the residential area are protected and not allowed to consider as a residential zone for now, but it may be possible with a new regulation. That is why no alternative has been selected in these protected areas. The last is the empty areas, which are allowed to settle, and the most possible areas considering the land-use planning.

Each area was evaluated based on each sub-criterion and by summing up the multiplication of the relative weight of the sub-criterion and the value of the evaluation score; the overall rating score of the related area was obtained. For instance, the rating score of Area 2 is 0.912, is calculated by summing up the scores of all criteria. $((1.000 \times 0.717) + (1.000 \times 0.706 + 0.125 \times 0.144 + 1.000 \times 0.093 + 0.143 \times 0.057) + (0.066 \times 0.244 + 0.385 \times 0.654 + 1.000 \times 0.062 + 0.270 \times 0.04))$. The rating scores of 13 determined areas are given in Table 17.3. These scores were used as an input for the Fuzzy Rule-Based System in order to obtain the suitability index of each.

Fuzzy Rule-Based System is designed by using the Fuzzy Inference Systems (FIS) Editor of MATLAB. As aforementioned before, the Mamdani-type FRBS is chosen due to the interpretability of the results and this type of FRBS has multiple inputs and single output. Three input variables representing the criteria set in AHP model and one output variable representing the suitability index of the determined area, which is aimed to be assessed, are built. As membership functions of the inputs and output, trapezoidal membership functions defined by quadruple (*sl*, *cl*, *cu*, and *su*) were used, where *sl* and *su*, and *cl* and *cu* are the lower and upper bounds of the support and the core, respectively (Botta et al. 2008). All input

Table 17.3 Rating scores of the areas

Areas	Land score	Location score	Transportation score	Rating score
Area 1	1.000	0.532	0.321	0.851
Area 2	1.000	0.825	0.340	0.912
Area 3	0.070	0.752	0.335	0.231
Area 4	0.070	0.193	0.365	0.118
Area 5	1.000	0.614	0.709	0.898
Area 6	1.000	0.413	0.913	0.873
Area 7	0.070	0.527	0.149	0.170
Area 8	0.265	0.719	0.063	0.342
Area 9	1.000	0.317	0.148	0.793
Area 10	0.265	0.722	0.059	0.342
Area 11	0.265	0.351	0.360	0.290
Area 12	0.265	0.483	0.102	0.297
Area 13	0.265	0.719	0.081	0.343

Fig. 17.4 The representation of the trapezoidal membership functions

variables and the output variable had the same trapezoidal membership functions as can be seen in Fig. 17.4.

After defining the membership functions, the IF-THEN rules, given in Table 17.4, were generated. There are 27 rules to represent each possible condition. To clarify the fuzzy rules, consider IF the land is "Low" (L), the location is "Medium" (M), and the transportation convenience is "High" (H), THEN the suitability index will be "Medium" (M).

The rating scores of each input variable corresponding to the areas were entered into FIS Editor of MATLAB, and for each area, the suitability index was calculated as an output. The suitability index calculations based on the fuzzy rules for Area 2 are given in Fig. 17.5 as a representative sample. The blue areas under the

Table 17.4 The generated fuzzy rules

Rule#	Land	Loc.	Trsp.	SI	Rule#	Land	Loc.	Trsp.	SI
1	L	L	L	L	15	M	M	L	M
2	M	M	M	M	16	M	M	H	H
3	H	H	H	H	17	M	H	L	H
4	L	L	M	L	18	M	H	M	H
5	L	L	H	L	19	M	H	H	H
6	L	M	L	L	20	H	L	L	M
7	L	M	M	L	21	H	L	M	M
8	L	M	H	M	22	H	L	H	H
9	L	H	L	L	23	H	M	L	H
10	L	H	M	M	24	H	M	M	H
11	L	H	H	M	25	H	M	H	H
12	M	L	L	M	26	H	H	L	H
13	M	L	M	M	27	H	H	M	H
14	M	L	H	M					

L Low, *M* Medium, *H* High

suitability index represent the fired rules. Note that rules 26 and 27 are fired for Area 2. In Table 17.5, the suitability index values of the 13 areas can be seen.

Area 6 has the highest suitability value (0.847) based on the integrated AHP Rating-FRBS Model. Being close to the hospital and the bus station, and also the suitability of the land may cause the highest score among the others. By being in the residential zone and also being one of the most suitable candidates to be a living space, it is easy to reach all necessary places (such as hospital, school, bus line, bus station, etc.) to live. Besides, construction works may be more manageable due to the suitable infrastructure and the easiness of building in and transporting to all necessary equipment. Area 2 and Area 1 are on the empty areas near the residential zone (as can be seen on the map) and besides the suitability of their land, being close to the port and the bus line may increase the suitability of these two areas. On the other hand, Area 7, which is on the closed military area, has the lowest suitability value. Areas in the residential zone, except Area 4, seem to be more suitable comparing to the others. The reason behind the lowest suitability index value of Area 4 may be its closeness to the ruined Temple of Apollo.

17.4.1 Scenario Analysis

The integrated AHP Rating-FRBS model provides to analyze the suitability of the determined areas in order to observe their usability as candidate areas to settle. Based on the current structure and land types of Didim, the 13 areas were evaluated

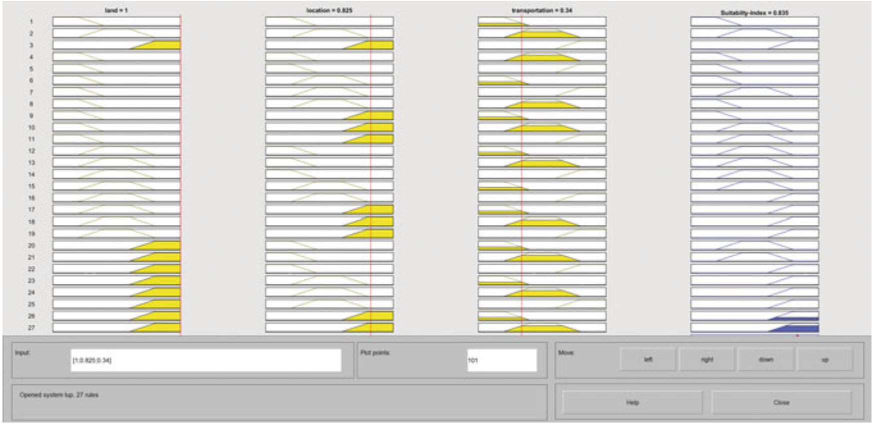

Fig. 17.5 The representation of fuzzy rules to find the SI of area 2

Table 17.5 Suitability index of the areas

Areas	Land score	Location score	Transportation score	Suitability index
Area 6	1.000	0.413	0.913	0.847
Area 2	1.000	0.825	0.340	0.835
Area 1	1.000	0.532	0.321	0.831
Area 5	1.000	0.614	0.709	0.828
Area 9	1.000	0.317	0.148	0.655
Area 8	0.265	0.719	0.063	0.429
Area 13	0.265	0.719	0.081	0.429
Area 10	0.265	0.722	0.059	0.426
Area 3	0.070	0.752	0.335	0.424
Area 11	0.265	0.351	0.360	0.312
Area 12	0.265	0.483	0.102	0.312
Area 4	0.070	0.193	0.365	0.160
Area 7	0.070	0.527	0.149	0.153

and their roles in the future land-use planning were determined. But what if the current situation will change?

Due to the touristic attractiveness and increasing population of Didim, there has to be some changes and restructuring decisions to overcome the problems such as the lack of health care services, the inadequacy of the existing bus line, basically the transportation problems both in the town and to the other cities. Thus, the possibilities of restructuring trigger the scenario analysis process.

In order to analyze the suitability of the determined areas under the changing conditions, four different scenarios have been determined: a new railway, a new protected are (the area involving area 9), a new hospital, and the revision of the current bus line. The new railway is the dashed line starting from the upper corner of the map on Fig. 17.6. The line surrounding the residential zone is the revised bus line, and the circle near Area 5 is the new hospital planned to build till the end of the first quarter of 2016.

For each scenario, the areas were evaluated based on the changing conditions of Didim and new scores for the inputs variables were obtained. These scores were entered to the FIS Editor of MATLAB and the new suitability index values for the areas under the determined scenarios were calculated. In Table 17.6, the suitability index of the areas under the determined scenarios is given.

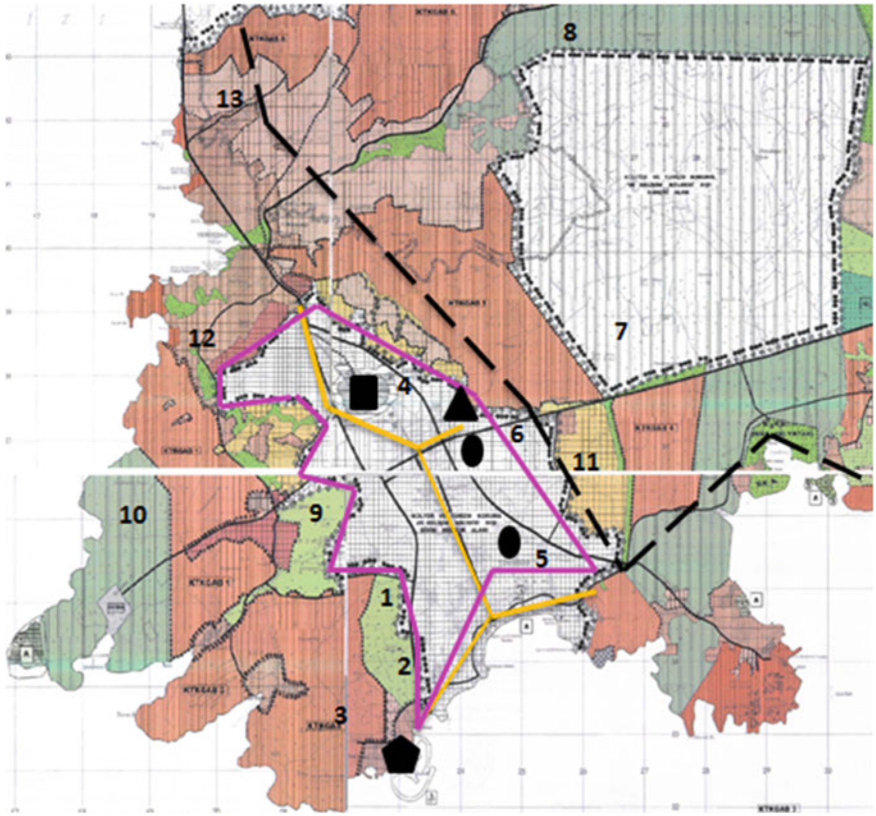

Fig. 17.6 The revised map of Didim based on the scenarios

Table 17.6 Suitability index of the areas for all scenarios

Scenario 1		Scenario 2		Scenario 3		Scenario 4	
Area	SI	Area	SI	Area	SI	Area	SI
Area 6	0.847	Area 6	0.847	Area 6	0.847	Area 6	0.847
Area 2	0.836	Area 2	0.835	Area 2	0.835	Area 2	0.836
Area 5	0.835	Area 1	0.831	Area 1	0.831	Area 1	0.832
Area 1	0.832	Area 5	0.828	Area 5	0.828	Area 5	0.828
Area 9	0.655	Area 8	0.429	Area 9	0.655	Area 9	0.649
Area 3	0.431	Area 13	0.429	Area 8	0.429	Area 11	0.518
Area 8	0.429	Area 10	0.426	Area 13	0.429	Area 8	0.429
Area 13	0.429	Area 3	0.424	Area 10	0.426	Area 13	0.429
Area 10	0.426	Area 11	0.312	Area 3	0.424	Area 10	0.426
Area 11	0.312	Area 12	0.312	Area 11	0.337	Area 3	0.424
Area 12	0.312	Area 9	0.170	Area 12	0.312	Area 12	0.331
Area 4	0.159	Area 4	0.160	Area 4	0.160	Area 4	0.160
Area 7	0.153	Area 7	0.153	Area 7	0.153	Area 7	0.153

For Scenario 1, a new railway will be built. The recalculated suitability index values show that there is a slight difference between the current values and the Scenario 1 because the weight of the distance to the railway is relatively small comparing to others. Besides, the new railway is almost near to the majority of the determined areas. Also, Area 4 and Area 7 have the lowest suitability indices in all scenarios due to being close to the historical places and being in the closed military area, respectively.

For Scenario 2, the light green area involving the Area 9 is changed from allowed to settle to protected area. Based on the evaluations under this scenario, the suitability index value of Area 9 decreases from 0.655 to 0.170. The rank of the Area 9 changed from 5th to 11th and all other areas has the same rank as the analysis.

For Scenario 3, there has not been any significant change in the suitability indices of the areas. The reasons behind this may be explained by the relatively high weight of the land criteria comparing to the others and the lower weight of being close to the nearest hospital among others in the location criteria set. The existing hospital is very close to the new one, so building a new hospital near to Area 5 has almost no impact on the suitability of the areas.

Area 11 becomes the 6th suitable area among others based on Scenario 4. In the current situation, it seems unfavorable to be a living space because it is far from the current bus line, the hospital and the bus station and it is relatively out of the city center. Revising the bus line makes Area 11 to be a more suitable candidate to be a living space.

17.5 Conclusion

Current urban studies consider numerous parameters to maximize beneficial use of land for a certain area. Several studies in several disciplines have been developed for land-use planning. Such studies have the potential for supporting land-use policy analysis. In addition, urban land-use planning provides the opportunity of obtaining accuracy and implementation of basic information to be improved and applied during the planning process.

In this context, this study contributes to the urban land-use planning literature by means of using AHP and FRBS in a sequential manner for the assessment of land-use suitability index. In this way, the convenience for factor rating (via AHP) and inference flexibility under fuzzy environment (via FRBS) can be obtained synchronously. This study is planned to provide quantitative decision support to assist planners during making decisions on land-use alternatives. In other words, a guide is proposed for planners in determining appropriate distribution of suitability for different development trends. The appropriateness of the proposed methodology for real life problems has been demonstrated via an application from Turkey. In addition, the methodology yields considerable changes for land-use suitability index values and land-use suitability order for sub-locations under different scenarios about land-type as well as location and transportation factors.

As far as critical implementation issues are concerned, the most crucial sub-step for AHP application is consistency analysis of pair-wise comparison matrices. In addition, the determination of fuzzy membership functions and rule generation should be executed meticulously for FRBS stage. The aforementioned suggestions should be considered to obtain accurate and consistent results from the methodology.

There are several research directions to be pursued in future. Firstly, the proposed methodology can be compared with pure AHP model. In addition, mathematical programming models can be developed for the problem. The proposed methodology can be applied to a larger area to gain more considerable results for urban land-use planning. Last but not least, the steps of the methodology can be coded as specialized decision support software.

References

Akimoto, F. (2009). The birth of "land-use planning" in American urban planning. *Planning Perspectives, 24*, 457–483.

Anagnostopoulos, K., & Vavatsikos, A. (2012). Site suitability analysis for natural systems for wastewater treatment with spatial fuzzy analytic hierarchy process. *Journal of Water Resources Planning and Management, 138*(2), 125–134.

Baffour Awuah, K. G., Hammond, F. N., Lamond, J. E., & Booth, C. (2014). Benefits of urban land-use planning in Ghana. *Geoforum, 51*, 37–46.

Bathrellos, G. D., Gaki-Papanastassiou, K., Skilodimou, H. D., Skianis, G. A., & Chousianitis, K. G. (2013). Assessment of rural community and agricultural development using geomorphological–

geological factors and GIS in the Trikala prefecture (Central Greece). *Stochastic Environmental Research and Risk Assessment, 27*, 573–588.

Booth, A. L., & Muir, B. R. (2011). Environmental and land-use planning approaches of indigenous groups in Canada: An overview. *Journal of Environmental Policy & Planning, 13* (4), 421–442.

Botta, A., Lazzerini, B., & Marcelloni, F. (2008). Context adaptation of Mamdani fuzzy rule based systems. *International Journal of Intelligent Systems, 23*, 397–418.

Busscher, T., Tillema, T., & Arts, J. (2013). Revisiting a programmatic planning approach: managing linkages between trans-port and land-use planning. *Planning Theory & Practice, 14* (4), 492–508.

Cengiz, T., & Akbulak, C. (2009). Application of analytical hierarchy process and geographic information systems in land-use suitability evaluation: A case study of Dümrek village (Çanakkale, Turkey). *International Journal of Sustainable Development and World Ecology, 16*(4), 286–294.

Chandio, I. A., Matori, A.-N., Lawal, D. U., & Sabri, S. (2011). GIS-based land suitability analysis using AHP for public parks planning in Larkana city. *Modern Applied Science, 5*(4), 177–189.

Cordon, O., Herrera, F., Hoffmann, F., & Magdalena, L. (2001). *Genetic fuzzy systems: Evolutionary tuning and learning of fuzzy knowledge bases*. Singapore: World Scientific Publishing.

Dai, F., Lee, C., & Zhang, X. (2001). GIS-based geo-environmental evaluation for urban land-use planning: A case study. *Engineering Geology, 61*(2001), 257–271.

Dai, L., Zhao, X., He, H.S., Deng, H., Yu, D., Zhou, L., & Wu, S. (2008). Evaluating land-use suitability of an industrial city in northeast China. *International Journal of Sustainable Development & World Ecology, 15*(4), 378–382.

Dou, Y., Luo, X., Dong, L., Wu, C., Liang, H., & Ren, J. (2016). An empirical study on transit-oriented low-carbon urban land use planning: Exploratory spatial data analysis (ESDA) on Shanghai, China. *Habitat International, 53*, 379–389.

Duhl, L. J., & Sanchez, A. K. (1999). *Healthy cities and the city planning process*. World Health Organization Regional Office for Europe.

He, J., Yi, H., & Liu, J. (2016). Urban green space recreational service assessment and management: A conceptual model based on the service generation process. *Ecological Economics, 124*, 59–68.

Hofmann. (1976). Mapping for urban land-use planning in Southeast Queensland—a first approach. *Bulletin of the International Associatiion of Engineering Geology 14,* 113–117.

Huang, Q., Liu, Y., Li, M., Mao, K., Li, F., Chen, Z., et al. (2012). Thematic maps for county-level land-use planning in contemporary China. *Journal of Maps, 8*(2), 185–188.

Joerin, F., Thériault, M., & Musy, A. (2001). Using GIS and outranking multi criteria analysis for land-use suitability assessment. *International Journal of Geographical Information Science, 15* (2), 153–174.

Junker, E. (2013). Legal requirements for risk and vulnerability assessments in Norwegian land-use planning. *Local Environment, 20*(4), 474–488.

Kaffashi, S., & Yavari, M. (2011). Land-use planning of Minoo Island, Iran, towards sustainable land-use management. *International Journal of Sustainable Development and World Ecology, 18*(4), 304–315.

Kang, S., Post, W., Wang, D., Nichols, J., Bandaru, V., & West, T. (2013). Hierarchical marginal land assessment for land-use planning. *Land Use Policy, 30*(1), 106–113.

Keirstead, J., & Shah, N. (2013). The changing role of optimization in urban planning. In A. Chinchuluun, et al. (Eds.), *Optimization, simulation, and control*. Springer Optimization and Its Applications. New York: Springer.

Kergosien, E., Laval, B., Roche, M., & Teisseire, M. (2014). Are opinions expressed in land-use planning documents? *International Journal of Geographical Information Science, 28*(4), 739–762.

Khalili-Damghani, K., Aminzadeh-Goharrizi, B., Rastegar, S., & Aminzadeh-Goharrizi, B. (2014). Solving land-use suitability analysis and planning problem by a hybrid meta-heuristic algorithm. *International Journal of Geographical Information Science, 28*(12), 2390–2416.

La Rosa, D., & Privitera, R. (2013). Characterization of non-urbanized areas for land-use planning of agricultural and green infrastructure in urban contexts. *Landscape and Urban Planning, 109* (1), 94–106.

Mamdani, E. H., & Assilian, S. (1975). An experiment in linguistic synthesis with a fuzzy logic controller. *International Journal of Man-Machine Studies, 7*(1), 1–13.

Meyer, S. R., Johnson, M. L., Lilieholm, R. J., & Cronand, C. S. (2014). Development of a stakeholder-driven spatial modeling framework for strategic landscape planning using Bayesian networks across two urban-rural gradients in Maine, USA. *Ecological Modelling, 291*, 42–57.

Mosadeghi, R., Warnken, J., Tomlinson, R., & Mirfenderesk, H. (2015). Comparison of Fuzzy-AHP and AHP in a spatial multi-criteria decision making model for urban land-use planning. *Computers, Environment and Urban Systems, 49*, 54–65.

Porta, J., Parapar, J., Doallo, R., Rivera, F. F., Santé, I., & Crecente, R. (2013). High performance genetic algorithm for land-use planning. *Computers, Environment and Urban Systems, 37*, 45–58.

Pourebrahim, S., Hadipour, M., & Bin Mokhtar, M. (2011). Integration of spatial suitability analysis for land-use planning in coastal areas; Case of Kuala Langat District, Selangor. *Malaysia. Landscape and Urban Planning, 101*(1), 84–97.

Requena, I., Blanco, A., & Delgado, M. (2003). A constructive method for building fuzzy rule-based systems. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, 11*(2), 217–233.

Riza, L. S., Bergmeir, C., Herrera, F., & Benitez, J. M. (2015). Fuzzy rule-based systems for classification and regression in R. *Journal of Statistical Software, 65*(6), 1–30.

Ross, T. J. (2010). *Fuzzy logic with engineering applications* (3rd ed.). United Kingdom: John Wiley & Sons.

Saaty, T. L. (1986). Axiomatic foundation of the analytic hierarchy process. *Management Science, 32*(7), 741–755.

Saaty, T. L. (1988). *The analytic hierarchy process-planning, priority setting, resource allocation* (pp. 2–48). Pittsburgh: University of Pittsburgh.

Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research, 48*, 9–26.

Saaty, T. L. (1999). Basic theory of the analytic hierarchy process: How to make a decision. *Rev. R. Acad. Cienc. Exact. Fis. Nat., 93*(4), 395–423.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Service Science, 1*(1), 83–98.

Saaty, T. L., & Shih, H.-S. (2009). Structures in decision making: On the subjective geometry of hierarchies and networks. *European Journal of Operational Research, 1699*, 867–872.

Saaty, T. L. (2003). Decision-making with the AHP: Why is the principal eigenvector necessary. *European Journal of Operational Research, 145*, 85–91.

Saaty, T. L. (2006). Rank from comparisons and from ratings in the analytic hierarchy/network processes. *European Journal of Operational Research, 168*, 557–570.

Sakieh, Y., Salmanmahiny, A., Jafarnezhad, J., Mehri, A., Kamyab, H., & Galdavi, S. (2015). Evaluating the strategy of decentralized urban land-use planning in a developing region. *Land Use Policy, 48*, 534–551.

Santé-Riveira, I., Crecente-Maseda, R., & Miranda-Barrós, D. (2008). GIS-based planning support system for rural land-use allocation. *Computers and Electronics in Agriculture, 63*, 257–273.

Shen, L. Y., Ochoa, J. J., Shah, M. N., & Zhang, X. (2011). The application of urban sustainability indicators: A comparison between various practices. *Habitat International, 35*, 17–29.

Takagi, T., & Sugeno, M. (1985). Fuzzy identification of systems and its applications to modeling and control. *IEEE Transactions on Systems, Man, and Cybernetics, 51*(1), 116–132.

Topcu, Y. I. (2004). A decision model proposal for construction contractor selection in Turkey. *Building and Environment, 39*, 469–481.
Ullah, K. M., & Mansourian, A. (2016). evaluation of land suitability for urban land-use planning: Case study Dhaka City. *Transactions in GIS, 20*(1), 20–37.
Ustundag, A., Kilinc, M. S., & Cevikcan, E. (2010). Fuzzy rule based system for the economic analysis of RFID investments. *Expert Systems with Applications, 37*(7), 5300–5306.
Ustundag, A., Kilinc, M. S., & Cevikcan, E. (2011). A hybrid fuzzy risk evaluation model for real estate investments. *Journal of Multi-Valued Logic & Soft Computing, 17*, 339–362.
Uy, P. D., & Nakagoshi, N. (2008). Application of land suitability analysis and landscape ecology to urban greenspace planning in Hanoi, Vietnam. *Urban Forestry & Urban Greening, 7*(1), 25–40.
Vaidya, O. S., & Kumar, S. (2006). Analytic hierarchy process: An overview of applications. *European Journal of Operational Research, 169*(1), 1–29.
Wang, H., Shen, Q., & Tang, B. (2015). GIS-Based framework for supporting land use planning in urban renewal: Case study in Hong Kong. *Journal of Urban Planning and Development, 141* (3), 05014015.
Yu, J., Chen, Y., Wu, J., & Khan, S. (2011). Cellular automata-based spatial multi-criteria land suitability simulation for irrigated agriculture. *International Journal of Geographical Information Science, 25*(1), 131–148.
Zadeh, L. A. (1965). Fuzzy Sets. *Information and Control, 8*(3), 338–353.
Zhang, X., & Chen, G. (2011). Application of improved GIS-based model to evaluate urban construction land suitability. *Proceedings of SPIE, 7752*, 77521G-1.
Zhou, M. (2015). An interval fuzzy chance-constrained programming model for sustainable urban land-use planning and land-use policy analysis. *Land Use Policy, 42*, 479–491.
Ziadat, F. M. (2007). Land suitability classification using different sources of information: Soil maps and predicted soil attributes in Jordan. *Geoderma, 140*(1–2), 73–80.

Part VIII
Sustainable Transportation

Chapter 18
Fuzzy Optimal Allocation of Service Centers for Sustainable Transportation Networks Service

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Abstract In this chapter questions of defining of service centers optimum allocation in transportation network are observed. It is supposed that transportation network is described by a fuzzy graph. In this case a task of definition of optimum allocation of the service centers can be transformed into the task of definition of base fuzzy set, antibase fuzzy set and vitality fuzzy set of fuzzy graph. The method of definition of these sets is considered in this chapter. The numerical example of optimum allocation of the service centers finding in the railway network in the form of the fuzzy graph is considered.

18.1 Introduction

The large-scale increasing and versatile introduction of a geographical information system (GIS) is substantially connected with the necessity of the perfection of information systems providing decision-making. GIS is applied practically in all spheres of human activity. Geographical information technologies have reached an unprecedented position now, offering a wide range of very powerful functions such as information retrieval and display, analytical tools, and decision support (Clarke 1995; Longley et al. 2001). Unfortunately, geographical data are often analyzed and communicated through largely non-negligible uncertainty. Uncertainty exists in the whole process from geographical abstraction, data acquisition, and geo-processing to the use (Zhang and Goodchild 2002; Goodchild 1989; Belyakov et al. 2014).

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One of the tasks solved with GIS is the task of the centers allocation (Kaufmann 1977). The search of the optimum placing of hospitals, police stations, fire brigades and many other necessary important enterprises and services on some sites of the considered territory are confined to this task. The task of selection of the best locations for service centers is relevant when considering sustainable transportation networks (Nagurney 2000; Sharma and Mathew 2011) and has important practical value, as the optimal allocation of the centers allows reducing the cost of the fuel and electricity, which will have a positive impact on the ecology.

In some cases, the criterion of optimality consists in the minimization of the journey time (or in the minimization of distances) from the service center to the most remote service station. In other cases, the criterion of optimality consists in the choice of such a place of allocating the centers that the route from them to any other place of service could be passed by some criterion of a way. In other words, the problem is the optimization of “the worst variant” (Christofides 1976).

However, very often, the information represented in GIS, happens to be of the approximate value or insufficiently authentic (Malczewski 1999). We consider that a certain railway system has n railway stations. There are k service centers, which can be placed into these railway stations. Each center serves a station, and some neighbouring stations with the given degree of service either. The centers can fail during the exploitation. It is necessary for the given number of centers to define their best allocation. In other words, it is necessary to define the places of k centers into n railway stations in such a way that the “control” of all the territory (all the railway stations) is carried out with the greatest possible service degree.

18.2 Main Concepts and Definitions

In this chapter we suppose that the service degree of a region is defined as the minimal meaning of service degrees of each area. Taking into account, that the service degree cannot always have symmetry property (for example, by specific character and relief of the region) the model of such task is a fuzzy directed graph $\widetilde{G} = (X, \widetilde{U})$ (Monderson and Nair 2000; Bershtein and Bozhenuk 2008; Rani and Dharmalingam 2016). Here, set $X = \{x_i\},\ i \in I = \{1, 2, \ldots, n\}$ is a set of vertices and $\widetilde{U} = \{\langle \mu_U \langle x_i, x_j \rangle / \langle x_i, x_j \rangle \rangle\}, \langle x_i, x_j \rangle \in X^2$ is a fuzzy set of directed edges with a membership function μ_U: $X^2 \rightarrow [0, 1]$. The membership function $\mu_U \langle x_i, x_j \rangle$ of graph $\widetilde{G} = (X, \widetilde{U})$ defines a service degree of area j in the case when a service center is placed into area i. We assume, that the service degree has property of transitivity, i.e. if the service center is in the area x_i and serves area x_j with a degree $\mu_U \langle x_i, x_j \rangle$, and if the service center is in area x_j and serves area x_k with a degree $\mu_U \langle x_j, x_k \rangle$ then a degree of service of area x_k from area x_i is not less than $\mu_U \langle x_i, x_j \rangle \,\&\, \mu_U \langle x_j, x_k \rangle$. Here, & operation is a minimum operation.

The task of the best allocation of centers on the fuzzy graph can be limited to the problem of finding a subset of vertices Y, which all the other vertices X/Y of the fuzzy graph achievable from with the greatest service degree.

Three strategies of the selection of vertices Y can be proposed:

– We "go" from each vertex of subset X/Y, and arrive at a vertex of Y;
– We "come out" of any of the vertices of Y, and reach all vertices of subset X/Y;
– We have "come out" of any of the vertices of Y, reach all vertices of subset X/Y and come back.

For considering the questions of the optimum allocation of the service centers (selecting a subset Y) we shall focus on the concepts of a fuzzy directed way, the fuzzy antibase set, fuzzy base set, and fuzzy vitality set of a fuzzy graph (Bershtein et al. 2011, 2013, 2015; Bozheniuk et al. 2015).

Definition 1 Fuzzy directed way $\widetilde{L}(x_i, x_m)$ of fuzzy directed graph $\widetilde{G} = (X, \widetilde{U})$ is called the sequence of fuzzy directed edges from vertex x_i to vertex x_m:

$$\widetilde{\mathrm{L}}(\mathrm{x_i}, \mathrm{x_m}) = \langle \mu_{\mathrm{U}}\langle \mathrm{x_i}, \mathrm{x_j}\rangle / \langle \mathrm{x_i}, \mathrm{x_j}\rangle\rangle, \langle \mu_{\mathrm{U}}\langle \mathrm{x_j}, \mathrm{x_k}\rangle / \langle \mathrm{x_j}, \mathrm{x_k}\rangle\rangle, \ldots, \langle \mu_{\mathrm{U}}\langle \mathrm{x_l}, \mathrm{x_m}\rangle / \langle \mathrm{x_l}, \mathrm{x_m}\rangle\rangle.$$

Conjunctive durability of way $\mu(\widetilde{L}(x_i, x_m))$ is defined as shown in Eq. (18.1):

$$\mu(\widetilde{L}(x_i, x_m)) = \underset{\langle x_\alpha, x_\beta\rangle \in \widetilde{L}(x_i, x_m)}{\&} \mu_U\langle x_\alpha, x_\beta\rangle. \tag{18.1}$$

Fuzzy directed way $\widetilde{L}(x_i, x_m)$ is called simple way between vertices x_i and x_m if its part is not a way between the same vertices.

Obviously, that this definition coincides with the same definition for nonfuzzy graphs.

Definition 2 Vertex y is called fuzzy accessible of vertex x in the graph $\widetilde{G} = (X, \widetilde{U})$ if a fuzzy directed way from vertex x to vertex y exists.

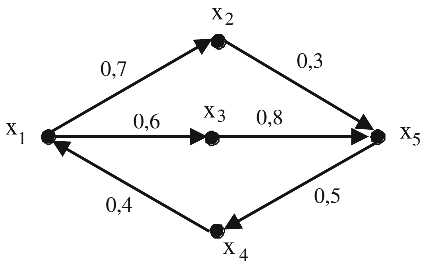
The accessible degree of vertex y from vertex x, ($x \neq y$) is defined by Eq. (18.2):

$$\gamma(x, y) = \max_{\alpha}(\mu(\widetilde{L}_\alpha(x, y))), \quad \alpha = 1, 2, \ldots, p, \tag{18.2}$$

where p—number of various simple directed ways from vertex x to vertex y. Let's consider, that each vertex $x \in X$ in the graph $\widetilde{G} = (X, \widetilde{U})$ is accessible from itself with an accessible degree γ $(x, x) = 1$.

Example 1 For the fuzzy graph 1 presented in Fig. 18.1, vertex x_5 is fuzzy accessible vertex from x_1 with an accessible degree:

Fig. 18.1 Fuzzy graph 1



$$\gamma(\mathrm{x}_1, \mathrm{x}_5) = \max\{(0.7 \,\&\, 0.3); (0.6 \,\&\, 0.8)\} = \max\{0.3;\ 0.6\} = 0.6.$$

Let a fuzzy graph $\widetilde{G} = (X, \widetilde{U})$ is given. Let's define fuzzy multiple-valued reflections $\widetilde{\Gamma}^1, \widetilde{\Gamma}^2, \widetilde{\Gamma}^3, \ldots, \widetilde{\Gamma}^k$ as:

$$\begin{aligned}
&\widetilde{\Gamma}^1(x_i) = \{\langle \mu_{\Gamma^1(x_i)}(x_j)/(x_j)\rangle\} \text{ here } (\forall x_j \in X)[\mu_{\Gamma^1(x_i)}(x_j) = \mu_U\langle x_i, x_j\rangle],\\
&\widetilde{\Gamma}^2(x_i) = \widetilde{\Gamma}\{\widetilde{\Gamma}(x_i)\}, \widetilde{\Gamma}^3(x_i) = \widetilde{\Gamma}\{\widetilde{\Gamma}^2(x_i)\}, \ldots, \widetilde{\Gamma}^k(x_i) = \widetilde{\Gamma}\{\widetilde{\Gamma}^{k-1}(x_i)\}\\
&\qquad = \{\langle \mu_{\Gamma^k(x_i)}(x_j)/x_j\rangle\},
\end{aligned}$$

here $(\forall x_j \in X)\left[\mu_{\Gamma^k(x_i)}(x_j) = \underset{\forall x_l \in X}{\vee} \mu_{\Gamma^{k-1}(x_i)}(x_l) \,\&\, \mu_U\langle x_l, x_j\rangle\right]$.

It is obvious, that $\widetilde{\Gamma}^k(x_i)$ is a fuzzy subset of vertices, accessible to reach from x_i, using fuzzy ways of length k.

Example 2 For the fuzzy graph presented in Fig. 18.1, we have: $\widetilde{\Gamma}^1(x_1) = \{\langle 0.7/(x_2)\rangle, \langle 0.6/x_3\rangle\}$, $\widetilde{\Gamma}^2(x_1) = \{\langle 0.6/x_5\rangle\}$.

Definition 3 Fuzzy transitive closure $\widehat{\widetilde{\Gamma}}(x_i)$ is fuzzy multiple-valued reflection defined by Eq. (18.3):

$$\widehat{\widetilde{\Gamma}}(x_i) = \widetilde{\Gamma}^0(x_i) \cup \widetilde{\Gamma}(x_i) \cup \widetilde{\Gamma}^2(x_i) \cup \ldots = \bigcup_{j=0}^{\infty} \widetilde{\Gamma}^j(x_i). \tag{18.3}$$

In (18.3) by definition: $\widetilde{\Gamma}^0(x_i) = \{\langle 1/x_i\rangle\}$.

In other words, $\widehat{\widetilde{\Gamma}}(x_i)$ is fuzzy subset of vertices, accessible to reach from x_i by some fuzzy way with the greatest possible conjunctive durability. As we consider final graphs, it is possible to set Eq. (18.4):

$$\widehat{\widetilde{\Gamma}}(x_i) = \bigcup_{j=0}^{n-1} \widetilde{\Gamma}^j(x_i). \tag{18.4}$$

Example 3 For the fuzzy graph presented in Fig. 18.1, fuzzy transitive closure of vertex x_1 is defined as $\widehat{\widetilde{\Gamma}}(x_1) = \{\langle 1/x_1\rangle, \langle 0.7/x_2\rangle, \langle 0.6/x_3\rangle, \langle 0.5/x_4\rangle, \langle 0.6/x_5\rangle\}$.

Let's define fuzzy reciprocal multiple-valued reflections $\widetilde{\Gamma}^{-1}, \widetilde{\Gamma}^{-2}, \widetilde{\Gamma}^{-3}, \ldots, \widetilde{\Gamma}^{-k}$ as:

$$\widetilde{\Gamma}^{-1}(x_i) = \{\langle \mu_{\Gamma^{-1}(x_i)}(x_j)/(x_j)\rangle\},\ \text{here}\ (\forall x_j \in X)\left[\mu_{\Gamma^{-1}(x_i)}(x_j) = \mu_U\langle x_j, x_i\rangle\right],$$

$$\widetilde{\Gamma}^{-1}(x_i) = \widetilde{\Gamma}^{-1}\{\widetilde{\Gamma}^{-1}(x_i)\}, \widetilde{\Gamma}^{-3}(x_i) = \widetilde{\Gamma}^{-1}\{\widetilde{\Gamma}^{-2}(x_i)\}, \ldots, \widetilde{\Gamma}^{-k}(x_i) = \widetilde{\Gamma}^{-1}\{\widetilde{\Gamma}^{-(k-1)}(x_i)\} = \{\langle \mu_{\Gamma^{-k}(x_i)}(x_j)/x_j\rangle\},$$

here $(\forall x_j \in X)\left[\mu_{\Gamma^{-k}(x_i)}(x_j) = \bigvee_{\forall x_l \in X} \mu_{\Gamma^{k-1}(x_i)}(x_l)\ \&\ \mu_U\langle x_j, x_l\rangle\right]$.

It is obvious, that $\widetilde{\Gamma}^{-k}(x_i)$ is a fuzzy subset of vertices, vertex x_i is accessible from, using fuzzy ways of length k.

Example 4 For the fuzzy graph presented in Fig. 18.1, we have $\widetilde{\Gamma}^{-1}(x_1) = \{\langle 0.4/x_4\rangle\}$, $\widetilde{\Gamma}^{-2}(x_1) = \{\langle 0.4/x_5\rangle\}$.

Definition 4 Fuzzy reciprocal transitive closure $\widehat{\widetilde{\Gamma}}^{-}(x_i)$ is fuzzy reciprocal multiple-valued reflection defined by Eq. (18.5):

$$\widehat{\widetilde{\Gamma}}^{-}(x_i) = \widetilde{\Gamma}^{0}(x_i) \cup \widetilde{\Gamma}^{-1}(x_i) \cup \widetilde{\Gamma}^{-2}(x_i) \cup \ldots = \bigcup_{j=0}^{n-1} \widetilde{\Gamma}^{-j}(x_i). \tag{18.5}$$

In other words, $\widehat{\widetilde{\Gamma}}^{-}(x_i)$ is fuzzy subset of vertices, vertex x_i is accessible from by some fuzzy way with the greatest possible conjunctive durability.

Example 5 For the fuzzy graph presented in Fig. 18.1, fuzzy reciprocal transitive closure of vertex x_1 is $\widehat{\widetilde{\Gamma}}^{-}(x_1) = \{\langle 1/x_1\rangle, \langle 0.3/x_2\rangle, \langle 0.4/x_3\rangle, \langle 0.4/x_4\rangle, \langle 0.4/x_5\rangle\}$.

Definition 5 Graph $\widetilde{G} = (X, \widetilde{U})$ is called fuzzy strongly connected graph if the condition is satisfied, that is reflected by the Eq. (18.6):

$$(\forall \mathrm{x_i} \in \mathrm{X})(\mathrm{S}_{\widehat{\widetilde{\Gamma}}(\mathrm{x_i})} = \mathrm{X}) \tag{18.6}$$

In (18.6) $\mathrm{S}_{\widehat{\widetilde{\Gamma}}(\mathrm{x_i})}$ is the carrier of fuzzy transitive closure $\widehat{\widetilde{\Gamma}}(\mathrm{x_i})$.

Differently, graph $\widetilde{G} = (X, \widetilde{U})$ is fuzzy strongly connected graph if there is a fuzzy directed way with the conjunctive durability between any of two vertices which is distinct from 0.

It is easy to show, that Eq. (18.6) is equivalent to Eq. (18.7):

$$(\forall \mathrm{x_i} \in \mathrm{X})(\mathrm{S}_{\widehat{\widetilde{\Gamma}}^{-}(\mathrm{x_i})} = \mathrm{X}). \tag{18.7}$$

In (18.7) $\mathrm{S}_{\widehat{\widetilde{\Gamma}}^{-}(\mathrm{x_i})}$ is the carrier of fuzzy reciprocal transitive closure $\widehat{\widetilde{\Gamma}}^{-}(\mathrm{x_i})$.

Definition 6 Let fuzzy transitive closure for vertex x_i looks like $\widehat{\widetilde{\Gamma}}(\mathrm{x_i}) = \{\langle \mu_{\mathrm{i1}}(\mathrm{x_1})/\mathrm{x_1}\rangle, \langle \mu_{\mathrm{i2}}(\mathrm{x_2})/\mathrm{x_2}\rangle, \ldots, \langle \mu_{\mathrm{in}}(\mathrm{x_n})/\mathrm{x_n}\rangle\}$, then the volume $\rho(\widetilde{\mathrm{G}}) = \mathop{\&}_{\mathrm{j}=\overline{1,\mathrm{n}}} \mathop{\&}_{\mathrm{i}=\overline{1,\mathrm{n}}} \mu_{\mathrm{ij}}(\mathrm{x_j})$ is called a degree of strong connectivity of fuzzy graph $\widetilde{G}$.

Let $\widetilde{G} = (X, \widetilde{U})$ is fuzzy graph with degree of strong connectivity $\rho(\widetilde{\mathrm{G}})$, and $\widetilde{G}' = (X', \widetilde{U}')$ is fuzzy subgraph with degree of strong connectivity $\rho(\widetilde{\mathrm{G}}')$.

Definition 7 Fuzzy subgraph $\widetilde{G}' = (X', \widetilde{U}')$ is called maximum strong connectivity fuzzy subgraph or fuzzy strong component connectivity if there is no other subgraph $\widetilde{G}'' = (X'', \widetilde{U}'')$ for which $\widetilde{\mathrm{G}}' \subset \widetilde{\mathrm{G}}'$, and $\rho(\widetilde{\mathrm{G}}') \le \rho(\widetilde{\mathrm{G}}'')$.

18.3 Fuzzy Antibase Set

Definition 8 A subset of vertices $\overline{B}_\alpha \subset X$ is called fuzzy antibase with the degree $\alpha \in [0, 1]$, if some vertex $y \in \overline{B}_\alpha$ can be accessible from any vertex $x \in X/\overline{B}_\alpha$ with a degree not less than α and which is minimal in the sense that there is no subset $\overline{B}' \in \overline{B}_\alpha$, having the same accessible property.

Let's designate by $\widetilde{R}(\overline{B})$ a fuzzy set of vertices, which the subset $\overline{B}$ is accessible from according to Eq. (18.8):

$$\widetilde{R}(\overline{B}) = \bigcup_{x_i \in \overline{B}} \widehat{\widetilde{\Gamma}}^{-}(x_i). \tag{18.8}$$

In (18.8) $\widehat{\widetilde{\Gamma}}^{-}(x_i)$ is a fuzzy reciprocal transitive closure of the vertex x_i. Then the set $\overline{B}_\alpha$ is fuzzy antibase with a degree α in only case, when the conditions defined by Eqs. (18.9)–(18.10) are carried out:

$$\widetilde{R}(\overline{B}_\alpha) = \{\langle \mu_j/x_j\rangle | x_j \in X \,\&\, (\forall j = \overline{1,n})(\mu_j \ge \alpha)\} \tag{18.9}$$

$$(\forall B' \subset \overline{B}_\alpha)\left[\widetilde{R}(B') = \{\langle \mu'_j/x_j\rangle | x_j \in X \,\&\, (\exists j = \overline{1,n})(\mu'_j < \alpha)\}\right] \tag{18.10}$$

The condition (18.9) designates, that any vertex either is included into set $\overline{B}_\alpha$, or is accessible from some vertex of the same set with a degree not less α. The condition (18.10) designates that any subset $\overline{B}' \in \overline{B}_\alpha$ does not have the property (9).

The following property follows from definition of fuzzy antibase:

Property 1 *There are no two vertices which are entered into same strong connectivity fuzzy subgraph with degree above or equal α in fuzzy antibase $\overline{B}_\alpha$.*

Let $\{\mu_1, \mu_2, \ldots, \mu_L\}$ be a set of all values of membership function which are attributed to edges of graph $\widetilde{G}$. Then the following properties are true:

Property 2 *Exactly L fuzzy antibases with degrees $\{\mu_1, \mu_2, \ldots, \mu_L\}$ exist in any fuzzy circuit-free graph.*

Property 3 *There is just one fuzzy antibase with degree α in any fuzzy circuit-free graph.*

Property 4 *If an inequality $\alpha_1 < \alpha_2$ is executed in a fuzzy circuit-free graph, then inclusion $\overline{B}_{\alpha_1} \supset \overline{B}_{\alpha_2}$ is carried out.*

Let's note interrelation between fuzzy antibases and strong connectivity fuzzy subgraphs. The following properties are true.

Property 5 *If subset $\overline{B}_\alpha$ is a fuzzy antibase with degree* α*, then there is such subset* $X' \subseteq X$*, that $\overline{B}_\alpha \subset X'$, and fuzzy subgraph $\widetilde{G}' = (X', \widetilde{U}')$ has degree of strong connectivity not less than* α.

Property 6 *If subset $\overline{B}_\alpha$* is a *fuzzy antibase with degree* α*, then there is no such a subset* $X' \subseteq X$*, that* $X' \subseteq \overline{B}_\alpha$ *and fuzzy subgraph* $\widetilde{G}' = (X', \widetilde{U}')$ *has degree of strong connectivity* α.

The following consequence follows from property (6):

Consequence 1 It is necessary that fuzzy graph $\widetilde{G}$ should be strong connective with degree α so that fuzzy graph $\widetilde{G}$ has fuzzy antibase with degree α, consisting of only one vertex.

Property 7 *Let γ (x_i, x_j)* is an *accessible degree of vertex x_j from vertex x_i. Then* Eq. (18.11) *is true*:

$$(\forall x_i, x_j \in \overline{B}_a)[\gamma(x_i, x_j) < \alpha]. \tag{18.11}$$

Differently, the accessible degree of any vertex $x_j \in \overline{B}_\alpha$ from any other vertex $x_i \in \overline{B}_\alpha$ is less than value α.

Let a set $\tau_k = \{X_{k1}, X_{k2}, \ldots, X_{kl}\}$ be given, where X_{ki} is a fuzzy k-vertex antibase with the degree of α_{ki}. We define $\alpha_k = \max\{\alpha_{k_1}, \alpha_{k_2}, \ldots, \alpha_{k_l}\}$. In the case $\tau_k = \varnothing$ we define $\alpha_k = \alpha_{k-1}$. Volume α_k means that fuzzy graph $\widetilde{G}$ includes k-vertex subgraph with the accessible degree α_k and doesn't include k-vertex subgraph with an accessible degree more than α_k.

Definition 9 A fuzzy set in Eq. (18.12)

$$\widetilde{B}^{-} = \{\langle \alpha_1/1 \rangle, \langle \alpha_2/2 \rangle, \ldots, \langle \alpha_n/n \rangle\}, \tag{18.12}$$

is called a antibases fuzzy set of fuzzy graph $\widetilde{G}$.

Example 6 For the fuzzy graph presented in Fig. 18.1, the antibases fuzzy set is defined by Eq. (18.13):

$$\widetilde{B}^{-} = \{\langle 0.5/1 \rangle, \langle 0.6/2 \rangle, \langle 0.7/3 \rangle, \langle 0.8/4 \rangle, \langle 1/5 \rangle\}. \tag{18.13}$$

The antibases fuzzy set for this graph means, in particular, that if we have 2 service centers, then at their optimal placement all the other vertices are achievable with a degree not less than 0.6.

Thus, it is necessary to determine an antibases fuzzy set for a finding of the greatest degree.

We will consider the method of finding a family of all fuzzy antibases with the highest degree. The given method is an analogue method for definition of all minimal fuzzy dominating vertex sets (Bershtein and Bozhenyuk 2001) and it is a generalization of the Maghout's method for crisp graphs (Kaufmann 1977).

Assume that a set $\overline{B}_\alpha$ is a fuzzy base of the fuzzy graph $\widetilde{G}$ with the degree α. Then for an arbitrary vertex $x_i \in X$, one of the following conditions must be true.

(a) $x_i \in \overline{B}_\alpha$;
(b) if $x_i \in \overline{B}_\alpha$, then there is such a vertex x_j that it belongs to the set $\overline{B}_\alpha$ with the degree $\gamma\ (x_i, x_j) \geq \alpha$.

In other words, the following statement, presented as Eq. (18.14) is true:

$$(\forall x_i \in X)\left[x_i \in \overline{B}_\alpha \vee (x_i \notin \overline{B}_\alpha \ \rightarrow \ (\exists x_j \in \overline{B}_\alpha | \gamma(x_i, x_j) \geq \alpha))\right] \tag{18.14}$$

We assign Boolean variable p_i that takes the value 1 to each vertex $x_i \in X$ if $x_i \in \overline{B}_\alpha$ and 0 otherwise. We assign a fuzzy variable $\xi_{iji} = \alpha$ for the proposition $\gamma\ (x_i, x_j) \geq \alpha$. Passing from the quantifier form of proposition (18.10) to the form in terms of logical operations, we obtain a true logical proposition, given in Eq. (18.15):

$$\Phi_{\overline{B}} = \underset{i}{\&}(p_i \vee (\overline{p}_i \rightarrow (\underset{j}{\vee}(p_j \,\&\, \gamma_{ij})))). \tag{18.15}$$

Taking into account interrelation between implication operation and disjunction operation ($\alpha \rightarrow \beta = \overline{\alpha} \vee \beta$), we receive Eq. (18.16):

$$\Phi_{\overline{B}} = \underset{i}{\&}(p_i \vee p_i \vee \underset{j}{\vee}(p_j \,\&\, \gamma_{ij})). \tag{18.16}$$

Supposing $\xi_{ii} = 1$ and considering that the equality $p_i \vee \underset{j}{\vee} p_i \,\&\, \xi_{ij} = \underset{j}{\vee} p_j \xi_{ij}$ is true for any vertex x_i, we finally obtain Eq. (18.17):

$$\Phi_{\overline{B}} = \underset{i}{\&}(\underset{j}{\vee}(p_j \,\&\, \gamma_{ij})). \tag{18.17}$$

We open the parentheses in (18.17) and reduce the similar terms the following rules in Eq. (18.18):

$$\mathrm{a} \vee \mathrm{a\&b} = \mathrm{a};\ \mathrm{a\&b} \vee \mathrm{a\&\bar{b}} = \mathrm{a};\ \xi'\mathrm{\&a} \vee \xi''\mathrm{\&a\&b}. \tag{18.18}$$

Here, a, b $\in \{0, 1\}$, $\xi' \geq \xi''$, $\xi', \xi'' \in [0, 1]$.

Then Eq. (18.17) can be rewritten as Eq. (18.19):

$$\Phi_{\overline{B}} = \underset{i=\overline{1,l}}{\vee}(p_{1_i} \,\&\, p_{2_i} \,\&\, \cdots \,\&\, p_{k_i} \,\&\, \alpha_i). \tag{18.19}$$

Property 8 *If further simplification on the basis of rules* (18.18) *in* Eq. (18.19) *is impossible, then any disjunctive member i defines antibase with the highest degree* α_i.

Proof Let's consider that further simplification is impossible in Eq. (18.19). Let, for definiteness, disjunctive member, given in Eq. (18.20)

$$(p_1 \,\&\, p_2 \,\&\, \ldots \,\&\, p_k \,\&\, \alpha), \quad k < n, \alpha \in (0, 1] \tag{18.20}$$

is included in Eq. (18.19).

Let's assume, that the subset $X' = \{x_1, x_2, \ldots, x_k\}$ is not an antibase with degree α. Then there is some vertex, for example $x_{k+1} \in X/X'$, that the statement $(\forall i = \overline{1,k})(\gamma(x_{k+1}, x_i) < \alpha)$ is true for. In other words, the accessible degree of any vertex of subset X' from vertex x_{k+1} is less than value α.

We present Eq. (18.17) in such a way:

$$\begin{aligned} \Phi_{\overline{B}} = {} & (1p_1 \vee \xi_{12}p_2 \vee \ldots \vee \xi_{1n}p_n) \,\&\, (\xi_{21}p_1 \vee 1p_2 \vee \ldots \vee \xi_{2n}p_n) \\ & \&\ldots\&, (\xi_{k+1,1}p_1 \vee \xi_{k+1,2}p_2 \vee \ldots \xi_{k+1,k}p_k \vee 1p_{k+1} \vee \ldots \vee \xi_{k+1,n}p_n) \\ & \&\ldots\&(\xi_{n1}p_1 \vee \xi_{n2}p_2 \vee \ldots \vee 1p_n). \end{aligned} \tag{18.21}$$

In Eq. (18.21) all coefficients $\xi_{k+1,i} < \alpha, \ \ \forall i = \overline{1,k}$. Therefore, all disjunctive members which do not contain variables $p_{k+1}, p_{k+2}, \ldots, p_n$ necessarily contain coefficients of the smaller value α in Eq. (18.19). From there, the disjunctive member (18.20) is not included in Eq. (18.19). The received contradiction proves that subset $X' = \{x_1, x_2, \ldots, x_k\}$ is antibase with degree α.

Let's prove now, that the disjunctive member (18.20) is the minimum member. We will assume the return. Then following conditions should be carried out:

(a) subset $X' = \{x_1, x_2, \ldots, x_k\}$ is antibase with degree $\beta > \alpha$;

or

(b) there is a subset $X'' \subset X'$ that is antibase with degree α.

Let the condition (a) is satisfied. Then Eq. (18.22) is true:

$$(\forall x_j, j = \overline{k+1, n})(\exists x_i, i \in \overline{1, k} | \gamma(x_j, x_i) \geq \beta) \tag{18.22}$$

Let's present equation Φ in the form of (18.21). If to make logic multiplication of each bracket against each other without rules of absorption (18.18) we will receive n^2 disjunctive members containing exactly n elements and on one element from each bracket of decomposition (18.21). We will choose one of n^2 disjunctive members as follows:

- From the first bracket we will choose element $1p_1$;
- From the second bracket—element $1p_2$; …;
- From kth bracket—element $1p_k$;
- From (κ + 1)th bracket we will choose element $\xi_{k+1,i_1} p_{i_1}$ such, that index $i_1 \in [1, k]$, and volume $\xi_{k+1,i_1} > \beta$;
- From (κ + 2)th bracket—element $\xi_{k+2,i_2} p_{i_2}$, for which index $i_2 \in [1, k]$, and volume $\xi_{k+2,i_2} > \beta$, etc.;
- From nth bracket—element $\xi_{n,i_{n-k1}} p_{i_{n-k}}$, for which index $i_{n-k} \in [1, k]$, and volume $\xi_{n,i_{n-k1}} > \beta$.

Using rules of absorption (18.8), the received disjunctive member can be led to the form of $(p_1 \,\&\, p_2 \,\&\, \ldots \,\&\, p_k \,\&\, \beta')$, in which the volume is $\beta' = \min\{\xi_{k+1,i_2}, \xi_{k+2,i_2}, \ldots, \xi_{n,i_{n-k}}\} \geq \beta > \alpha$ and which will be necessarily absorbed disjunctive member (18.20). (Decomposition (18.19) of the disjunctive member cannot include the received contradiction (18.20)) that proves impossibility of case (a).

Let's assume now, that the condition is satisfied. Let $X'' = \{x_1, x_2, \ldots, x_{k-1}\}$ for clarity. Considering equation Φ in the form of decomposition (18.18), we will choose a disjunctive member as follows:

- From the first bracket we will choose element $1p_1$,
- From the second bracket—element $1p_2$, …,
- From (κ − 1)th bracket—element $1p_{k-1}$,
- From kth bracket we will choose element $\xi_{k,i_1} p_{i_1}$ such, that index $i_1 \in [1, k-1]$, and volume $\xi_{k,i_1} \geq \alpha$,
- From (κ + 1)th bracket—element $\xi_{k+1,i_2} p_{i_2}$, for which index $i_2 \in [1, k-1]$, and volume $\xi_{k+1,i_2} \geq \alpha$, etc.,

- From nth bracket—element $\xi_{n,i_{n-k+11}} p_{i_{n-k+1}}$, for which index $i_{n-k+1} \in [1, k-1]$, and volume $\xi_{n,i_{n-k+1}} \geq \alpha$.

Using rules of absorption (18.18) the received disjunctive member can be led to the form $(p_1 \,\&\, p_2 \,\&\, \ldots \,\&\, p_{k-1} \,\&\, \alpha)$, in which size $\beta = \min\{\xi_{k,i_2}, \xi_{k+1,i_2}, \ldots, \xi_{n,i_{n-k+1}}\} \geq \alpha$ and which will be necessarily absorbed by a disjunctive member (18.20). (Decomposition (18.19) of the disjunctive member cannot include the received contradiction (18.20)) that proves impossibility of case (b).

Property (8) is proved.

The following method of foundation of fuzzy antibases can be proposed on the base of property (18.8):

- We write proposition (18.7) for given fuzzy graph $\widetilde{G}$;
- We simplify proposition (18.7) by proposition (18.8) and present it as proposition (18.9);
- We define all fuzzy antibases, which correspond to the disjunctive members of proposition (18.9).

18.4 Fuzzy Base Set

Definition 10 A fuzzy base with the degree $\beta \in [0, 1]$ is called a subset of vertices $B_\beta \subset X$ which any vertex of a fuzzy graph is accessible from with the degree not less than β and which is minimal in the sense that there is no subset $B' \subset B_\beta$, having the same accessible property.

Formally, any subset of vertices of the fuzzy graph can be considered as a fuzzy base with β degree.

Let's designate through $\widetilde{R}(B)$ a fuzzy set of vertices, accessible of any subset $B \subset X$. Then set B_β is a fuzzy base with degree α only in the case the following Eqs. (18.23)–(18.24) are carried out:

$$\widetilde{R}(B_\beta) = \{\langle \mu_j / x_j \rangle | x_j \in X \,\&\, (\forall j = \overline{1, n})(\mu_j \geq \beta)\}. \tag{18.23}$$

$$(\forall B' \subset B_\beta)\left[\widetilde{R}(B') = \{\langle \mu'_j / x_j \rangle | x_j \in X \,\&\, (\exists j = \overline{1, n})(\mu'_j < \beta)\}\right]. \tag{18.24}$$

Condition (18.23) designates that any vertex either is included into set B_β, or is accessible from some vertex of the same set with the degree not less than β. Condition (18.24) designates that some subset $B' \subset B_\beta$ does not have condition (18.23).

It should be noted that the fuzzy bases performed similar properties (18.1–18.7) for fuzzy antibases.

The following property follows from definition of fuzzy base:

Let set $\tau_k = \{X_{k1}, X_{k2}, \ldots, X_{kl}\}$ be given, where X_{ki} is a fuzzy k-vertex base with the degree of β_{ki}. We define β_k as $\beta_k = \max\{\beta_{k1}, \beta_{k2}, \ldots, \beta_{kl}\}$. In case $\tau_k = \varnothing$ we define $\beta_k = \beta_{k-1}$. Volume β_k means that fuzzy graph $\widetilde{G}$ includes a k-vertex subgraph with the accessible degree of domination β_k and doesn't include k-vertex subgraph with an accessible degree more than β_k.

Definition 11 Equation (18.25) defines, that fuzzy set

$$\widetilde{B} = \{\langle \beta_1/1\rangle, \langle \beta_2/2\rangle, \ldots, \langle \beta_n/n\rangle\} \tag{18.25}$$

is called a bases fuzzy set of fuzzy graph $\widetilde{G}$.

The bases fuzzy set as antibases fuzzy set is a fuzzy invariant of a fuzzy graph. The bases fuzzy set determines the highest degree of the reachability of the vertices for any given number of service centers.

Example 7 For the fuzzy graph presented in Fig. 18.1, the bases fuzzy set is presented by Eq. (18.26).

$$\widetilde{B} = \{\langle 0.5/1\rangle, \langle 0.6/2\rangle, \langle 0.7/3\rangle, \langle 0.8/4\rangle, \langle 1/5\rangle\}. \tag{18.26}$$

The bases fuzzy set for this graph means, in particular, that if we have 2 service centers, then at their optimal placement all the other vertices are achievable with a degree of not less than 0.6.

Now we will consider the method of finding a family of all fuzzy bases with the highest degree. This method is similar to the method for the definition of all fuzzy antibases for fuzzy graphs which was considered above.

Let us assume that set B_β is a fuzzy base of the fuzzy graph $\widetilde{G}$ with degree β. Then for an arbitrary vertex $x_i \in X$ one of the following conditions must be true.

(a) $x_i \in B_\beta$;
(b) if $x_i \notin B_\beta$, then there is a vertex x_j such that it belongs to set B_β with the degree $\gamma\ (x_j, x_i) \geq \beta$.

In other words, the Eq. (18.27) is true:

$$(\forall x_i \in X)\left[x_i \in B_\beta \vee (x_i \notin B_\beta \rightarrow (\exists x_j \in B_\beta | \gamma(x_j, x_i) \geq \beta))\right]. \tag{18.27}$$

To each vertex $x_i \in X$ we assign Boolean variable p_i that takes value 1, if $x_i \in B_\beta$ and 0 otherwise. We assign the fuzzy variable $\xi_{ji} = \beta$ for the proposition $\gamma\ (x_j, x_i) \geq \beta$. Passing from the quantifier form of proposition (18.27) to the form in terms of logical operations, we obtain a true logical proposition in the form of Eq. (18.28):

$$\Phi_B = \underset{i}{\&}(p_i \vee (\bar{p}_i \rightarrow (\underset{j}{\vee}(p_j \,\&\, \gamma_{ji})))). \tag{18.28}$$

Taking into account the interrelation between the implication operation and disjunction operation, we come to Eq. (18.29):

$$\Phi_B = \underset{i}{\&}(p_i \vee p_i \vee \underset{j}{\vee}(p_j \,\&\, \gamma_{ji})). \tag{18.29}$$

Supposing $\xi_{ii} = 1$ and considering that the equality $p_i \vee \underset{j}{\vee} p_i \,\&\, \xi_{ij} = \underset{j}{\vee} p_j \xi_{ij}$ is true for any vertex x_i, we finally obtain Eq. (18.30):

$$\Phi_B = \underset{i}{\&}(\underset{j}{\vee}(p_j \,\&\, \gamma_{ji})). \tag{18.30}$$

We open the parentheses in Eq. (18.30) and reduce the similar terms by following rules (18.18). Then Eq. (18.30) may be presented as Eq. (18.31):

$$\Phi_B = \underset{i=\overline{1,l}}{\vee}(p_{1_i} \,\&\, p_{2_i} \,\&\, \ldots \,\&\, p_{k_i} \,\&\, b_i). \tag{18.31}$$

We may prove the next property:

Property 9 *Each disjunctive member in* Eq. (18.31) *gives a fuzzy base with the highest degree* b_i.

The proof of this property is similar to the property (8).

18.5 Vitality Fuzzy Set

Let k be a service center ($k < n$), placed in the vertices of subset Y, $|Y| = k$, $Y \subset X$, and $\gamma(x_i, x_j)$ is a reachability degree of vertex x_j from vertex x_i.

Definition 12 Value $V(Y) = \underset{\forall x_j \in X/Y}{\&}(\underset{\forall x_i \in Y}{\vee} \gamma(\mathrm{x_i}, \mathrm{x_j}) \,\&\, \gamma(\mathrm{x_j}, \mathrm{x_i}))$ is a vitality degree of fuzzy graph $\widetilde{G}$ which is served by k-centers from vertex set Y.

Vitality degree $\mathrm{V}(Y)$ determines the minimax strong connectivity value between each vertex from set X/Y and a center from set Y.

In other words, one can "leave" the vertex of subset Y, "reach" any vertex of the graph, "serve" it, return to the "initial" vertex while the conjunctive strength of the route will not be less than value $\mathrm{V}(Y)$.

It is clear that value $V(Y) \in [0, 1]$ depends either on the number of centers k, or the allocation of the centers on the vertices of graph $\widetilde{G}$ (i.e. on the choice of set Y).

Thus, the problem of the allocation of k service centers ($k < n$) in fuzzy graph $\widetilde{G}$ is reduced to determining such a subset of vertices $Y \subset X$, that value of vitality degree $\mathrm{V}(Y)$ reaches its maximum value, that is value $V(k) = \max\limits_{\substack{\forall Y \subset X \\ |Y| = k}} \{V_{\widetilde{G}}(Y)\}$.

Definition 13 Fuzzy set $\widetilde{\mathrm{V}} = \{\langle V_1/1\rangle, \langle V_2/2\rangle, \ldots, \langle V_n/n\rangle\}$, defined on vertex set X, is called a *vitality fuzzy set* of graph $\widetilde{G} = (X, \widetilde{U})$. Fuzzy set of vitality $\widetilde{\mathrm{V}}$ determines the greatest vitality degrees of graph $\widetilde{G}$ if it is served by 1, 2, …, n centers.

Values V_k ($1 \le k \le n$) signify that we can place k-centers in graph $\widetilde{G}$ so that there is a route from at least one center to any vertex of graph $\widetilde{G}$ and back. The conjunctive strength of the graph will be not less than V_k.

Let us consider the method of finding a family of all service centers with the largest vitality degree (Bozhenyuk and Rozenberg 2012; Bozheniuk et al. 2015).

The given method is a similar to the method for the definition of all fuzzy base sets and fuzzy antibase sets for fuzzy graphs. Let Y be a subset of the vertices of fuzzy graph $\widetilde{G} = (X, \widetilde{U})$ which the service centers are located in and the vitality degree equals to V. Therefore, one of the two conditions for any vertex $x_i \in X$ can be satisfied:

(a) vertex x_i belongs to the set Y;
(b) there is vertex x_j that belongs to the set Y and inequalities $\gamma(x_i, x_j) \ge V$ and $\gamma(x_j, x_i) \ge V$ are found.

Using the notation quantifier form we can get the truth of the following Eq. (18.32):

$$(\forall \mathrm{x_i} \in X)\left[x_i \in Y \vee (\exists x_j)(x_j \in Y \,\&\, \gamma(x_i, x_j) \ge V \,\&\, \gamma(x_j, x_i) \ge V)\right]. \tag{18.32}$$

Logical variable p_i can be set in correspondence to each vertex $x_i \in X$. If $x_i \in Y$, the logical variable possesses value 1, otherwise 0. Fuzzy variable $\xi_{\mathrm{ij}} = \gamma(x_i, x_j)$ can be set in the correspondence to equation $\gamma(x_i, x_j) \ge V$. So we can get the truth of the logical Eq. (18.33):

$$\Phi_{\mathrm{V}} = \mathop{\&}_{i=\overline{1,n}} (p_i \vee \mathop{\vee}_{j=\overline{1,n}} (p_j \,\&\, \xi_{ij} \,\&\, \xi_{ij})). \tag{18.33}$$

Let $\xi_{\mathrm{ii}} = 1$ and equality $p_i \vee \bigvee\limits_j p_i \,\&\, \xi_{ij} \,\&\, \xi_{ji} = \bigvee\limits_j p_j \,\&\, \xi_{ij} \,\&\, \xi_{ji}$ is true for any x_i then obtain Eq. (18.34):

$$\Phi_V = \mathop{\&}_{i=\overline{1,n}} \mathop{\vee}_{j=\overline{1,n}} (\xi_{ij} \,\&\, \xi_{ji} \,\&\, p_j). \tag{18.34}$$

While removing the brackets in formula (18.34), let us use the following rule of absorption (18.18).

Consequently Eq. (18.34) will be represented as Eq. (18.35):

$$\Phi_{\mathrm{V}} = \underset{i=\overline{1,l}}{\vee}(p_{1_i} \,\&\, p_{2_i} \,\&\, \ldots \,\&\, p_{k_i} \,\&\, V_i). \tag{18.35}$$

We can prove the following property:

Property 10 *If further simplification in the formula* (18.35) *based on the rules* (18.18) *is not possible, then the totality of all vertices, conforming to variables, for each disjunctive term i defines the subset of vertices* $Y \subseteq X$ *with vitality degree* V_i *of fuzzy graph* $\widetilde{G} = (X, \widetilde{U})$*. Here subset Y is minimal, in other words, any subset of Y does not have this property.*

Property 11 *For antibases fuzzy set, bases fuzzy set, and vitality fuzzy set the following propositions are true:*

$$0 \le \alpha_1 \le \alpha_2 \le \ldots \le \alpha_n = 1.$$
$$0 \le \beta_1 \le \beta_2 \le \ldots \le \beta_n = 1.$$
$$0 \le V_1 \le V_2 \le \ldots \le V_n = 1.$$

18.6 Example of Service Centers Finding

Let us consider a railway network limited by the stations Novosibirsk, Kemerovo, Barnaul and Novokuzneck. The network is presented in Fig. 18.2.

The fuzzy graph of this railway network, obtained from the GIS "Object Land" (Rozenberg et al. 2000; Bozhenyuk et al. 2015), is represented in Fig. 18.3.

Here the vertices of the fuzzy graph correspond to the network of railway stations, and the edges of the fuzzy graph correspond to the railway between the stations. The membership functions of the edges are calculated according to the characteristics of the railway. For example, "if the period of the maintenance of the railway is less than 15 years and the length is less than 20 km, the membership function is equal to 0.9". It is necessary to find the allocation of service centers. For the sake of simplicity, we will present that all subgraphs with a strong connection degree equals 1 by one vertex.

As a result, we will receive the aggregative fuzzy graph with n = 9, which is represented in Fig. 18.4:

The vertex matrix for this graph has the following form:

We raise the contiguity matrix to 2, 3, …, 9 powers. Uniting them, we find an accessible matrix:

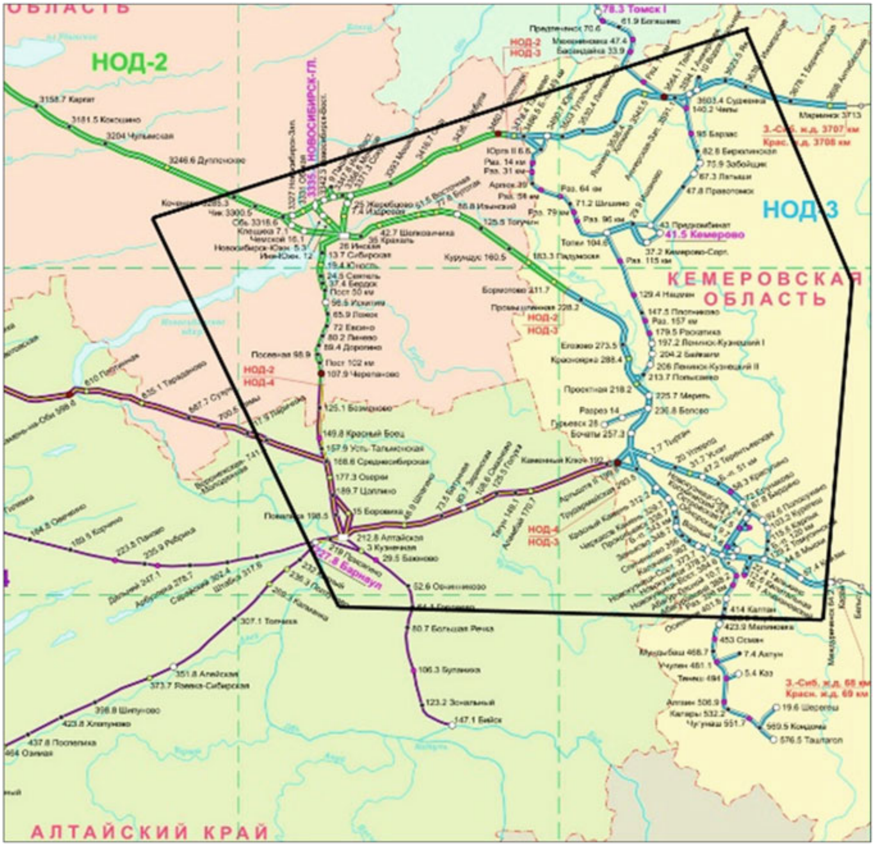


Fig. 18.2 Railway network

$$
R = \begin{array}{c} \\ x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \end{array}
\begin{array}{c}
\begin{array}{ccccccccc} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 \end{array} \\
\left|\begin{array}{ccccccccc}
0 & 1 & 0 & 0 & 0.7 & 0 & 0 & 0.7 & 0 \\
0.7 & 0 & 0.6 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.6 & 0 & 0 & 0 & 0 & 0 & 0 & 0.7 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.7 \\
0.6 & 0 & 0 & 0 & 0 & 0.9 & 0.3 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.6 & 0 & 0.4 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.3 & 0.4 & 0 & 0.4 & 0 \\
0.6 & 0 & 0 & 0 & 0 & 0 & 0.4 & 0 & 0.7 \\
0 & 0 & 0.6 & 1 & 0 & 0 & 0 & 0.7 & 0
\end{array}\right|
\end{array}
$$

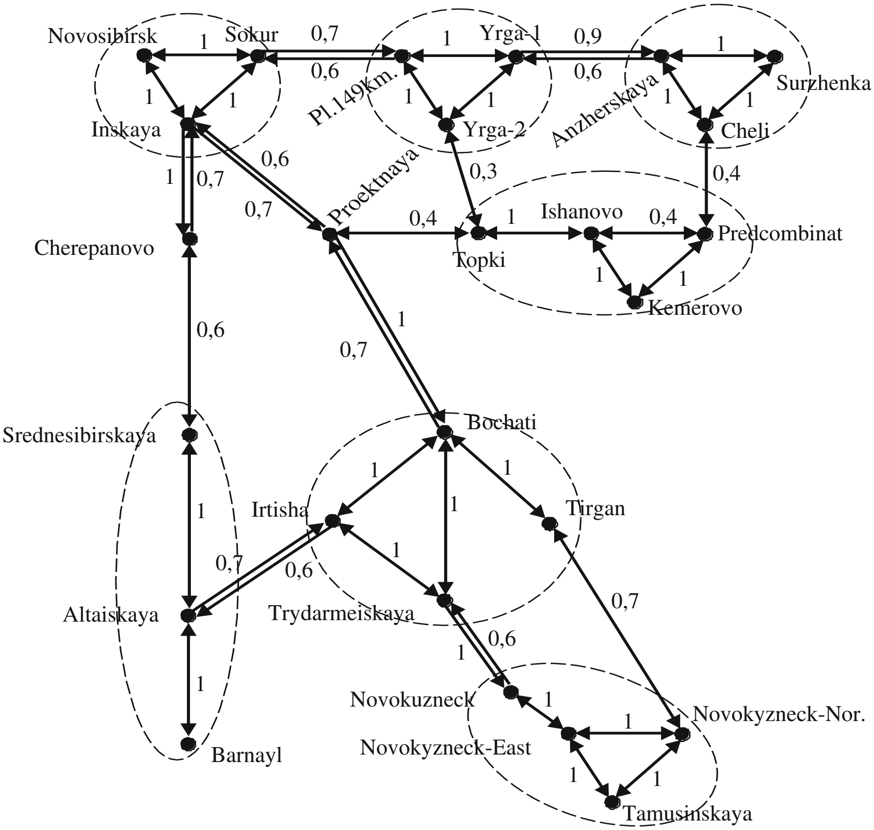
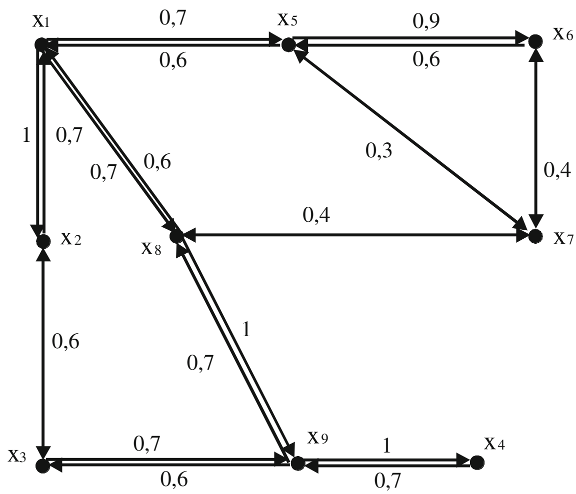


Fig. 18.3 Fuzzy graph of the railway network

Fig. 18.4 Aggregative fuzzy graph of the railway network



$$
\mathrm{N} = \begin{array}{c} \\ x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \end{array}
\begin{array}{c}
\begin{array}{ccccccccc} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 \end{array} \\
\left|\begin{array}{ccccccccc}
1 & 1 & 0.7 & 0.7 & 0.7 & 0.7 & 0.4 & 0.7 & 0.7 \\
0.7 & 1 & 0.6 & 0.7 & 0.7 & 0.7 & 0.4 & 0.7 & 0.7 \\
0.6 & 0.6 & 1 & 0.7 & 0.6 & 0.6 & 0.4 & 0.7 & 0.7 \\
0.6 & 0.6 & 0.6 & 1 & 0.6 & 0.6 & 0.4 & 0.7 & 0.7 \\
0.6 & 0.6 & 0.6 & 0.6 & 1 & 0.9 & 0.4 & 0.6 & 0.6 \\
0.6 & 0.6 & 0.6 & 0.6 & 0.6 & 1 & 0.4 & 0.6 & 0.6 \\
0.4 & 0.4 & 0.4 & 0.4 & 0.4 & 0.4 & 1 & 0.4 & 0.4 \\
0.6 & 0.6 & 0.6 & 1 & 0.6 & 0.6 & 0.4 & 1 & 1 \\
0.6 & 0.6 & 0.6 & 1 & 0.6 & 0.6 & 0.4 & 0.7 & 1
\end{array}\right|
\end{array}
$$

We define all fuzzy bases for this graph. The corresponding Eq. (18.15) has the following form:

$$
\begin{aligned}
\Phi_B = {} & (1\mathrm{p}_1 \vee 0.7\mathrm{p}_2 \vee 0.6\mathrm{p}_3 \vee 0.6\mathrm{p}_4 \vee 0.6\mathrm{p}_5 \vee 0.6\mathrm{p}_6 \vee 0.4\mathrm{p}_7 \vee 0.6\mathrm{p}_8 \vee 0.6\mathrm{p}_9) \\
& \&(1\mathrm{p}_1 \vee 1\mathrm{p}_2 \vee 0.6\mathrm{p}_3 \vee 0.6\mathrm{p}_4 \vee 0.6\mathrm{p}_5 \vee 0.6\mathrm{p}_6 \vee 0.4\mathrm{p}_7 \vee 0.6\mathrm{p}_8 \vee 0.6\mathrm{p}_9) \\
& \&(0.7\mathrm{p}_1 \vee 0.6\mathrm{p}_2 \vee 1\mathrm{p}_3 \vee 0.6\mathrm{p}_4 \vee 0.6\mathrm{p}_5 \vee 0.6\mathrm{p}_6 \vee 0.4\mathrm{p}_7 \vee 0.6\mathrm{p}_8 \vee 0.6\mathrm{p}_9) \\
& \&(0.7\mathrm{p}_1 \vee 0.7\mathrm{p}_2 \vee 0.7\mathrm{p}_3 \vee 1\mathrm{p}_4 \vee 0.6\mathrm{p}_5 \vee 0.6p_6 \vee 0.4\mathrm{p}_7 \vee 1\mathrm{p}_8 \vee 1\mathrm{p}_9) \\
& \&(0.7\mathrm{p}_1 \vee 0.7\mathrm{p}_2 \vee 0.6\mathrm{p}_3 \vee 0.6\mathrm{p}_4 \vee 1\mathrm{p}_5 \vee 0.6\mathrm{p}_6 \vee 0.4\mathrm{p}_7 \vee 0.6\mathrm{p}_8 \vee 0.6\mathrm{p}_9) \\
& \&(0.7\mathrm{p}_1 \vee 0.7\mathrm{p}_2 \vee 0.6\mathrm{p}_3 \vee 0.6\mathrm{p}_4 \vee 0.9\mathrm{p}_5 \vee 1\mathrm{p}_6 \vee 0.4\mathrm{p}_7 \vee 0.6\mathrm{p}_8 \vee 0.6\mathrm{p}_9) \\
& \&(0.4\mathrm{p}_1 \vee 0.4\mathrm{p}_2 \vee 0.4\mathrm{p}_3 \vee 0.4\mathrm{p}_4 \vee 0.4\mathrm{p}_5 \vee 0.4p_6 \vee 1\mathrm{p}_7 \vee 0.4\mathrm{p}_8 \vee 0.4\mathrm{p}_9) \\
& \&(0.7\mathrm{p}_1 \vee 0.7\mathrm{p}_2 \vee 0.7\mathrm{p}_3 \vee 0.7\mathrm{p}_4 \vee 0.6\mathrm{p}_5 \vee 0.6\mathrm{p}_6 \vee 0.4\mathrm{p}_7 \vee 1\mathrm{p}_8 \vee 0.7\mathrm{p}_9) \\
& \&(0.7\mathrm{p}_1 \vee 0.7\mathrm{p}_2 \vee 0.7\mathrm{p}_3 \vee 0.7\mathrm{p}_4 \vee 0.6\mathrm{p}_5 \vee 0.6\mathrm{p}_6 \vee 0.4\mathrm{p}_7 \vee 1\mathrm{p}_8 \vee 1\mathrm{p}_9).
\end{aligned}
$$

The first parenthesis absorbs the second parenthesis, the eighth parenthesis absorbs the ninth parenthesis in the received equation. Multiplying parenthesis 3 and 4, parenthesis 5 and 6, parenthesis 7 and 8, and using rules (18.8) we obtain:

$$
\begin{aligned}
\Phi_B = {} & (1\mathrm{p}_1 \vee 0.7\mathrm{p}_2 \vee 0.6\mathrm{p}_3 \vee 0.6\mathrm{p}_4 \vee 0.6\mathrm{p}_5 \vee 0.6\mathrm{p}_6 \vee 0.4\mathrm{p}_7 \vee 0.6\mathrm{p}_8 \vee 0.6\mathrm{p}_9) \\
& \&(0.7\mathrm{p}_1 \vee 0.6\mathrm{p}_2 \vee 0.7\mathrm{p}_3 \vee 0.6\mathrm{p}_4 \vee 0.6\mathrm{p}_5 \vee 0.6\mathrm{p}_6 \vee 0.4\mathrm{p}_7 \vee 0.6\mathrm{p}_8 \vee 0.6\mathrm{p}_9 \\
& \vee 1\mathrm{p}_3\mathrm{p}_4 \vee 1\mathrm{p}_3\mathrm{p}_8 \vee 1\mathrm{p}_3\mathrm{p}_9) \\
& \&(0.7\mathrm{p}_1 \vee 0.7\mathrm{p}_2 \vee 0.6\mathrm{p}_3 \vee 0.6\mathrm{p}_4 \vee 0.9\mathrm{p}_5 \vee 0.6\mathrm{p}_6 \vee 0.4\mathrm{p}_7 \vee 0.6\mathrm{p}_8 \vee 0.6\mathrm{p}_9 \vee 1\mathrm{p}_5\mathrm{p}_6) \\
& \&(0.4\mathrm{p}_1 \vee 0.4\mathrm{p}_2 \vee 0.4\mathrm{p}_3 \vee 0.4\mathrm{p}_4 \vee 0.4\mathrm{p}_5 \vee 0.4\mathrm{p}_6 \vee 0.4\mathrm{p}_7 \vee 0.4\mathrm{p}_8 \vee 0.4\mathrm{p}_9 \vee 0.7\mathrm{p}_1\mathrm{p}_7 \\
& \vee 0.7\mathrm{p}_2\mathrm{p}_7 \vee 0.7\mathrm{p}_3\mathrm{p}_7 \vee 0.7\mathrm{p}_4\mathrm{p}_7 \vee 0.6\mathrm{p}_5\mathrm{p}_7 \vee 0.6\mathrm{p}_6\mathrm{p}_7 \vee 1\mathrm{p}_7\mathrm{p}_8 \vee 0.7_7\mathrm{p}_9).
\end{aligned}
$$

Multiplying parenthesis 1 and 2, parenthesis 2 and 4 and using rules (18.8) we obtain:

$$\begin{aligned}\Phi_B = {} & (0.7p_1 \vee 0.6p_2 \vee 0.6p_3 \vee 0.6p_4 \vee 0.6p_5 \vee 0.6p_6 \vee 0.4p_7 \vee 0.4p_8 \vee 0.6p_9 \\ & \vee 0.7p_2p_3 \vee 1p_1p_3p_4 \vee 1p_1p_3p_8 \vee 1p_1p_3p_9)\,\&\,(0.4p_1 \vee 0.4p_2 \vee 0.4p_3 \vee 0.4p_4 \\ & \vee 0.4p_5 \vee 0.4p_6 \vee 0.4p_7 \vee 0.4p_8 \vee 0.4p_9 \vee 0.7p_1p_7 \vee 0.7p_2p_7 \vee 0.6p_3p_7 \\ & \vee 0.6p_4p_7 \vee 0.6p_5p_7 \vee 0.6p_7p_8 \vee 0.6p_7p_9 \vee 0.7p_4p_5p_7 \vee 0.9p_5p_7p_8 \\ & \vee 0.7p_5p_7p_9 \vee 0.7p_3p_5p_6p_7 \vee 1p_5p_6p_7p_8 \vee 0.7p_5p_6p_7p_9).\end{aligned}$$

Multiplying the parentheses, we finally obtain:

$$\begin{aligned}\Phi_B = {} & \underline{0.4p_1} \vee 0.4p_2 \vee 0.4p_3 \vee 0.4p_4 \vee 0.4p_5 \vee 0.4p_6 \vee 0.4p_7 \vee 0.4p_8 \vee 0.4p_9 \vee \underline{0.7p_1p_7} \\ & \vee 0.6p_2p_7 \vee 0.6p_3p_7 \vee 0.6p_4p_7 \vee 0.6p_5p_7 \vee 0.6p_7p_9 \vee 0.7p_2p_3p_7 \vee \underline{0.9p_1p_3p_5p_7p_9} \\ & \vee \underline{1p_1p_3p_5p_6p_7p_8}.\end{aligned}$$

Graph $\widetilde{G}$ has 18 fuzzy bases that follows from the last equality and the bases fuzzy set is defined as:

$$\widetilde{B} = \{\langle 0.4/1\rangle, \langle 0.7/2\rangle, \langle 0.9/5\rangle, \langle 1/6\rangle\}.$$

The bases fuzzy set defines the following optimum allocation of the service centers: If we have 6 or more service centers then we must place these centers into vertices 1, 3, 5, 6, 7 and 8 (Inskaya, Barnaul, Yrga-2, Surzhenka, Kemerovo, Proektnaya). The degree of service equals 1 in this case. If we have 5 service centers then we must place these centers into vertices 1, 3, 5, 7 and 9 (Inskaya, Barnaul, Yrga-2, Kemerovo, Tirgan). In this case the degree of service equals 0.9. If we have 2 service centers then we must place both centers into vertices 1 and 7 (Inskaya, Kemerovo). In this case the degree of service equals 0.7. If we have only one service center then we can place it in any vertex (for example, Inskaya). In the last case the degree of service equals 0.4.

We define all fuzzy antibases for this graph. The corresponding Eq. (18.7) has the following form:

$$\begin{aligned}\Phi_{\overline{B}} = {} & (1p_1 \vee 1p_2 \vee 0.7p_3 \vee 0.7p_4 \vee 0.7p_5 \vee 0.7p_6 \vee 0.4p_7 \vee 0.7p_8 \vee 0.7p_9) \\ & \&(0.7p_1 \vee 1p_2 \vee 0.6p_3 \vee 0.7p_4 \vee 0.7p_5 \vee 0.7p_6 \vee 0.4p_7 \vee 0.7p_8 \vee 0.7p_9) \\ & \&(0.6p_1 \vee 0.6p_2 \vee 1p_3 \vee 0.7p_4 \vee 0.6p_5 \vee 0.6p_6 \vee 0.4p_7 \vee 0.7p_8 \vee 0.7p_9) \\ & \&(0.6p_1 \vee 0.6p_2 \vee 0.6p_3 \vee 1p_4 \vee 0.6p_5 \vee 0.6p_6 \vee 0.4p_7 \vee 0.7p_8 \vee 0.7p_9) \\ & \&(0.6p_1 \vee 0.6p_2 \vee 0.6p_3 \vee 0.6p_4 \vee 1p_5 \vee 0.9p_6 \vee 0.4p_7 \vee 0.6p_8 \vee 0.6p_9) \\ & \&(0.6p_1 \vee 0.6p_2 \vee 0.6p_3 \vee 0.6p_4 \vee 0.6p_5 \vee 1p_6 \vee 0.4p_7 \vee 0.6p_8 \vee 0.6p_9) \\ & \&(0.4p_1 \vee 0.4p_2 \vee 0.4p_3 \vee 0.4p_4 \vee 0.4p_5 \vee 0.4p_6 \vee 1p_7 \vee 0.4p_8 \vee 0.4p_9) \\ & \&(0.6p_1 \vee 0.6p_2 \vee 0.6p_3 \vee 1p_4 \vee 0.6p_5 \vee 0.6p_6 \vee 0.4p_7 \vee 1p_8 \vee 1p_9) \\ & \&(0.6p_1 \vee 0.6p_2 \vee 0.6p_3 \vee 1p_4 \vee 0.6p_5 \vee 0.6p_6 \vee 0.4p_7 \vee 0.7p_8 \vee 1p_9).\end{aligned}$$

Multiplying the parentheses, we finally obtain:

$$\begin{aligned}\Phi_{\overline{B}} = {} & \underline{0.4p_1} \vee 0.4p_2 \vee 0.4p_3 \vee 0.4p_4 \vee 0.4p_5 \vee 0.4p_6 \vee 0.4p_7 \vee 0.4p_8 \vee 0.4p_9 \\ \vee \quad & \underline{0.6p_1p_7} \vee 0.6p_2p_7 \vee 0.6p_3p_7 \vee 0.6p_4p_7 \vee 0.6p_5p_7 \vee 0.6p_6p_7 \vee 0.6p_7p_8 \vee 0.6p_7p_9 \\ \vee \quad & \underline{0.7p_6p_7p_9} \vee 0.7p_4p_5p_6p_7 \vee 0.7p_4p_6p_7p_8 \vee 0.7p_1p_6p_7p_8 \vee 0.7p_2p_6p_7p_8 \vee 0.7p_5p_6p_7p_8 \\ \vee \quad & 0.9p_2p_3p_4p_6p_7p_9 \vee \underline{1p_2p_3p_4p_5p_6p_7}.\end{aligned}$$

Graph $\widetilde{G}$ has 25 fuzzy antibases, which follows from the last equality, and the antibases fuzzy set is defined as:

$$\widetilde{B}^{-} = \{\langle 0.4/1\rangle, \langle 0.6/2\rangle, \langle 0.7/3\rangle, \langle 1/6\rangle\}.$$

The antibases fuzzy set defines the following optimum allocation of the service centers: if we have 6 service centers, we should place them into vertices 2, 3, 4, 5, 6 and 7 (Cherepanovo, Barnaul, Novokuzneck, Yrga-2, Surzhenka, Kemerovo). The greatest vitality degree equals to 1 in this case. If we have 3 service centers, we should place the centers, for example, into vertices 6, 7 and 9 (Tirgan, Suzhenko, Kemerovo). In this case the degree of service equals to 0.7. If we have 2 service centers, we should place the centers, for example, into vertices 1 and 7 (Inskaya, Kemerovo). In this case the degree of service equals to 0.6. If we have only one service center then we can place it in any vertex (for example, Inskaya). Here, the degree of service equals to 0.4. The antibases fuzzy set also indicates that, for example, there is no need to place 4, or 5 centers. In this case the greatest degree will be the same as in the case of 3 centers.

We now determine the best placement of centers when we place the centers in the vertices which other vertices are acceptable from and then return back (the third strategy). For this we define a vitality fuzzy set.

The corresponding Eq. (18.17) for this graph has the following form:

$$\begin{aligned}\Phi_V = {} & (1p_1 \vee 0.7p_2 \vee 0.6p_3 \vee 0.6p_4 \vee 0.6p_5 \vee 0.6p_6 \vee 0.4p_7 \vee 0.6p_8 \vee 0.6p_9) \\ & \&(0.7p_1 \vee 1p_2 \vee 0.6p_3 \vee 0.6p_4 \vee 0.6p_5 \vee 0.6p_6 \vee 0.4p_7 \vee 0.6p_8 \vee 0.6p_9) \\ & \&(0.6p_1 \vee 0.6p_2 \vee 1p_3 \vee 0.6p_4 \vee 0.6p_5 \vee 0.6p_6 \vee 0.4p_7 \vee 0.6p_8 \vee 0.6p_9) \\ & \&(0.6p_1 \vee 0.6p_2 \vee 0.6p_3 \vee 1p_4 \vee 0.6p_5 \vee 0.6p_6 \vee 0.4p_7 \vee 0.7p_8 \vee 0.7p_9) \\ & \&(0.6p_1 \vee 0.6p_2 \vee 0.6p_3 \vee 0.6p_4 \vee 1p_5 \vee 0.6p_6 \vee 0.4p_7 \vee 0.6p_8 \vee 0.6p_9) \\ & \&(0.6p_1 \vee 0.6p_2 \vee 0.6p_3 \vee 0.6p_4 \vee 0.6p_5 \vee 1p_6 \vee 0.4p_7 \vee 0.6p_8 \vee 0.6p_9) \\ & \&(0.4p_1 \vee 0.4p_2 \vee 0.4p_3 \vee 0.4p_4 \vee 0.4p_5 \vee 0.4p_6 \vee 1p_7 \vee 0.4p_8 \vee 0.4p_9) \\ & \&(0.6p_1 \vee 0.6p_2 \vee 0.6p_3 \vee 0.7p_4 \vee 0.6p_5 \vee 0.6p_6 \vee 0.4p_7 \vee 1p_8 \vee 0.7p_9) \\ & \&(0.6p_1 \vee 0.6p_2 \vee 0.6p_3 \vee 0.7p_4 \vee 0.6p_5 \vee 0.6p_6 \vee 0.4p_7 \vee 0.7p_8 \vee 1p_9).\end{aligned}$$

Multiplying the parentheses, we finally obtain:

$$\begin{aligned}\Phi_B = {} & \underline{0.4p_1} \vee 0.4p_2 \vee 0.4p_3 \vee 0.4p_4 \vee 0.4p_5 \vee 0.4p_6 \vee 0.4p_7 \vee 0.4p_8 \vee 0.4p_9 \\ \vee \quad & \underline{0.6p_1p_7} \vee 0.6p_2p_7 \vee 0.6p_3p_7 \vee 0.6p_4p_7 \vee 0.6p_5p_7 \vee 0.6p_6p_7 \vee 0.6p_7p_8 \vee 0.6p_8p_9 \\ \vee \quad & \underline{0.7p_1p_3p_4p_5p_6p_7} \vee 0.7p_1p_3p_6p_6p_7p_8 \vee 0.7p_1p_3p_5p_6p_7p_9 \vee 0.7p_2p_3p_4p_5p_6p_7 \\ \vee \quad & 0.7p_2p_3p_5p_6p_7p_8 \vee 0.7p_2p_3p_5p_6p_7p_9 \vee \underline{1p_1p_2p_3p_4p_5p_6p_7p_8p_9}.\end{aligned}$$

Graph $\widetilde{G}$ has 24 subsets of vertices with the greatest vitality degree, which follows from the last equality, and the vitality fuzzy set is defined as:

$$\widetilde{V} = \{\langle 0.4/1\rangle, \langle 0.6/2\rangle, \langle 0.7/6\rangle, \langle 1/9\rangle\}.$$

The vitality fuzzy set defines the following optimum allocation of the service centers: if we have 9 service centers, we should place them into all vertices. The greatest vitality degree equals 1. If we have 6 service centers, we should place them, for example, into vertices 1, 3, 4, 5, 6 and 7 (Inskaya, Barnaul, Novokuzneck, Yrga-2, Surzhenka, Kemerovo). The greatest vitality degree equals 0.7 in this case. If we have 2 service centers, we should place the centers, for example, into vertices 1 and 7 (Inskaya, Kemerovo). In this case the degree of service equals 0.6. If we have only one service center, then we can place it in any vertex (for example, Inskaya). Here, the degree of service equals 0.4. The fuzzy set of vitality also indicates that, for example, there is no need to place 3, 4, or 5 centers. In this case the greatest vitality degree will be the same as in the case of 2 centers.

18.7 Conclusion

The task of defining of the optimum allocation of centers was considered as the task of the definition of antibases fuzzy set, bases fuzzy set, and vitality fuzzy set of fuzzy graph. It should be noted that the introduced method makes it possible to define the best service allocations only if the centers are placed in the vertices of a graph (the case of generating new vertices on the edges is not considered). In our future work we are going to examine the problem of the centers allocation in the temporal fuzzy graphs, i.e. the graphs, edges membership functions of which change in discrete time. The task of selection of the best locations for service centers is relevant in sustainable transportation networks and has important practical value, as the optimal allocation of the centers allows reducing the cost of the fuel and electricity, which will have a positive impact on the ecology. The potential application benefit of the proposed method is that it allows to locate centers more optimal on the models, represented as fuzzy graphs, taking into account fuzzy information.

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References

Belyakov, S. L., Bozhenyuk, A. V., Belykova, M. L., & Rozenberg, I. N. (2014). Model of intellectual visualization of geoinformation service. In 28th European Conference on Modelling and Simulation ECMS 2014 (pp. 326–332). Brescia.

Bershtein, L. S., & Bozhenuk, A. V. (2008). Fuzzy graphs and fuzzy hypergraphs. In J. Dopico, J. de la Calle, & A. Sierra (Eds.), *Encyclopedia of artificial intelligence, information SCI* (pp. 704–709). New York: Hershey.

Bershtein, L. S., & Bozhenyuk, A. V. (2001). Maghout method for determination of fuzzy independent, dominating vertex sets and fuzzy graph kernels. *Journal of General Systems, 30*, 45–52.

Bershtein, L., Bozhenyuk, A., & Knyazeva, M. (2015). Definition of cliques fuzzy set and estimation of fuzzy graphs isomorphism. *Procedia Computer Science*, *77*, 3–10. doi:10.1016/j.procs.2015.12.353.

Bershtein, L. S., Bozhenyuk, A. V., & Rozenberg, I. N. (2011). Service centers finding by fuzzy antibases of fuzzy graph. In the International Workshop on Soft Computing Applications and Knowledge Discovery (SCAKD 2011) (pp. 12–2), 2011, June 25. Moscow, Russia.

Bershtein, L. S., Bozhenyuk, A. V., & Rozenberg, I. N. (2013). Optimum allocation of centers in transportation networks by means of fuzzy graph bases. In G. Pasi, J. Montero, & D. Ciucci (Eds.), *8th conference of the European Society for Fuzzy Logic and Technology (EUSFLAT-13). Advances in Intelligent Systems Research* (pp. 230–235), 2013, September 11–13. Atlantis Press.

Bozheniuk, V. A., Bozhenyuk, A. V., & Belyakov, S. L. (2015). Optimum allocation of centers in fuzzy transportation networks with the largest vitality degree. In *2015 Conference of the International Fuzzy System Association and the European Society for Fuzzy Logic and Technology* (pp. 1006–1011). Atlantis Press.

Bozhenyuk, A., Gerasimenko, E., & Rozenberg, I. (2015). Determining the minimum cost flow in fuzzy dynamic network with GIS «ObjectLand». In *Proceedings of 9th International Conference on Application of Information and Communication Technologies*, *AICT 2015* (pp. 294–298). Rostov on Don, Russia. doi:10.1109/ICAICT.2015.7338566.

Bozhenyuk, A. V., & Rozenberg, I. N. (2012). Allocation of service centers in the GIS with the largest vitality degree. In S. Greco, et al. (Eds.), *IPMU 2012, Part II, communications in computer and information science CCIS* (Vol. 298, pp. 98–106). Berlin Heidelberg: Springer.

Christofides, N. (1976). *Graph theory. An algorithmic approach*. London: Academic press.

Clarke, K. (1995). *Analytical and computer cartography*. Englewood Cliffs, N.J.: Prentice Hall.

Goodchild, M. (1989). Modelling error in objects and fields. In M. Goodchild & S. Gopal (Eds.), *Accuracy of spatial databases* (pp. 107–113). Basingstoke: Taylor & Francis, Inc.

Kaufmann, A. (1977). *Introduction a la theorie des sous-ensemles flous*. Paris: Masson.

Longley, P., Goodchild, M., Maguire, D., & Rhind, D. (2001). *Geographic information systems and science*. New York: Wiley.

Malczewski, J. (1999). *GIS and multicriteria decision analysis*. New York: Willey.

Monderson, J. N., & Nair, P. S. (2000). *Fuzzy graphs and fuzzy hypergraphs*. Heidelberg, New-York: Physica-Verl.

Nagurney, A. (2000). *Sustainable transportation networks*. Edward Elgar Publishers.

Rani, M., & Dharmalingam, K. M. (2016). Equitable associate fuzzy graph of a fuzzy graph. *Journal of Mathematics and Computer Science, 1*, 1–7.

Rozenberg, I. N., Gittis, C. A., & Svyatov, D. C. (2000). Geoinformation system object land. In *Proceedings of IPI RAN "Systems and Means of Informatics", Science*. Moscow.

Sharma, S., & Mathew, T. V. (2011). Multiobjective network design for emission and travel-time trade-off for a sustainable large urban transportation network. *Environment and Planning B: Planning and Design, 38*, 520–538.

Zhang, J., & Goodchild, M. (2002). *Uncertainty in geographical information*. New York: Taylor & Francis Inc.

Chapter 19
Intelligent Control of Traffic Flows for Sustainable Transportation Networks

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Abstract The following chapter deals with the problems of the sustainable transportation network from the geographic information systems for intelligent control. For this we developed the dynamic geoinformation model with temporal dependence of the parameters and the procedural model of routing with temporal dependence and fuzzy given distance and time. The tasks of routing problem with fuzzy conditions are described and solved.

19.1 Introduction

One of the key properties of sustainable transport networks is their ability to maintain the effectiveness in the present and in the future (Nagurney 2000). Explicitly or implicitly, the time factor presents in all the procedures and methods of design and implementation of the transport networks. The infrastructure and the components must shoulder a certain part of the responsibility for getting the necessary values of sustainability such as the environmental impact, the power consumption, the accidents and the quality of service. This responsibility should be realized for a long time in an ever-changing real world. Environmental dynamics affects the properties of the transport networks significantly. These transportation networks are the part of the same environment since they appear. It turns out that the final effect of the use of complex transport systems depends on the state of the environment, the transport network and the traffic flow generated by the movement

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of material objects in the network. Any sustainable transport system has to be continually adapted to the environment. Structure of the transport network and behavior of the traffic flow are the parameters of adaptation (Bozhenyuk et al. 2015a). Parameters are used in circuit of adaptation in different ways (Timmer et al. 2015). However, in any case, these two parameters are important in getting more sustainability.

In this work, we consider the approach to the intelligent management of the adaptation process. This approach is based on the use of geoinformation systems. As we know, geoinformation systems use cartographic representation of the real world and have a developed system for modeling processes and events. Therefore, it seems reasonable to develop methods that support these mechanisms in conditions of partial uncertainty and lack of information. The intelligent methods are methods that are based on knowledge, compensating incompleteness, uncertainty and lack of information. For this we do the following:

- introducing a formally dynamic GIS model and separating its temporal components. These components define the sustainable transport system;
- developing a fuzzy routing methods for temporal networks. Geoinformation system includes software tools for these methods and GIS is able to simulate the process of routing, using the knowledge.

19.2 Description of the Dynamic Geoinformation Model of Transport Systems

Geoinformation model of transport systems is the information model for a cartographic representation of components (Dodge et al. 2011; Mackaness et al. 2011) and relations in transport systems (Bozhenyuk et al. 2015b).

Dynamic geoinformation model is created for information support of transportation systems (Bulavatsky and Krivonos 2012). The model describes the information object, allowing solving problems of analysis and synthesis of transport systems (Scheider et al. 2016). The model includes four elements:

$$W_D = \langle M, \Omega, R, Q \rangle, \tag{19.1}$$

where M is the representation of the transport system as a logistics network;

Ω is a set of map objects and spatial relationships of cartographic database of geoinformation system;

R is a binding logistics network to the cartographic basis, i.e.

$$\mathrm{M} \times \Omega \rightarrow \mathrm{R}, \tag{19.2}$$

$Q = \{Q_P, Q_T, Q_R, Q_M\}$ is a set of estimation procedures for the quality of transport system, including the costs for the planned movements Q_P; the time for the planned movements Q_T; the risk at the planned movements Q_R; and the costs of the transport system modification Q_M due to a change of the environmental conditions.

All these procedures are functionally depending on the parameters of cartographic objects and relationships. Parameters of any object or relation depending on time and are divided into three groups:

$$\omega_i(\bar{X}(t), \bar{T}, \bar{A}(t)) \in \Omega, \quad i = \overline{1, n}, \tag{19.3}$$

where ω_i is cartographic object or relation; $\bar{X}(t)$ are parameters of georeferencing; $\bar{T}$ are timing parameters; $\bar{A}(t)$ are semantic attributes.

Therefore, the expression

$$Q = F(\bar{X}(t), \bar{T}, \bar{A}(t)) \tag{19.4}$$

determines the completeness of the proposed model. Completeness is viewed as an opportunity to simulate the four situation in the transport systems, such as:

1. provide the minimum of costs when moving a target date (Q_T^*), the required level of risk (Q_R^*) and limiting potential losses (Q_M^*):

$$\underset{Q_T < Q_T^*, Q_R < Q_R^*, Q_M < Q_M^*}{Q_P \to min}. \tag{19.5}$$

2. achieve an operational work of the transport system with limited resources (Q_P^*), observing the limits of risk (Q_R^*) and the possible losses (Q_M^*):

$$\underset{Q_P < Q_P^*, Q_R < Q_R^*, Q_M < Q_M^*}{Q_T \to min}. \tag{19.6}$$

3. implement a reliable transport system with limited resources, a given level of risk and the possible losses:

$$\underset{Q_P < Q_P^*, Q_T < Q_T^*, Q_M < Q_M^*}{Q_R \to min}. \tag{19.7}$$

4. make the transportation system stability with the available resources, the given level of risk and temporal boundaries of movement:

$$\underset{Q_P < Q_P^*, Q_T < Q_T^*, Q_R < Q_R^*}{Q_M \to min}. \tag{19.8}$$

Let us describe the logistical network of the transport system as follows:

$$\mathrm{M} = \langle \mathrm{A}, \mathrm{B}, \mathit{\Lambda}, \mathit{\Gamma}, \mathrm{T} \rangle, \tag{19.9}$$

where $\mathrm{A} = \left\{\mathrm{A}_i, \Lambda^i, \mathrm{O}_i, \tau_i^A\right\}, i = \overline{1,n}$ is a set of nodes of material flow transformation. These nodes perform a variety of logistics operations without transactions cannot be transported.

$\{\mathrm{A}_i\}, i = \overline{1,n}$ is a node of material flow transformations.

$\Lambda^i = \left\{\Lambda_j^i\right\} \neq \emptyset, i = \overline{1,n}, j = \overline{1,m}$ is a subset of logistics operations in A_i. Each node has a minimum of one logistics operation. There may be several logistics operations in one node of material flow transformation. It means there are any logistics operations, which are made above the material flow in the node, and that the operations can be different. For example, in one node can perform next operations: product packaging and temporary placement of product in warehouse.

The same logistics operation can be performed several times in the same node:

$$\Lambda_j^i = \Lambda_{j+1}^i. \tag{19.10}$$

$\{\Lambda^i\} \subset \Lambda$ is a subset of node logistics operations and always included in the set of logistics operations.

$\{\mathrm{O}_i\}, \overline{1,n}$ are the properties of the material flow in the node A_i. These properties will change after operations.

$\left\{\tau_i^A\right\}, i = \overline{1,n}$ is the total time required to perform all subsets of logistics operations in the node A_i.

$\mathrm{B} = \left\{\mathrm{B}_{uv}, \mathrm{P}_{uv}, \Pi_{uv}, \tau_{uv}^R\right\}, u = \overline{1,n}, v = \overline{1,n}$ is a set of edges between the nodes of material flow transformation. Each edge is a segment of the transport network. The segment can be an independent network. Any routing algorithm is realized on the segment. The algorithm can be different from the algorithm used for the whole transport network.

$\{\mathrm{B}_{uv}\}, u = \overline{1,n}, v = \overline{1,n}$ is the edge between the nodes of material flow transformation, where u, v are final nodes of the edge from the set $\{\mathrm{A}_i\}$. Final nodes of the edge may not be the same.

$$u = \mathrm{A}_u, v = \mathrm{A}_v;\ \mathrm{A}_u, \mathrm{A}_v \in \mathrm{A}_i;\ \mathrm{A}_u \neq \mathrm{A}_v \tag{19.11}$$

$\{\mathrm{P}_{uv}\}, u = \overline{1,n}, v = \overline{1,n}$ is the distance between the nodes of transformation material flow.

$\{\Pi_{uv}\}, u = \overline{1,n}, v = \overline{1,n}$ is the network capacity between nodes of material flow transformation.

$\{\tau_{uv}^R\}, u = \overline{1,n}, v = \overline{1,n}$ is the transportation time in the edge B_{uv}.

$\Lambda = \left\{\Lambda_j\right\}, j = \overline{1,m}$ is a set of logistics operations used in a dynamic geoinformation model.

$T = \{T_k\}, k = \overline{0, l}$ are stable intervals of the edges weights:

$$T_k \cap T_{k+1} = \emptyset, \quad k = \overline{0, l-1}. \tag{19.12}$$

$\Gamma = \left\{\Gamma^s, \widetilde{\Gamma}^t\right\}$ is a set of spatial objects of the geoinformation model.

$\{\Gamma^s\}$ is a subset of static spatial objects that do not depend on time.

$\{\widetilde{\Gamma}^t\}$ is a subset of dynamic spatial objects, i.e. objects change their attributes in time:

$$\Gamma^s \cap \widetilde{\Gamma}^t = \emptyset. \tag{19.13}$$

Analyzing the proposed model it is necessary to note the following:

1. information components of the model M, Ω and R determine the implementation complexity of the geographic information systems for specific transport systems. These components represent the temporal dependence of logistics operations on the environment. The degree of incompleteness and uncertainty of parameters determines the result quality of geoinformation modeling directly;
2. the procedural component of the model Q is focused on the evaluation of the network structure parameters. This evaluation occurs during the binding component M to map Ω;
3. component procedures Q lead to solving the problem of routing in temporal networks, as the component M describes the movement of single material objects or material flows;
4. component procedures Q compensate incompleteness, uncertainty and fuzziness for the description of parameters M, Ω, and R. The fuzziness exists in the actual operating conditions of transport systems.

19.3 Development of Routing Procedural Model Under Given Fuzzy Distance with Temporal Dependence

The aim of this section is to develop procedural models of routing taking the temporal dependencies under fuzzy given distance into account. Development of the model taking the fuzzy given distance is relevant, as is still being upgraded maps and update or change the settings on the map into account (Dodge et al. 2016).

This model is necessary to solve the following problem. To find the shortest path L from the initial point s to the final point r, using time parameter:

$$L^* = \min_t \min_{w(t)} \{ (\tilde{w}(t)/\langle s, x_i \rangle), \left(\tilde{w}(t)/\langle x_i, x_j \rangle\right), \left(\tilde{w}(t)\langle x_j, r \rangle\right) \}, \tag{19.14}$$

where $\tilde{w}(t)$ is the distance between destinations.

There are arcs which are absent in a period of time ("absence of arcs" means that the arc lengths at the relevant point in time tends to infinity). Arcs are fuzzy values. Time is a discrete value, a period transit time in each arc is equal to 1. The time period T_j, where $j = \overline{0, m}$, is the time interval that given by the user. The user determines the number of time periods determined by the set:

$$T = \{T_0, T_1, \ldots, T_m\} = \{T_{j_s}, T_j, T_{j_r}\}, \tag{19.15}$$

where $\{T_{j_s}\}, j_s = \overline{0, m-1}$ is the departure time from the initial point;

$\{T_j\}, j = \overline{1, m-1}$ is the movement time without taking the time of departure and arrival into account; $\{T_{j_r}\}, j_r = \overline{1, m}$ is the arrival time at the destination.

It is necessary to find the shortest path from the initial to the final point. The arcs lengths are fuzzy defined, so they are represented as fuzzy numbers.

This problem is solved by using the apparatus of graph theory (Berstein and Bozhenyuk 2010). The difficulty in solving this problem is the ambiguity of arcs lengths of the transport network, edges depend on the time period, and the distances represented as fuzzy numbers. Therefore, to solve this problem it is rationally use fuzzy temporal graph (Berstein and Bozhenyuk 2005).

We shall say that the fuzzy temporal graph is a triple $\widetilde{G} = (X, \widetilde{U}_t, T)$, where X is set of vertices with number of vertices $|X| = \mathrm{n}, \mathrm{T} = \{1, 2, \ldots, \mathrm{N}\}$ is set of natural numbers determining (discrete) time, $U_t = \{\langle \mu_t(x_i, x_j) | (x_i, x_j) \rangle\}$ is fuzzy set of edges, where $x_i, x_j \in X, \mu_t(x_i, x_j) \in [0, 1]$ is value of the membership function μ_t for the edge (x_i, x_j) at time $t \in T$. At different periods of time for the same edge (x_i, x_j) values of the membership functions (generally) is different (Berstein and Bozhenyuk 2005; Kostakos 2008).

The vertex x_j is fuzzy adjacent to vertex x_i on the moment of time $t \in T$ if the condition $\mu_t(x_i, x_j) > 0$ is satisfied (Bozhenyuk et al. 2012).

Solution to this problem involves consideration of three situations. Depending on these situations the following procedural models were developed.

A1. Procedural routing model with temporal dependence and given starting time.
A2. Procedural routing model with temporal dependence and given time of arrival.
A3. Procedural model routing with temporal dependence and given time interval of movement.

19.3.1 Situation A1

Step 1. It is assumed that the original fuzzy temporal graph does not depend on the time at the initial stage, i.e. the arcs exist at any moment of time. We find the shortest path L^* for this graph. Before starting all vertices and arcs are not painted (It uses the notion of painting vertices that means that all the vertices processed and marked with the same color) (Minieka 1981; Savelyeva and Belyakov 2015).

Step 2. Each vertex is assigned a fuzzy number $\tilde{d}(x_i)$. This number $\tilde{d}(x_i)$ is equal to the length of the shortest path from s to x_i, this path includes only the painted vertices.

Put $\tilde{d}(s) = 0$ and $\tilde{d}(x_i) = \infty$ for all the $x_i \neq$ s. Paint the vertex s and put $y = s$ (y is the last of the colored vertices).

Step 3. Each unpainted vertex x_i follows to calculate the value $\tilde{d}(x_i)$:

$$\tilde{d}(x_i) = \min\{\tilde{d}(x_i), \tilde{d}(y) + \tilde{d}(y, x_i)\}, \tag{19.16}$$

where $\tilde{a}(y, x_i)$ is length of edge (y, x_i).

Comparison of the fuzzy number values is done by Index centroid of fuzzy number.

If $\tilde{d}(x_i) = \infty$ for all unpainted vertices x_i then finish the procedure of the algorithm and assume that there are no paths from s to unpainted vertices in the original graph. Otherwise, paint the vertex x_i for which the value $\tilde{d}(x_i)$ is the lowest. In addition, paint the arc, which leads to the selected at this step vertex x_i [minimum is reached for the arc according to the expression (19.16)]. Put $y = x_i$.

Step 4. If $y = r$, then finish the procedure. The shortest path L^* from vertex s into r without time parameter is found (it is the only path from s to r, which is composed of colored arcs). Otherwise, go to step 3.

Step 5. Go to search the shortest path in the fuzzy temporal graph in which there are no arcs at certain time periods. Do this requires step by step to build a graph presenting it in a static form. Construct the shortest path L^* obtained in Step 4, which begins in the time period $\{T_{j_s}\}, j_s = \overline{0, m-1}$, where m is defined by the user. When constructing arcs are checked for their existence. If the arc exists, it is necessary to increase $\{T_j\}, j = \overline{0, m}$ by the time unit because the time period of movement along the arc equals 1. If the arc is not available at a given moment then stop testing and go to step 6.

Step 6. The initial vertex s belongs to the period of time $\{T_{j_s}\}, j_s = \overline{0, m-1}$. As described in Step 3, find new value $\tilde{d}(x_i)$ by (19.16) and check the existence of arc (y, x_i). If the arc (y, x_i) exists, paint the vertex x_i, increase $T_{j_s} = T_j$ by 1, and accept $x_i = y$. If the arc is absent in a given time period, then this arc is not considered and selected other minimum vertex. If other arcs don't exist, then starting period j_s is increased by 1 and go to step 5.

Step 7. If $y = r$, finish the procedure, then the shortest path L^* from the vertex s to r is found. Otherwise, go to step 6.

Step 8. Make defuzzification for the found values of the shortest routes (Zimmermann 1996).

Step 9. Check all shortest paths from the set $L = \{L_1, L_2, \ldots, L_n\}$, which have the time of departure equal to $T^*_{j_s}$. From the given set of the shortest routes choose minimum route after defuzzification, i.e.:

$$L^* = \min\{L_1, L_2, \ldots, L_n\}. \tag{19.17}$$

Step 10. If several equal routes exist, then:

$$\begin{cases} L_1\left(T^*_{j_s}\right) = L_2\left(T^*_{j_s}\right) = \ldots = L_n\left(T^*_{j_s}\right) \\ t_{\min} = \min\{t\left(L_1\left(T^*_{j_s}\right)\right), t\left(L_2\left(T^*_{j_s}\right)\right), \ldots, t\left(L_n\left(T^*_{j_s}\right)\right)\} \end{cases} = > L^*(t_{\min}), \tag{19.18}$$

where $t = T_{j_r} - T_{j_s}$ is the movement time along the route from the initial point to the destination point. Necessary path L^* is found.

19.3.2 Situation A2

Steps 1–7. Coincide with the situation A1.
Step 8. Compare the start time T_{j_s} with user-defined time of arrival at destination $T^*_{j_r}$. If $T_{j_s} = T^*_{j_r}$, then finish the search of the route and go to Step 9. If $T_{j_s} < T^*_{j_r}$, increase the start period T_{j_s} by one unit and go to Step 5. If $T_{j_s} > T^*_{j_r}$, the shortest path does not exist in the given initial period of time.
Step 9. Make defuzzification for the found values of the shortest routes (Zimmermann 1996).
Step 10. Check all shortest paths from the set $L = \{L_1, L_2, \ldots, L_n\}$, which have the time of arrival equals $T^*_{j_r}$. From the given set of the shortest routes choose minimum route after defuzzification, i.e.:

$$L^* = \min\{L_1, L_2, \ldots, L_n\}. \tag{19.19}$$

Step 11. If several equal routes exist, then:

$$\begin{cases} L_1\left(T^*_{j_r}\right) = L_2\left(T^*_{j_r}\right) = \ldots = L_n\left(T^*_{j_r}\right) \\ t_{min} = \min\{t\left(L_1\left(T^*_{j_r}\right)\right), t\left(L_2\left(T^*_{j_r}\right)\right), \ldots, t\left(L_n\left(T^*_{j_r}\right)\right)\} \end{cases} = > L^*(t_{\min}), \tag{19.20}$$

where $t = T_{j_r} - T_{j_s}$ is the movement time along the route from the initial point to the final point. Necessary path L^* is found.

19.3.3 Situation A3

Steps 1–7. Coincide with the situation A1.
Step 8. Calculate the time of the found path t as:

$$t = T_{j_r} - T_{j_s}. \tag{19.21}$$

Step 9. If $t^* < t$ (t^* is given by user time of the movement along the route), then go to step 10. If $t^* \geq t$, then stop path searching and go to step 11.
Step 10. We increase by 1. Go to Step 5.
Step 11. Make defuzzification for the found values of the shortest routes (Zimmermann 1996). We obtain the desired route with the defined conditions.
Step 12. If several routes, which satisfy this condition, exist, then:

$$\begin{cases} L_1 = L_2 = \cdots = L_n \\ t_{\min} = \min\{t(L_1), t(L_2), \ldots, t(L_n)\} \end{cases} = \; > L^*(t_{\min}). \tag{19.22}$$

L^* is desired route with given conditions.

Now made the asymptotic performance evaluation of the developed procedural model:

$$\mathrm{O}\big((k+1)\big(n^2 + m\big) + (t-k)n\big), \tag{19.23}$$

where n is the number of vertices; m is the number of the arcs; t is the number of the time periods, k is the number of the time periods when there exist all arcs on the shortest path.

19.4 Example of the Routing Procedural Model Under Fuzzy Given Distance with Temporal Dependence

The aim of this section is to present the work of developed routing procedural model with temporal dependence and fuzzy given distance.

Find the shortest route for the given parameters of the initial vertex 1 to the final vertex 10. The arcs of the graph have a length represented by fuzzy number. The arc length is the distance. The square brackets are time periods when the arc does not exist or its capacity is almost equal to 0.

Figure 19.1 shows the original graph.

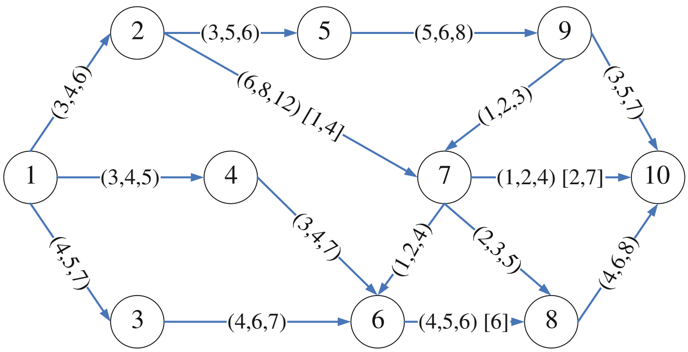


Fig. 19.1 Example of the problem. The original graph illustrating the problem under fuzzy given parameters of the distance

19.4.1 Situation A1. Define the Time of Departure of the Material Flow $T_{j_s} = 0$.

First, find the shortest path for the original graph without time parameter.

Fuzzy shortest path L^* is calculated as follows:

$$\tilde{d}(1) = (0,0,0). \tag{19.24}$$

$$\begin{aligned}\tilde{d}(2) &= \min\{\tilde{d}(2), \tilde{d}(1) + \tilde{a}(1,2)\} = \min\{(\infty,\infty,\infty); (0,0,0) + (3,4,6)\} \\ &= \min\{(\infty,\infty,\infty); (3,4,6)\} = (3,4,6) = > Q_2 = \{1,2\}.\end{aligned} \tag{19.25}$$

$$\begin{aligned}\tilde{d}(3) &= \min\{\tilde{d}(3), \tilde{d}(1) + \tilde{d}(1,3)\} = \min\{(\infty,\infty,\infty); (0,0,0) + (4,5,7)\} \\ &= \min\{(\infty,\infty,\infty); (4,5,7)\} = (4,5,7) = > Q_3 = \{1,3\}.\end{aligned} \tag{19.26}$$

$$\begin{aligned}\tilde{d}(4) &= \min\{\tilde{d}(4), \tilde{d}(1) + \tilde{a}(1,4)\} = \min\{(\infty,\infty,\infty); (0,0,0) + (3,4,5)\} \\ &= \min\{(\infty,\infty,\infty); (3,4,5)\} = (3,4,5) = > Q_4 = \{1,4\}.\end{aligned} \tag{19.27}$$

$$\begin{aligned}\tilde{d}(5) &= \min\{\tilde{d}(5), \tilde{d}(2) + \tilde{a}(2,5)\} = \min\{(\infty,\infty,\infty); (3,4,6) + (3,5,6)\} \\ &= \min\{(\infty,\infty,\infty); (6,9,12)\} = (6,9,12) = > Q_5 = \{1,2,5\}.\end{aligned} \tag{19.28}$$

$$\begin{aligned}\tilde{d}(6) &= \min\{\tilde{d}(6), \tilde{d}(3) + \tilde{a}(3,6), \tilde{d}(4) + \tilde{a}(4,6), \tilde{d}(7) + \tilde{a}(7,6)\} \\ &= \min\{(\infty,\infty,\infty); (4,5,7) + (4,6,7); (3,4,5) + (3,4,7); (\infty,\infty,\infty) + (1,2,4)\} \\ &= \min\{(\infty,\infty,\infty); (8,11,14); (6,8,12); (\infty,\infty,\infty)\} = (6,8,12)(\mathit{tentative}) \\ &= > Q_6 = \{1,4,6\}.\end{aligned} \tag{19.29}$$

$$\begin{aligned}\tilde{d}(7) &= \min\{\tilde{d}(7), \tilde{d}(2) + \tilde{a}(2,7), \tilde{d}(9) + \tilde{a}(9,7)\} \\ &= \min\{(\infty,\infty,\infty); (3,4,6) + (6,8,12); (\infty,\infty,\infty) + (1,2,3)\} \\ &= \min\{(\infty,\infty,\infty); (9,12,18); (\infty,\infty,\infty)\} = (9,12,18)(\mathit{tentative}) \\ &=> Q_7 = \{1,2,7\}.\end{aligned} \tag{19.30}$$

$$\begin{aligned}\tilde{d}(9) &= \min\{\tilde{d}(9), \tilde{d}(5) + \tilde{a}(5,9)\} = \min\{(\infty,\infty,\infty); (6,9,12) + (5,6,8)\} \\ &= \min\{(\infty,\infty,\infty); (11,15,20)\} = (11,15,20) => Q_9 = \{1,2,5,9\}.\end{aligned} \tag{19.31}$$

$$\begin{aligned}\tilde{d}(7) &= \min\{\tilde{d}(7), \tilde{d}(9) + \tilde{a}(9,7)\} = \min\{(9,12,18); (11,15,20) + (1,2,3)\} \\ &= \min\{(9,12,18); (12,17,23)\} = (9,12,18) => Q_7 = \{1,2,7\}.\end{aligned} \tag{19.32}$$

$$\begin{aligned}\tilde{d}(6) &= \min\{\tilde{d}(6), \tilde{d}(7) + \tilde{a}(7,6)\} = \min\{(6,8,12); (9,12,18) + (1,2,4)\} \\ &= \min\{(6,8,12); (10,14,22)\} = (6,8,12) => Q_6 = \{1,4,6\}.\end{aligned} \tag{19.33}$$

$$\begin{aligned}\tilde{d}(8) &= \min\{\tilde{d}(8), \tilde{d}(6) + \tilde{a}(6,8), \tilde{d}(7) + \tilde{a}(7,8)\} \\ &= \min\{(\infty,\infty,\infty); (6,8,12) + (4,5,6); (9,12,18) + (2,3,5)\} \\ &= \min\{(\infty,\infty,\infty); (10,13,18); (11,15,23)\} = (10,13,18) \\ &=> Q_8 = \{1,4,6,8\}.\end{aligned} \tag{19.34}$$

$$\begin{aligned}\tilde{d}(10) &= \min\{\tilde{d}(10), \tilde{d}(7) + \tilde{a}(7,10), \tilde{d}(8) + \tilde{a}(8,10), \tilde{d}(9) + \tilde{a}(9,10)\} \\ &= \min\{(\infty,\infty,\infty); (9,12,18) + (1,2,4); (10,13,18) + (4,6,8); (11,15,20) + (3,5,7)\} \\ &= \min\{(\infty,\infty,\infty); (10,14,22); (14,19,26); (14,20,27)\} = (10,14,22) \\ &=> Q_{10} = \{1,2,7,10\}.\end{aligned} \tag{19.35}$$

Therefore, the shortest path graph is $L^* = \{1,2,7,10\} = (10,14,22)$. Now, go to the search of solution, using the temporal dependence.

We build the route L^* (Fig. 19.2), checking each arc step by step. The arc (1,2) is $\tilde{a}(1,2) = (3,4,6), T_0(1,2) \neq \emptyset$. Hence, go to checking the next arc. The arc (2,7) is $\tilde{a}(2,7) = (6,8,12), T_1(2,7) = \emptyset$.

This path is shown in red in Fig. 19.2 Because arc (2.7) cannot be used in the construction of the optimal route in the time period $T_j = 1$, then go to the next step.

Again, the route search is performed by (19.16) taking into account the absence of arc in the time period $T_j = 1$ as follows:

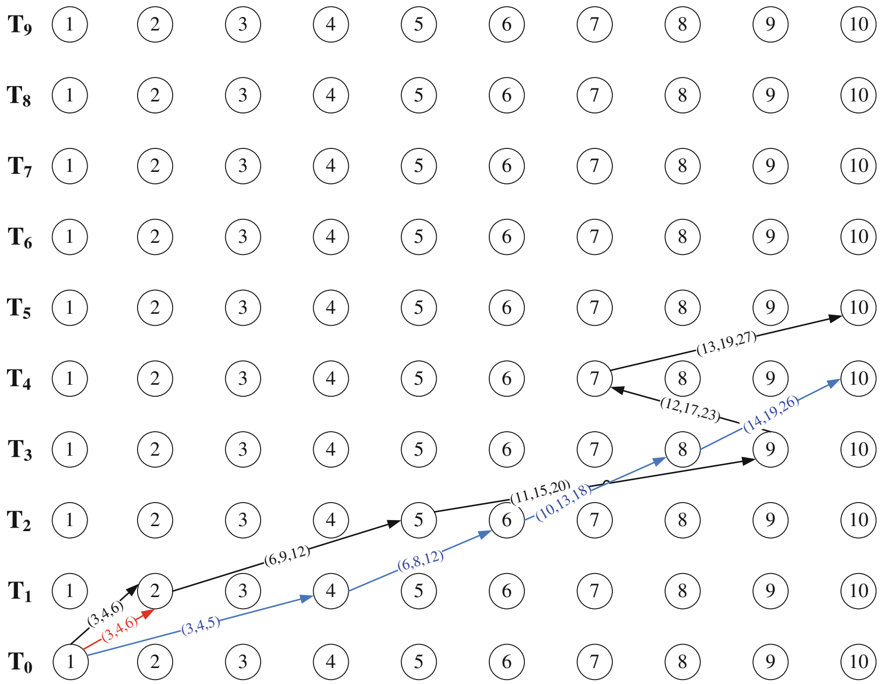


Fig. 19.2 Illustration of solving the problem for the situation A1

$$\tilde{d}(1) = (0, 0, 0). \tag{19.36}$$

$$\begin{aligned}\tilde{d}(2) &= \min\{\tilde{d}(2), \tilde{d}(1) + \tilde{a}(1,2)\} = \min\{(\infty,\infty,\infty); (0,0,0) + (3,4,6)\} \\ &= \min\{(\infty,\infty,\infty); (3,4,6)\} = (3,4,6) = > Q_2 = \{1,2\}.\end{aligned} \tag{19.37}$$

$$\begin{aligned}\tilde{d}(3) &= \min\{\tilde{d}(3), \tilde{d}(1) + \tilde{a}(1,3)\} = \min\{(\infty,\infty,\infty); (0,0,0) + (4,5,7)\} \\ &= \min\{(\infty,\infty,\infty); (4,5,7)\} = (4,5,7) = > Q_3 = \{1,3\}.\end{aligned} \tag{19.38}$$

$$\begin{aligned}\tilde{d}(4) &= \min\{\tilde{d}(4), \tilde{d}(1) + \tilde{a}(1,4)\} = \min\{(\infty,\infty,\infty); (0,0,0) + (3,4,5)\} \\ &= \min\{(\infty,\infty,\infty); (3,4,5)\} = (3,4,5) = > Q_4 = \{1,4\}.\end{aligned} \tag{19.39}$$

$$\begin{aligned}\tilde{d}(5) &= \min\{\tilde{d}(5), \tilde{d}(2) + \tilde{a}(2,5)\} = \min\{(\infty,\infty,\infty); (3,4,6) + (3,5,6)\} \\ &= \min\{(\infty,\infty,\infty); (6,9,12)\} = (6,9,12) = > Q_5 = \{1,2,5\}.\end{aligned} \tag{19.40}$$

$$\begin{aligned}\tilde{d}(6) &= \min\{\tilde{d}(6), \tilde{d}(3) + \tilde{a}(3,6), \tilde{d}(4) + \tilde{a}(4,6), \tilde{d}(7) + \tilde{a}(7,6)\} \\ &= \min\{(\infty,\infty,\infty); (4,5,7) + (4,6,7); (3,4,5) + (3,4,7); (\infty,\infty,\infty) + (1,2,4)\} \\ &= \min\{(\infty,\infty,\infty); (8,11,14); (6,8,12); (\infty,\infty,\infty)\} \\ &= (6,8,12)(\mathit{tentative}) = \; > \; Q_6 = \{1,4,6\}.\end{aligned} \tag{19.41}$$

$$\begin{aligned}\tilde{d}(7) &= \min\{\tilde{d}(7), \tilde{d}(2) + \tilde{a}(2,7), \tilde{d}(9) + \tilde{a}(9,7)\} \\ &= \min\{(\infty,\infty,\infty); (3,4,6) + \emptyset; (\infty,\infty,\infty) + (1,2,3)\} \\ &= \min\{(\infty,\infty,\infty); \emptyset; (\infty,\infty,\infty)\} \\ &= (\infty,\infty,\infty)(\mathit{tentative}) = \; > \; Q_7 = \{\mathit{path\ is\ not\ defined}\}.\end{aligned} \tag{19.42}$$

$$\begin{aligned}\tilde{d}(9) &= \min\{\tilde{d}(9), \tilde{d}(5) + \tilde{a}(5,9)\} = \min\{(\infty,\infty,\infty); (6,9,12) + (5,6,8)\} \\ &= \min\{(\infty,\infty,\infty); (11,15,20)\} = (11,15,20) = \; > \; Q_9 = \{1,2,5,9\}.\end{aligned} \tag{19.43}$$

$$\begin{aligned}\tilde{d}(7) &= \min\{\tilde{d}(7), \tilde{d}(9) + \tilde{a}(9,7)\} = \min\{(\infty,\infty,\infty); (11,15,20) + (1,2,3)\} \\ &= \min\{(\infty,\infty,\infty); (12,17,23)\} = (12,17,23) = \; > \; Q_7 = \{1,2,5,9,7\}.\end{aligned} \tag{19.44}$$

$$\begin{aligned}\tilde{d}(6) &= \min\{\tilde{d}(6), \tilde{d}(7) + \tilde{a}(7,6)\} = \min\{(6,8,12); (12,17,23) + (1,2,4)\} \\ &= \min\{(6,8,12); (13,19,27)\} = (6,8,12) = \; > \; Q_6 = \{1,4,6\}.\end{aligned} \tag{19.45}$$

$$\begin{aligned}\tilde{d}(8) &= \min\{\tilde{d}(8), \tilde{d}(6) + \tilde{a}(6,8), \tilde{d}(7) + \tilde{a}(7,8)\} \\ &= \min\{(\infty,\infty,\infty); (6,8,12) + (4,5,6); (12,17,23) + (2,3,5)\} \\ &= \min\{(\infty,\infty,\infty); (10,13,18); (14,20,28)\} = (10,13,18) = \; > \; Q_8 = \{1,4,6,8\}.\end{aligned} \tag{19.46}$$

$$\begin{aligned}\tilde{d}(10) &= \min\{\tilde{d}(10), \tilde{d}(7) + \tilde{a}(7,10), \tilde{d}(8) + \tilde{a}(8,10), \tilde{d}(9) + \tilde{a}(9,10)\} \\ &= \min\{(\infty,\infty,\infty); (12,17,23) + (1,2,4); (10,13,18) + (4,6,8); (11,15,20) + (3,5,7)\} \\ &= \min\{(\infty,\infty,\infty); (13,19,27); (14,19,26); (14,20,27)\} \\ &= (13,19,27) = (14,19,26)) = \; > \; Q_{10} = \{1,2,5,9,7,10\} = \{1,4,6,8,10\}.\end{aligned} \tag{19.47}$$

Therefore, the new shortest paths are $L_1^* = \{1,4,6,8,10\} = (14,19,26)$, $L_2^* = \{1,2,5,9,7,10\} = (13,19,27)$.

Perform parallel construction and verification, as two shortest routes are found. The route L_1^* is $L_1^* : \{T_0(1,4) \neq \emptyset, T_1(4,6) \neq \emptyset, T_2(6,8) \neq \emptyset, T_3(8,10) \neq \emptyset\}$ and the route L_2^* is $L_2^* : \{T_0(1,2) \neq \emptyset, T_1(2,5) \neq \emptyset, T_2(5,9) \neq \emptyset, T_3(9,7) \neq \emptyset, T_4(7,10) \neq \emptyset\}$.

Consequently, all arcs exist at given time periods and can be constructed. Go to the next step.

Because the arcs lengths are presented as triangular fuzzy number, and these fuzzy number is a function with a single extremum, then the result of defuzzification is an extremum (Zimmermann 1996):

$$\begin{cases} L_1^*(T_0^*) = L_2^*(T_0^*) \\ t_{\min} = \min\{t(L_1^*(T_0^*)), t(L_2^*(T_0^*))\} \end{cases} = \begin{cases} L_1^*(T_0^*) = L_2^*(T_0^*) = 19 \\ t_{\min} = \min\{4; 5\} = 4 \end{cases} = > L^*(T_0^*) = L_1^*(T_0^*). \tag{19.48}$$

Hence, the shortest route for a given starting period T_0^* is $L_1^* = \{1, 4, 6, 8, 10\} = 19$ and time of the movement on this route is $t = 4$.

19.4.2 Situation A2. Define the Time of Arrival of the Material Flow $T_{j_r} = 8$.

First, find the shortest path for the original graph without time parameter.

The procedure for calculating the shortest path of the original graph without time parameter was demonstrated in Situation A1. Thus, the shortest route is $L^* = \{1, 2, 7, 10\} = (10, 14, 22)$.

Then go to the next step of the procedural model. Step by step we build the route L^* checking the existence of each arc and time of arrival at the destination vertex, as shown in Fig. 19.3. The arc (1,2) is $\tilde{a}(1,2) = (3,4,6), T_0(1,2) \neq \emptyset$.

Hence, go to check the next arc. The arc (2,7) is $\tilde{a}(2,7) = (6,8,12)$, $T_1(2,7) = \emptyset$.

Again, find the route as shown in Situation A1, the result is the new shortest routes: $L_1^* = \{1, 4, 6, 8, 10\} = (14, 19, 26), L_2^* = \{1, 2, 5, 9, 7, 10\} = (13, 19, 27)$.

$$T_{j_s} = 0 = > T_{j_r} = 4(L_1^*) = 5(L_2^*), \tag{19.49}$$

$$T_{j_s} = 1 = > T_{j_r} = 4(L^*), \tag{19.50}$$

$$T_{j_s} = 2 = > T_{j_r} = 5(L^*), \tag{19.51}$$

$$T_{j_s} = 3 = > T_{j_r} = 7(L_1^*) \tag{19.52}$$

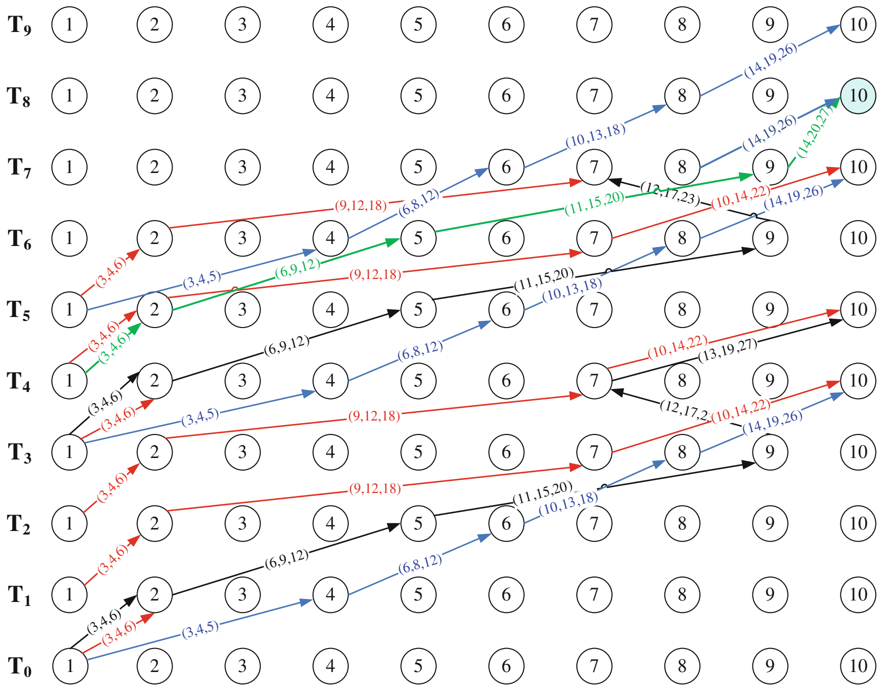


Fig. 19.3 Illustration of solving the problem for the situation A2

$$T_{j_s} = 4 = \; > T_{j_r} = 7(L^*), \tag{19.53}$$

$$T_{j_s} = 5 T_{j_r} = 9\left(L_1^*\right). \tag{19.54}$$

$T_{j_r}^* - T_{j_s} = 8 - 5 = 3$, therefore, it is not necessary to check the routes of the following further time periods and it is necessary to construct a new route by using information about the route when arcs are absent in the construction and verification.

We consider the search of arcs from the final vertex based on the shortest route L^*. The arc (7,10) is $\tilde{a}(7,10) = (1,2,4), T_7(7,10) = \emptyset$.

Hence, go to the recalculation of the route. Determining the shortest route L^*, calculations before $\tilde{d}(10)$ is obtained equal Situation A1:

$$\begin{aligned} \tilde{d}(10) &= \min\{\tilde{d}(10), \tilde{d}(7) + \tilde{a}(7,10), \tilde{d}(8) + \tilde{a}(8,10), \tilde{d}(9) + \tilde{a}(9,10)\} \\ &= \min\{(\infty,\infty,\infty); (9,12,18) + \emptyset; (10,13,18) + (4,6,8); (11,15,20) + (3,5,7)\} \\ &= \min\{(\infty,\infty,\infty); \emptyset; (14,19,26); (14,20,27)\} = (14,19,26). \end{aligned} \tag{19.55}$$

The found route is $L = \{1, 4, 6, 8, 10\} = L_1^*$, therefore, begin to re-check, based now on the route L_1^*.

The arc (8,10) is $\tilde{a}(8, 10) = (4, 6, 8), T_7(8, 10) \neq \emptyset$.
The arc (6,8) is $\tilde{a}(6, 8) = (4, 5, 6), T_6(6, 8) = \emptyset$.

Therefore, the next time we will not use the arc (8.10) for the calculation of the arc and denote it in the same way as an arc, which is absent. We make new route recalculation.

$$\begin{aligned}\tilde{d}(10) &= \min\{\tilde{d}(10), \tilde{d}(7) + \tilde{a}(7, 10), \tilde{d}(8) + \tilde{a}(8, 10), \tilde{d}(9) + \tilde{a}(9, 10)\} \\ &= \min\{(\infty, \infty, \infty); (9, 12, 18) + \emptyset; (10, 13, 18) + \emptyset; (11, 15, 20) + (3, 5, 7)\} \\ &= \min\{(\infty, \infty, \infty); \emptyset; \emptyset; (14, 20, 27)\} = (14, 20, 27).\end{aligned} \tag{19.56}$$

The found route is $L = \{1, 2, 5, 9, 10\}$, therefore, begin to re-check.

The arc (9,10) is $\tilde{a}(9, 10) = (14, 20, 27), T_7(9, 10) \neq \emptyset$.
The arc (5,9) is $\tilde{a}(5, 9) = (11, 15, 20), T_6(5, 9) \neq \emptyset$.
The arc (2,5) is $\tilde{a}(2, 5) = (6, 9, 12), T_5(2, 5) \neq \emptyset$.
The arc (1,2) is $\tilde{a}(1, 2) = (3, 4, 6), T_4(1, 2) \neq \emptyset$.

This check showed that the route exists and it is equal to $L_3^* = \{1, 2, 5, 9, 10\} = (14, 20, 27)$ and time of the movement on the route $t = 4$. The final route is marked in green on the Fig. 19.3.

Because the arcs lengths are presented as triangular fuzzy number, and these fuzzy number is a function with a single extremum, then the result of defuzzification is an extremum (Zimmermann 1996). Consequently, the route L_3^* after defuzzification is 20.

It follows that the best route for the given time of arrival T_8^* is $L_3^* = \{1, 2, 5, 9, 10\} = 20$ and time of the movement on this route is $t = 4$.

19.4.3 Situation A3. Set Interval of Time $T_{j_s} = 3$ and $T_{j_r} = 8$, Which is Necessary to Move from the Initial Vertex to the End Vertex.

First, find the shortest path for the original graph without time parameter.

The procedure for calculating the shortest path of original graph without time parameter was demonstrated in Situation A1. Thus, the shortest route is $L^* = \{1, 2, 7, 10\} = (10, 14, 22)$.

Then go to the next step of the procedural model. Step by step we build the route L^* checking the existence and time of arrival at the destination of each arc, as

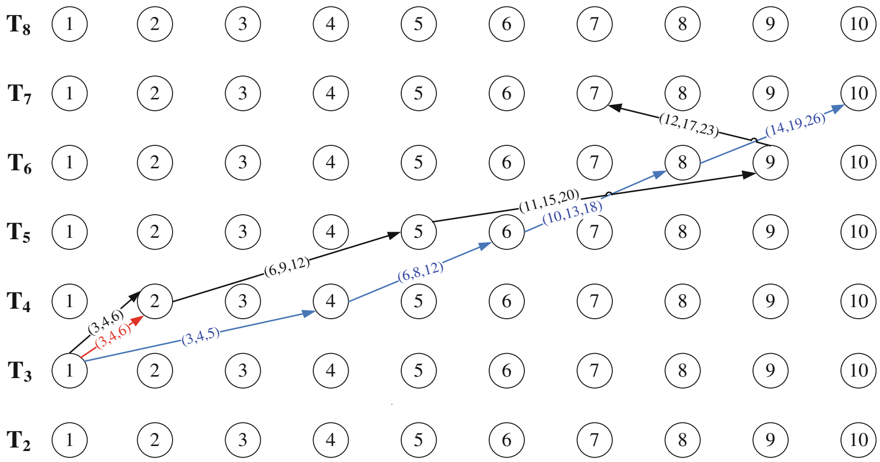


Fig. 19.4 Illustration of solving the problem for the situation A3

shown in Fig. 19.4. The arc (1,2) is $\tilde{a}(1,2) = (3,4,6), T_0(1,2) \neq \emptyset$. Hence, go to check the next arc. The arc (2,7) is $\tilde{a}(2,7) = (6,8,12), T_1(2,7) = \emptyset$.

Again, find the route as shown in Situation A1, the result is the new shortest routes $L_1^* = \{1,4,6,8,10\} = (14,19,26), L_2^* = \{1,2,5,9,7,10\} = (13,19,27)$.

Make a new verification of received routes.

The arc (1,4) is $\tilde{a}(1,4) = (3,4,5), T_3(1,4) \neq \emptyset$. Hence, go to the next arc.
The arc (1,2) is $\tilde{a}(1,2) = (3,4,6), T_3(1,2) \neq \emptyset$.
The arc (4,6) is $\tilde{a}(4,6) = (6,8,12), T_4(4,6) \neq \emptyset$.
The arc (2,5) is $\tilde{a}(2,5) = (6,9,12), T_4(2,5) \neq \emptyset$.
The arc (6,8) is $\tilde{a}(6,8) = (10,13,18), T_5(6,8) \neq \emptyset$.
The arc (5,9) is $\tilde{a}(5,9) = (11,15,20), T_5(5,9) \neq \emptyset$.
The arc (8,10) is $\tilde{a}(8,10) = (14,19,26), T_6(8,10) \neq \emptyset$.
The arc (9,7) is $\tilde{a}(9,7) = (12,17,23), T_6(9,7) \neq \emptyset$.
The arc (7,10) is $\tilde{a}(7,10) = (13,19,27), T_7(7,10) = \emptyset$.

As you can see, there is only one route $L_1^* = \{1,4,6,8,10\} = (14,19,26)$.

Because the arcs length are presented as triangular fuzzy number, and these fuzzy number is a function with a single extremum, then the result of defuzzification is an extremum (Zimmermann 1996). Consequently, the route L_1^* after defuzzification is 19.

It follows that the best route for the given interval is $L_1^* = \{1,4,6,8,10\} = 19$ and the movement time on this route is $t = 4$.

19.5 Development of Routing Procedural Model Under Fuzzy Given Distance and Time

The aim of this section is to develop routing procedural models taking temporal dependencies under different conditions with fuzzy given parameters into account. The models have to be implemented in the dynamic information model. It is a necessary form of parameter settings, as the distance is inaccurate because the developed maps are subjective and there is no information on the entire map, and the movement time is always a fuzzy parameter because the reality is constantly changing.

This model is necessary for solving the following problem. To find the shortest path L from the initial point s to the final point r, using time parameter:

$$L^* = \min_{\tilde{t}} \min_{w(\tilde{t})} \{ (\tilde{w}(\tilde{t}) / < s, x_i >), \left(\tilde{w}(\tilde{t}) / < x_i, x_j > \right), \left(\tilde{w}(\tilde{t}) < x_j, r > \right)\}, \tag{19.57}$$

where $\tilde{w}(t)$ is the distance between destinations.

There are arcs which are absent in a period of time (“absence of edges” means that the arcs lengths at the relevant point in time tends to infinity). Edges are fuzzy values. Time is a discrete value, a period transit time in each arc is a fuzzy value. The time period T_j, where $j = \overline{0, m}$, is the time interval that specifies the user.

The user determines the number of time periods determined by the set:

$$T = \{T_0, T_1, \ldots, T_m\} = \left\{T_{j_s}, T_j, T_{j_r}\right\}, \tag{19.58}$$

where $\{T_{j_s}\}, j_s = \overline{0, m-1}$ is the departure time from the initial point;

$\{T_j\}, j = \overline{1, m-1}$ is the traveling time without taking the time of departure and arrival into account;

$\{T_{j_r}\}, j_r = \overline{1, m}$ is the arrival time at the destination.

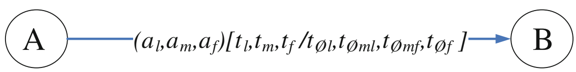
It is necessary to find the shortest path from the initial to the final point. The values of the arcs and time are fuzzy defined, so they are represented as fuzzy numbers (Savelyeva and Beliacov 2014). The arc of the graph shown in Fig. 19.5 is represented as follows:

$$(\tilde{a}_i)[\tilde{t}_i / \tilde{t}_{\emptyset i}], \tag{19.59}$$

where $\tilde{a}_i = (a_l, a_m, a_f)$ is the arc length of fuzzy temporal graph,

$\tilde{t}_i = [t_l, t_m, t_f]$ is the movement time along the arc of a fuzzy temporal graph and presented in the form of a triangular fuzzy number,

Fig. 19.5 The arc of fuzzy temporal graph



$\tilde{t}_{\emptyset i} = [t_{\emptyset l}, t_{\emptyset ml}, t_{\emptyset mf}, t_{\emptyset f}]$ is the absence time of an arc fuzzy temporal graph (the arc length is equal to ∞) and presented in the form of a trapezoidal fuzzy number.

Solution of this problem involves consideration of three situations. Depending on these situations following procedural models were developed:

A4. Procedural routing model with temporal dependence and given starting time.
A5. Procedural routing model with temporal dependence and given time of arrival.
A6. Procedural model routing with temporal dependence and given movement time interval.

19.5.1 Situation A4

Step 1. It is assumed that the original fuzzy temporal graph does not depend on the time at the initial stage, i.e. the arcs exist at any moment of time. We find the shortest path L^* for this graph Before starting all vertices and arcs are not painted (Minieka 1981).

Step 2. Each vertex is assigned a fuzzy number $\tilde{d}(x_i)$. This number $\tilde{d}(x_i)$ is equal to the length of the shortest path from s to x_i, this path includes only the painted vertices.

Put $\tilde{d}(s) = 0$ and $\tilde{d}(x_i) = \infty$ for all the $x_i \neq$ s . Paint the vertex s and put y = s (y is the last of the colored vertices).

Step 3. Calculate the value $\tilde{d}(x_i)$ of each unpainted vertex x_i as follows:

$$\tilde{d}(x_i) = \min\{\tilde{d}(x_i), \tilde{d}(y) + \tilde{a}(y, x_i)\}, \tag{19.60}$$

where $\tilde{a}(y, x_i)$ is the arc length (y, x_i).

Comparison of the fuzzy number values is done by Index centroid of fuzzy number.

If $\tilde{d}(x_i) = \infty$ for all unpainted vertices x_i then finish the procedure of the algorithm and assume that there are no paths from s to unpainted vertices in the original graph. Otherwise, paint the vertex x_i for which the value $\tilde{d}(x_i)$ is the lowest. In addition, paint the arc, which leads to the selected vertex x_i [minimum is reached for the arc according to the expression (19.60)] at this step. Put $y = x_i$.

Step 4. If y = r, then finish the procedure. The shortest path L^* from vertex s into r without time parameter is found (it is the only path from s to r, which is composed of colored arcs). Otherwise, go to step 3.

Step 5. Go to the search of the shortest path in the fuzzy temporal graph in which there are no arcs at certain time periods. It requires building a graph and presenting it in a static form step by step. Construct the shortest path L^* obtained in Step 4, which begins at time period $\{T_{j_s}\}, j_s = \overline{0, m-1}$, where m is defined by the user. If the arc exists, movement begins at the first step from the start time $\{T_j\}, j = \overline{0, m}$ and the movement time along the arc is:

$$\tilde{t}(x_i) = T_{j_s} + \tilde{t}(y, x_i), \tag{19.61}$$

where $\tilde{t}(x_i)$ is the total movement time to the vertex $x_i, \tilde{t}(y, x_i)\tilde{t}(y, x_i)$ is the movement along the arc.

In the following steps the time is determined by the following formula:

$$\tilde{t}(x_i) = \tilde{t}(y) + \tilde{t}(y, x_i), \tag{19.62}$$

where $\tilde{t}(y)$ is the total movement time to the vertex y.

If the arc is not available at a given moment, then stop testing and go to step 6.

Step 6. The initial vertex s belongs to the period of time $\{T_{j_s}\}, j_s = \overline{0, m-1}$. As described in Step 3, find new value $\tilde{d}(x_i)$ by (19.60) and check the existence of arc (y, x_i) based on time parameter as follows:

$$\left(t_{\emptyset l}, t_{\emptyset ml}, t_{\emptyset mf}, t_{\emptyset f}\right) \in (t_{l1}, t_{l2}) \cup (t_{m1}, t_{m2}) \cup \left(t_{f1}, t_{f2}\right), \tag{19.63}$$

where $(t_{\emptyset l}, t_{\emptyset ml}, t_{\emptyset mf}, t_{\emptyset f})$ is the fuzzy value of arc absence time, t_{l1} is the left parameter of the fuzzy time value and belongs to the beginning of the considering arc, t_{l2} is the left parameter of the fuzzy time value and belongs to the end of the considering arc, t_{m1} is mid the parameter of the fuzzy time value and belongs to the beginning of the considering arc, t_{m2} is the mid parameter of the fuzzy time value and belongs to the end of the considering arc, t_{f1} is the right parameter of the fuzzy time value and belongs to the beginning of considering arc, t_{f2} is the right parameter of the fuzzy time value and belongs to the end of the considering arc.

If (19.63) is not satisfied, therefore, the arc (y, x_i) exists in the considering period, then paint the vertex x_i, increase $T_{j_s} = T_j$ by $\tilde{t}(y, x_i)$ by (19.62) and accept $x_i = y$.

If (19.63) is correct, then arc (y, x_i) is absent in a given time period, then this arc is not considered and another minimum vertex is selected.

If there aren't other arcs, there is no solution under the given conditions. If you want to find any solution, then the starting period j_s is increased by one unit and go to step 5.

Step 7. If $y = r$, finish the procedure, then the shortest path L^* from vertex s^* to r is found. Otherwise, go to step 6.

Step 8. Make defuzzification for the found values of the shortest routes (Zimmermann 1996).

Step 9. Check all shortest paths from the set $L = \{L_1, L_2, \ldots, L_n\}$, which have the departure time equal to $T^*_{j_s}$. Choose the minimum route from the given set of the shortest routes after defuzzification, i.e.:

$$L^* = \min\{L_1, L_2, \ldots, L_n\}. \tag{19.64}$$

This set of the shortest routes arises due to the fuzziness of the initial data.
Step 10. Make defuzzification for the fuzzy values of the obtained movement time of the shortest routes (Zimmermann 1996).
Step 11. If several equal routes exist, then:

$$\begin{cases} L_1\left(T^*_{j_s}\right) = L_2\left(T^*_{j_s}\right) = \ldots = L_n\left(T^*_{j_s}\right) \\ t_{min} = min\{t\left(L_1\left(T^*_{j_s}\right)\right), t\left(L_2\left(T^*_{j_s}\right)\right), \ldots, t\left(L_n\left(T^*_{j_s}\right)\right)\} \end{cases} = > L^*(t_{min}), \tag{19.65}$$

where $t = t(r) - T_{j_s}$ is the movement time along the route from the initial point to the destination point. Necessary path L^* is found.

19.5.2 Situation A5

Steps 1–7. Coincide with the situation A4.
Step 8. Compare start time T_{j_s} with user-defined time of arrival at destination $T^*_{j_r}$. If $T_{j_s} = T^*_{j_r}$, then finish the search of the route and go to Step 9. If $T_{j_s} < T^*_{j_r}$, increase the start period T_{j_s} by 1 and go to Step 5. If $T_{j_s} > T^*_{j_r}$, the shortest path does not exist in the given initial period of time.
Step 9. Make defuzzification for the found values of the shortest routes (Zimmermann 1996).
Step 10. Check all shortest paths from the set $L = \{L_1, L_2, \ldots, L_n\}$, which have the departure time equal to $T^*_{j_s}$. Choose the minimum route from the given set of the shortest routes after defuzzification, i.e.:

$$L^* = \min\{L_1, L_2, \ldots, L_n\}. \tag{19.66}$$

This set of the shortest routes arises due to the fuzziness of the initial data.
Step 11. Make defuzzification for the fuzzy values of the obtained movement time of the shortest routes (Zimmermann 1996).
Step 12. If several equal routes exist, then:

$$\begin{cases} L_1\left(T^*_{j_r}\right) = L_2\left(T^*_{j_r}\right) = \ldots = L_n\left(T^*_{j_r}\right) \\ t_{\min} = \min\{t\left(L_1\left(T^*_{j_r}\right)\right), t\left(L_2\left(T^*_{j_r}\right)\right), \ldots, t\left(L_n\left(T^*_{j_r}\right)\right)\} \end{cases} = > L^*(t_{\min}), \tag{19.67}$$

where $t = T_{j_r} - t(r)$ is the movement time along the route from the initial point to the final point. Necessary path L^* is found.

19.5.3 Situation A6

Steps 1–4. Coincide with the situation A4.
Step 5. Determine calculated time $\tilde{t}^*$ based on the found shortest route L^*, step by step adding the time of the arc length, without time parameter, when the arc is absent. The calculated time is the minimum possible time of movement.
Step 6. Make defuzzification of the parameter $\tilde{t}^*$(Zimmermann 1996). The result is the parameter t^*.
Step 7. Compare the parameter t^* with user-defined interval t_u^*. If $t^* \le t_u^*$, then go to step 8. If $t^* > t_u^*$, then finish the implementation, there is no solution. It is necessary to set the interval.
Step 8. Go to the search of the shortest path in the fuzzy temporal graph in which there are no arcs at certain time periods. Do this requires step by step to build a graph in a static form. Construct the shortest path L^* obtained in Step 4, which begins in the time period $\{T_{j_s}\}, j_s = \overline{0, m-1}$, where m is defined by the user. Arcs are checked for their existence when constructing. If the arc exists, movement begins at the first step from the start time $\{T_j\}, j = \overline{0, m}$ and the movement time along the arc is:

$$\tilde{t}(x_i) = T_{j_s} + \tilde{t}(y, x_i), \tag{19.68}$$

where $\tilde{t}(x_i)$ is the total movement time to the vertex $x_i, \tilde{t}(y, x_i)$ is the movement along the arc.

In the following steps the time is determined by (19.62).

If the arc is not available at a given moment, then stop testing and go to step 9.

Step 9. The initial vertex s belongs to the period of time $\{T_{j_s}\}, j_s = \overline{0, m-1}$. As described in Step 3, find new value $\tilde{d}(x_i)$ according to (19.60) and check the existence of arc (y, x_i) based on time parameter by (19.63).
If (19.63) is not satisfied, therefore, the arc (y, x_i) exists in the considering period, then paint the vertex x_i, increase $T_{j_s} = T_j$ by $\tilde{t}(y, x_i)$ according to (19.62) and accept $x_i = y$.
If (19.63) is correct, then arc (y, x_i) is absent in a given time period and it is not considered and another minimum vertex is chosen.
If there aren't other arcs, there is no solution under the given conditions. If you want to find any solution, then the starting period j_s is increased by 1 and go to step 8.
Step 10. If $y = r$, finish the procedure, then the shortest path L^* from vertex s * to r is found. Otherwise, go to step 9.

Step 11. Calculate the time of the found path $\tilde{t}$ as follows:

$$\tilde{t} = \tilde{t}(r) - T_{j_s}. \tag{19.69}$$

Step 12. Make defuzzification of the parameter $\tilde{t}^*$ in step 11 (Zimmermann 1996).
Step 13. If $t_u^* \leq t$ (where t_u^* is given by the user time of the movement along the route), then go to step 14. If $t_u^* > t$, then there is no decision for the given initial and final conditions, therefore it is necessary to increase the starting period j_s by one unit and go to step 8.
Step 14. Make defuzzification for the found values of the shortest routes (Zimmermann 1996).
Step 15. Check all shortest paths from the set $L = \{L_1, L_2, \ldots, L_n\}$, which have the time interval of movement equal to t_u^*. Choose the minimum route from the given set of the shortest routes after defuzzification, i.e.:

$$L^* = \min\{L_1, L_2, \ldots, L_n\}. \tag{19.70}$$

This set of the shortest routes arises due to the fuzziness of the initial data.
Step 16. If several equal routes exist, then:

$$\begin{cases} L_1 = L_2 = \ldots = L_n \\ t_{\min} = \min\{t(L_1), t(L_2), \ldots, t(L_n)\} \end{cases} = > L^*(t_{\min}). \tag{19.71}$$

L^* is the found route with specified conditions.

Now carry out the asymptotic performance evaluation of the developed procedural model.

$$\mathrm{O}\big(l\big((k+1)\big(n^2+m\big) + (t-k)n\big)\big) \approx \mathrm{O}\big((k+1)\big(n^2+m\big) + (t-k)n\big), \tag{19.72}$$

where n is the number of the vertices; m is the number of the arcs; t is the number of the time periods; k is the number of the time periods when all arcs exist on the shortest path; l is the number of the operations required for defuzzification of the time parameter.

19.6 Example of the Routing Procedural Model Under Fuzzy Given Distance and Time

The aim of this section is to present the work of the developed routing procedural model with temporal dependence and fuzzy given distance and time.

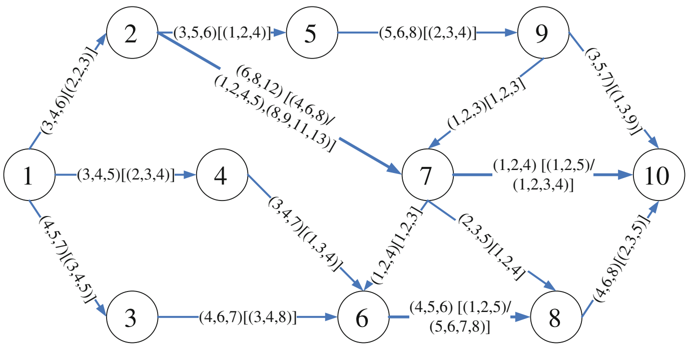


Fig. 19.6 Example of the problem. The original graph illustrating the problem under fuzzy given parameters of the distance and time

Find the shortest route under the given parameters from the initial vertex 1 to the final vertex 10 (Fig. 19.6).

The arcs of the graph have a length represented by fuzzy number. Square brackets have time of the movement along the arc as triangular fuzzy number. Trapezoidal fuzzy represents the time of absence.

The square brackets indicate the time of the movement along the arc and the time of absence of the arc. The absence of the arc signed by "/".

19.6.1 Situation A4. Define the Time of Departure of the Material Flow $T_{j_s} = 0$.

First, find the shortest path for the original graph without time parameter.

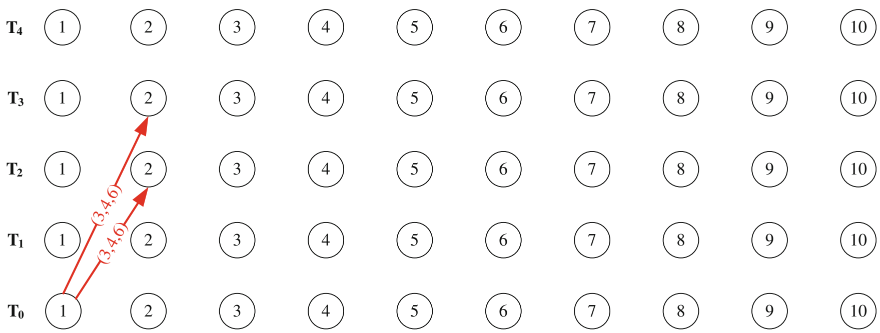


Fig. 19.7 Construction of the shortest route L^* with the parameters of fuzzy distance and time at $T_{j_s} = 0$

The procedure for calculating the shortest path of original graph without time parameter was demonstrated in Situation A1. Thus, the shortest route is $L^* = \{1, 2, 7, 10\} = (10, 14, 22)$.

Next, go to the search of the shortest route in fuzzy temporal graph.

We build the route L^* (Fig. 19.7), checking each arc step by step. The arc (1,2) is

$$\tilde{a}(1,2) = (3,4,6),\ T_0(1,2) = (0,0,0) \notin \tilde{t}_{\emptyset}. \tag{19.73}$$

Hence, go to check the next arc. The arc (2,7) is $\tilde{a}(2,7) = (6,8,12), T_1(2,7) = (2,2,3) \in \tilde{t}_{\emptyset} = (1,2,4,5)$.

Therefore it is impossible to construct arcs (2,7) and hence the whole shortest route L^*. Consequently, go to the next step.

Again, the route search is performed by (19.60) taking into account the absence of arc (2.7) in the time period $\tilde{t}_{\emptyset} = (1,2,4,5)$. The search of this decision also was performed by the example in Situation A1 for the fuzzy given parameters of the distance and the found shortest path $L_1^* = \{1,4,6,8,10\} = (14,19,26), L_2^* = \{1,2,5,9,7,10\} = (13,19,27)$.

Perform parallel construction and verification, as two shortest routes are found.

The route L_1^* (Fig. 19.8 is shown the route L_1^* by blue) is:

$$T_0(1,4) = (0,0,0) \notin \tilde{t}_{\emptyset}; \tag{19.74}$$

$$T_1(4,6) = (0,0,0) + (2,3,4) = (2,3,4) \notin \tilde{t}_{\emptyset}; \tag{19.75}$$

$$T_2(6,8) = (2,3,4) + (1,3,4) = (3,6,8) \in \tilde{t}_{\emptyset} = (5,6,7,8). \tag{19.76}$$

As can be seen, the arc (6.8) is absent, therefore, you cannot build the route L_1^*.

The route L_2^* (Fig. 19.8 is shown the route L_1^* by black) is:

$$T_0(1,2) = (0,0,0) \notin \tilde{t}_{\emptyset}; \tag{19.77}$$

$$T_1(2,5) = (0,0,0) + (2,2,3) = (2,2,3) \notin \tilde{t}_{\emptyset}; \tag{19.78}$$

$$T_2(5,9) = (2,2,3) + (1,2,4) = (3,4,7) \notin \tilde{t}_{\emptyset}; \tag{19.79}$$

$$T_3(9,7) = (3,4,7) + (2,3,4) = (5,7,11) \notin \tilde{t}_{\emptyset}; \tag{19.80}$$

$$T_3(7,10) = (5,7,11) + (1,2,3) = (6,9,14) \notin \tilde{t}_{\emptyset} = (1,2,3,4). \tag{19.81}$$

Hence, the shortest arc path L_2^* exists at all times and therefore can be built.

As a result of the construction of routes we received the following solution: the route $L_2^* = (13,19,27)$ and the movement of $t = (7,11,19)$.

Go to the next step.

Because the arcs lengths are presented as triangular fuzzy numbers, and these fuzzy numbers are functions with a single extremum, then the result of defuzzification is an extremum (Zimmermann 1996).

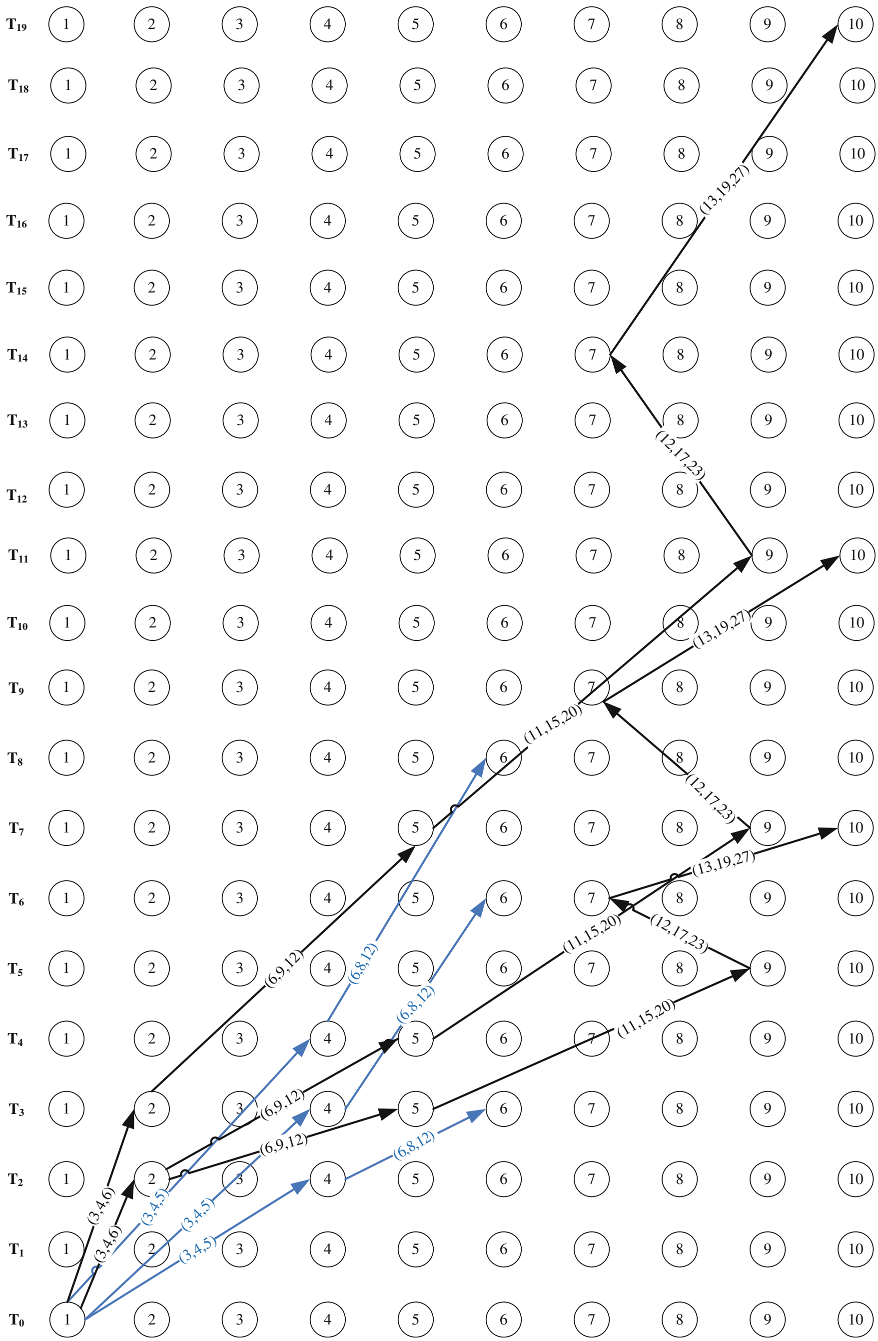


Fig. 19.8 Illustration of solving the problem for the situation A4

Hence, the route L_2^* after defuzzification is 19 and the time of the movement after defuzzification is 11.

Situation A5 and Situation A6 are solved in a similar way.

19.7 Conclusion

This chapter describes the sustainability problems in transportation networks that arise when considering transportation networks in fuzzy environment. This is achieved through the development of dynamic geoinformation models of transport systems. This dynamic geoinformation model takes into account the spatial, temporal, and semantic parameters. The present paper describes the problem statement and solution of routing problem with temporal dependence and fuzzy given distance and with temporal dependence and fuzzy given distance and time. The problem with these parameters is more adaptable to obtaining data from map. An important aspect of the developed models is the time parameter that should be considered for the functioning of the transport system. This parameter is considered depending on conditions when logistics operations are executed. These conditions are the start time, the end time and the interval of operation moved from the initial point to the final point. We performed the asymptotic performance evaluations of developed procedural models. We illustrate the examples of the implementation of procedural models. The field of our future researches is task of fuzzy data representation in the form of membership functions for fuzzy temporal graph to improve sustainability in transportation network. This representation is even more close to the description of real situations.

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References

Berstein, L. S., & Bozhenyuk, A. V. (2005) *Fuzzy graphs and hypergraphs*. Scientific World (in Russian).

Berstein, L. S., & Bozhenyuk, A. V. (2010). The use of temporal graphs as models of complex systems, In *Proceedings of the SFU. Technical Engineering*, *4*(105), 198–203 (in Russian).

Bozhenyuk, A., Gerasimenko, E., & Rozenberg, I. (2012). The task of minimum cost flow finding in transportation networks in fuzzy conditions. In: *Proceedings of the 10th International FLINS Conference on Uncertainty Modeling in Knowledge Engineering and Decision Making* (pp. 354–359). Word Scientific, Istanbul, Turkey, August 26–29, 2012.

Bozhenyuk, A., Gerasimenko, E., Rozenberg, I., & Perfilieva, I. (2015a). Method for the minimum cost maximum flow determining in fuzzy dynamic network with nonzero flow bounds. In M. A. José, B. Humberto & R. Marek (Eds.), *2015 Conference of the International Fuzzy*

Systems Association and the European Society for Fuzzy Logic and Technology (Vol. 89, pp. 385–392). Atlantic Press, Gijón, Asturias, 30 June–3 July

Bozhenyuk, A., Gerasimenko, E., & Rozenberg, I. (2015b). Determining the minimum cost flow in fuzzy dynamic network with GIS «ObjectLand». In *Proceedings of the 2015 9th International Conference on Application of Information and Communication Technologies (AICT)* (pp. 294–298). Rostov-on-Don, Russia, October, 14–16.

Bulavatsky, V. M., & Krivonos, Y. G. (2012). Mathematical modeling in the geoinformation problem of the dynamics of geomigration under space–time nonlocality. *Cybernetics and Systems Analysis, 48*(4), 539–546.

Dodge, M., Kitchin, R., & Perkins, C. (2011). *The map reader: Theories of mapping practice and cartographic representation*. London: Wiley.

Dodge, S., Weibel, R., Ahearn, S. C., Buchin, M., & Miller, J. A. (2016). Analysis of movement data. *International Journal of Geographical Information Science, 30*(5), 825–834.

Kostakos, V. (2008). Temporal graphs. In: *Proceedings of Physica A: Statistical Mechanics and its Applications* (Vol. 388, No. 6, pp. 1007–1023). Amsterdam: Elsevier.

Mackaness, W. A., Ruas, A., & Sarjakoski, L. T. (2011). *Generalisation of geographic information: Cartographic modelling and applications*. Amsterdam: Elsevier.

Minieka, E. (1981). *Optimization algorithms for networks and graphs*. Berlin: Springer.

Nagurney, A. (2000) *Sustainable transportation networks*. Cheltenham: Edward Elgar Publishers.

Savelyeva, M., & Beliacov, S. (2014). Fuzzy routing in supply chain management with temporal dependence. In *Proceedings of the MENDEL 2014—20th International Conference on Soft Computing: Evolutionary Computation, Genetic Programming, Swarm Intelligence, Fuzzy Logic, Neural Networks, Fractals, Bayesian Methods* (pp. 195–200). Brno, Czech Republic.

Savelyeva, M., & Belyakov, S. (2015). Solution of the problem supply chain management in temporal dependence. *Advances in intelligent systems and computing* (Vol. 323, pp. 489–496). Berlin: Springer.

Scheider, S., Graeler, B., Pebesma, E., & Stasch, C. (2016). Modeling spatiotemporal information generation. *International Journal of Geographical Information Science.* doi:10.1080/13658816.2016.1151520 (in press).

Timmer, J., Pel, B., Kool, L., van Est, R., & Brom, F. (2015). *Converging roads—Linking self-driving cars to public goals*. The Hague: Rathenau Instituut.

Zimmermann, H. J. (1996). *Fuzzy set theory and its applications* (3rd ed.). Boston: Kluwer Academic Publishers.

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