Innovation, Technology, and Knowledge Management

Tugrul U. Daim *Editor*

Hierarchical Decision Modeling

Essays in Honor of Dundar F. Kocaoglu

Springer

Innovation, Technology, and Knowledge Management

Series Editor
Elias G. Carayannis

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Series Foreword

The Springer book series *Innovation, Technology, and Knowledge Management* was launched in March 2008 as a forum and intellectual, scholarly "podium" for global/local, transdisciplinary, transsectoral, public-private, and leading/ "bleeding"-edge ideas, theories, and perspectives on these topics.

The book series is accompanied by the Springer *Journal of the Knowledge Economy,* which was launched in 2009 with the same editorial leadership.

The series showcases provocative views that diverge from the current "conventional wisdom," that are properly grounded in theory and practice, and that consider the concepts of ***robust competitiveness,***[1] ***sustainable entrepreneurship***,[2] and ***democratic capitalism***,[3] central to its philosophy and objectives. More specifically, the aim of this series is to highlight emerging research and practice at the dynamic

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[1] We define *sustainable entrepreneurship* as the creation of viable, profitable, and scalable firms. Such firms engender the formation of self-replicating and mutually enhancing innovation networks and knowledge clusters (innovation ecosystems), leading toward robust competitiveness (E.G. Carayannis, *International Journal of Innovation and Regional Development* 1(3), 235–254, 2009).

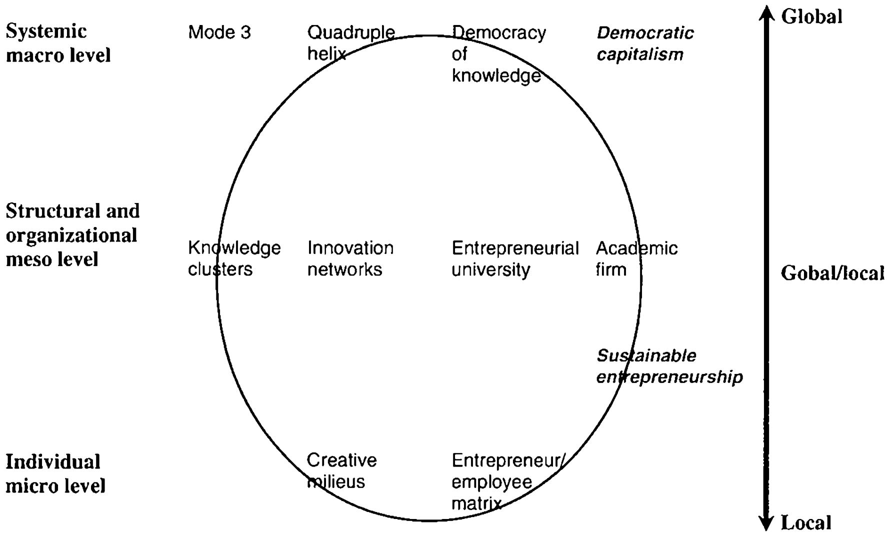
[2] We understand *robust competitiveness* to be a state of economic being and becoming that avails systematic and defensible "unfair advantages" to the entities that are part of the economy. Such competitiveness is built on mutually complementary and reinforcing low-, medium- and high-technology and public and private sector entities (government agencies, private firms, universities, and nongovernmental organizations) (E.G. Carayannis, *International Journal of Innovation and Regional Development* 1(3), 235–254, 2009).

[3] The concepts of *robust competitiveness* and *sustainable entrepreneurship* are pillars of a regime that we call *"democratic capitalism*" (as opposed to "popular or casino capitalism"), in which real opportunities for education and economic prosperity are available to all. especially—but not only—younger people. These are the direct derivative of a collection of top-down policies as well as bottom-up initiatives (including strong research and development policies and funding, but going beyond these to include the development of innovation networks and knowledge clusters across regions and sectors) (E.G. Carayannis and A. Kaloudis. *Japan Economic Currents,* p. 6–10, January 2009).

intersection of these fields, where individuals, organizations, industries, regions, and nations are harnessing creativity and invention to achieve and sustain growth.

Books that are part of the series explore the impact of innovation at the "macro" (economies, markets), "meso" (industries, firms), and "micro" levels (teams, individuals), drawing from such related disciplines as finance, organizational psychology, research and development, science policy, information systems, and strategy, with the underlying theme that for innovation to be useful it must involve the sharing and application of knowledge.

Some of the key anchoring concepts of the series are outlined in the figure below and the definitions that follow (all definitions are from E.G. Carayannis and D.F.J. Campbell, *International Journal of Technology Management*, 46, 3–4, 2009).



Conceptual profile of the series Innovation, Technology, and Knowledge Management

- The "Mode 3" Systems Approach for Knowledge Creation, Diffusion, and Use: "Mode 3" is a multilateral, multinodal, multimodal, and multilevel systems approach to the conceptualization, design, and management of real and virtual, "knowledge-stock" and "knowledge-flow," modalities that catalyze, accelerate, and support the creation, diffusion, sharing, absorption, and use of cospecialized knowledge assets. "Mode 3" is based on a system-theoretic perspective of socioeconomic, political, technological, and cultural trends and conditions that shape the coevolution of knowledge with the "knowledge-based and knowledge-driven, global/local economy and society."
- Quadruple Helix: Quadruple helix, in this context, means to add to the triple helix of government, university, and industry a "fourth helix" that we identify as the "media-based and culture-based public." This fourth helix associates with

"media," "creative industries," "culture," "values," "life styles," "art," and perhaps also the notion of the "creative class."
- Innovation Networks: Innovation networks are real and virtual infrastructures and infratechnologies that serve to nurture creativity, trigger invention, and catalyze innovation in a public and/or private domain context (for instance, government–university–industry public–private research and technology development coopetitive partnerships).
- Knowledge Clusters: Knowledge clusters are agglomerations of cospecialized, mutually complementary, and reinforcing knowledge assets in the form of "knowledge stocks" and "knowledge flows" that exhibit self-organizing, learning-driven, dynamically adaptive competences and trends in the context of an open systems perspective.
- Twenty-First Century Innovation Ecosystem: A twenty-first century innovation ecosystem is a multilevel, multimodal, multinodal, and multiagent system of systems. The constituent systems consist of innovation metanetworks (networks of innovation networks and knowledge clusters) and knowledge metaclusters (clusters of innovation networks and knowledge clusters) as building blocks and organized in a self-referential or chaotic fractal knowledge and innovation architecture (Carayannis 2001), which in turn constitute agglomerations of human, social, intellectual, and financial capital stocks and flows as well as cultural and technological artifacts and modalities, continually coevolving, cospecializ- ing, and cooperating. These innovation networks and knowledge clusters also form, reform, and dissolve within diverse institutional, political, technological, and socioeconomic domains, including government, university, industry, and nongovernmental organizations and involving information and communication technologies, biotechnologies, advanced materials, nanotechnologies, and next- Generation energy technologies.

Who is this book series published for? The book series addresses a diversity of audiences in different settings:

1. *Academic communities:* Academic communities worldwide represent a core group of readers. This follows from the theoretical/conceptual interest of the book series to influence academic discourses in the fields of knowledge, also carried by the claim of a certain saturation of academia with the current concepts and the postulate of a window of opportunity for new or at least additional concepts. Thus, it represents a key challenge for the series to exercise a certain impact on discourses in academia. In principle, all academic communities that are interested in knowledge (knowledge and innovation) could be tackled by the book series. The interdisciplinary (transdisciplinary) nature of the book series underscores that the scope of the book series is not limited a priori to a specific basket of disciplines. From a radical viewpoint, one could create the hypothesis that there is no discipline where knowledge is of no importance.
2. *Decision makers—private/academic entrepreneurs and public (governmental, subgovernmental) actors:* Two different groups of decision makers are being addressed simultaneously: (1) private entrepreneurs (firms, commercial firms,

academic firms) and academic entrepreneurs (universities), interested in optimizing knowledge management and in developing heterogeneously composed knowledge-based research networks; and (2) public (governmental, subgovernmental) actors that are interested in optimizing and further developing their policies and policy strategies that target knowledge and innovation. One purpose of public *knowledge and innovation policy* is to enhance the performance and competitiveness of advanced economies.

3. *Decision makers in general:* Decision makers are systematically being supplied with crucial information, for how to optimize knowledge-referring and knowledge-enhancing decision-making. The nature of this "crucial information" is conceptual as well as empirical (case-study-based). Empirical information highlights practical examples and points toward practical solutions (perhaps remedies), conceptual information offers the advantage of further-driving and further-carrying tools of understanding. Different groups of addressed decision makers could be decision makers in private firms and multinational corporations, responsible for the knowledge portfolio of companies; knowledge and knowledge management consultants; globalization experts, focusing on the internationalization of research and development, science and technology, and innovation; experts in university/business research networks; and political scientists, economists, and business professionals.
4. *Interested global readership:* Finally, the Springer book series addresses a whole global readership, composed of members who are generally interested in knowledge and innovation. The global readership could partially coincide with the communities as described above ("academic communities," "decision makers"), but could also refer to other constituencies and groups.

Elias G. Carayannis
Series Editor

Preface

We, doctoral graduates of Dundar F Kocaoglu, compiled this Festschrift[4] to honor him and his work in Engineering Management and especially in Hierarchical Decision Modeling (HDM). He is known to us all as “Dr. K”.

Dr. K is a legend in the field of Engineering Management. His contributions to Engineering Management began with his creation of the “Engineering Management Program” at the University of Pittsburgh in the late 1970s. In the 1980s, he moved to Portland State University to start his second engineering management program. Dr. K graduated 26 PhD from 1981 to 2014. Their topics and current position of employment are listed below.

At University of Pittsburgh:

1. **John Shepherd**, 1981; Optimal Project Portfolio Under Multiple Criteria; Management Consultant, Pennsylvania
2. **Amir Sadrian**, 1986; Portfolio Selection and Resource Allocation for R&D Projects Using 0-1 Goal Programming, Bell Labs (retired), New Jersey
3. **Margaret Shipley**, 1986; HDM for Strategic Planning and Resource Allocation in Academic Institutions, University of Houston, Texas
4. **Hugo Gomez-Guzman**, 1986; Production Scheduling in a Manufacturing Cell, Management Consultant, Mexico
5. **Jang Ra**, 1988; Analysis of Expert Judgments in HDM, University of Alaska (retired), Alaska

At Portland State University:

1. **Guven Iyigun**, 1994; Strategic R&D Portfolio Selection; Unilever, Europe
2. **Sida Zhou**, 1995; Aggregation of Group Decisions; Intel Corp., Oregon

[4] In academic world, a Festschrift is defined as a volume written to honor an academic during his or her life. Generally the volume is composed of articles by the doctoral students of the academic person—Wikipedia.

3. **Karen Beekman Eden**, 1997; Information Technology in the Health Care Industry; OHSU, Oregon
4. **Tugrul Daim**, 1998; Technology Eval'n. and Acquisition Strategies in the U.S. Electronics Mfg. Industry; PSU, Portland
5. **Tom Long**, 1998; Culture and Strategy in the Electronics Industry; CEO, Oregon
6. **Erwin L. "Al" Herman**, 1998; Strategies in the U.S. Electronics Industry; CEO, Ohio
7. **Razif Abd. Razak**, 1999; Site Selection for Petroleum Explorations; Universite Technologia, Malaysia
8. **Robert Martin**, 2002; A Unified Model for the Software Development Process; Management Consultant, Oregon
9. **Toryos Pandejpong**, 2002; Technology Selection in the Petrochemical Industry; King Mongkut University, Thailand
10. **Stacey E. Ewton** (**Schultz**), 2003; Impacts of E-Commerce Technologies on Business Processes; CEO, Oregon
11. **Nathasit Gerdsri**, 2004; Technology Roadmapping for Emerging Technologies; Mahidol University, Thailand
12. **Jonathan Ho**, 2004; Strategic Technology Choices for Semiconductor Manufacturing Industry , Yuan Ze University, Taiwan
13. **Audrey Alvear**, 2005; Technology Strategies in a Developing Economy; Consultant, California
14. **Hongyi Chen**, 2007; Sensitivity Analysis in Decision Making; Univ. of Minnesota, Minnesota
15. **Iwan Sudrajat**, 2007; Supply Chain Management in U.S. Electronics Manufacturing Industry; Research Manager, Indonesia
16. **Pisek Gerdsri**, 2009; Nat'l Technology Policies for Emerging Nano-Tech. Applications; SCG, Thailand
17. **Kenny Phan**, 2013; Innovation Measurement; PSU, Portland
18. **Pattharaporn Suntharasaj**, 2013; International Collaboration in Science & Technology; NSTDA, Thailand
19. **Nasir Sheikh**, 2013; Solar Photovoltaic Technology Assessment; SUNY-Stony Brook, South Korea
20. **Thien Tran**, 2013; University Knowledge and Technology Transfer; Consultant, Texas
21. **Ilknur Tekin**, 2014; Green Innovativeness and Financial Performance; Nike, Portland

Dr. K's contributions to our field have been in multiple dimensions. He was the second Editor-in-Chief for the IEEE Transactions on Engineering Management. Under his tenure, the journal became one of the top journals. Dr. K started PICMET (Portland International Center for Management of Engineering and Technology) in 1991. Since then, the annual PICMET conference has become the premier conference in our field. It now alternates between Portland and an international location.

The recent out-of-Portland conferences have been held in Korea, Turkey, South Africa, Thailand, Canada, and Japan.

This book has 15 chapters written by PSU doctoral graduates. The theme of the book is concentrated on Hierarchical Decision Modeling.

The first four chapters (1, 2, 3, 4) present HDM applications for Technology Assessment. The following four chapters (5, 6, 7, 8) present HDM applications for Strategic Planning. Next three chapters (9, 10, 11) present National Technology Planning applications. Final four chapters (12, 13, 14, 15) present Decision-Making Tools developed either by development of new HDM applications or for use with existing HDM applications

We would like to thank Dr. K for his contributions to the field. The following section describes the introductory fundamentals of HDM in his own words:

> Implicit in the development of decision models is a complex process through which relative values are assigned to the various decision elements. The coefficients in the objective function of an optimization model are the weighted contributions of the decision variables to the objective. The scores used in project selection methods are the relative importance measures of the various criteria and attributes. Probability distributions reflect the relative likelihood of the occurrence of various events.
>
> In some cases, these relative values can be obtained by a straightforward measurement of a quantitative or quantifiable characteristic of the system. Cost, distance, time, and probabilities of repetitive events are examples of such measurable values. In most cases, however, the values are not in a readily measurable form. It is seldom that the decision maker deals with repetitive events. A vast majority of decisions involves uncertainty of the occurrence of a one-time event and the risk of its outcome. For example, in many cases, probabilities cannot be determined from previous observations because of the non-repetitive nature of the events. Relative impact of emerging technologies on a company's objectives cannot be measured because the technologies have not even been developed yet.
>
> However, the decision makers can typically make educated guesses about the likelihood of the outcomes. Their judgment based on years of experience on similar conditions in the past reflects the relative strength of their belief in the occurrence of an outcome in comparison with another outcome. Similarly, the weights assigned to criteria, attributes and other parameters in decision models represent the final impacts of interrelated actions on the outcome of those models.
>
> Subjective probabilities, importance weights, and the relative contributions of decision variables have two characteristics in common: First, the measurements are in ratio scale. Second, although they cannot be measured by direct objective methods, they are implicit in the value judgments of the decision makers.
>
> In HDM, the subjective judgments expressed in pairwise comparisons are converted to relative weights in ratio scale. This is done by a series of mathematical operations on three matrices. The methodology can be used for quantifying the judgment of a single decision maker, or multiple decision makers. When multiple decision makers are involved, the HDM approach is an effective way to form consensus among decision makers where the members of the group have different goals. HDM links the decision elements at multiple levels of organizational entities, in which decisions at the operational level are made in support of higher level goals and objectives, and when the objectives are met, the final results of the operational decisions are transformed into benefits for the organization. This is a systematic process, but it is difficult to quantify the direct relationships between the benefits at the top of decision hierarchy and the operational decisions at the bottom without dividing the space between the top and bottom of decision hierarchy into intermediate levels. That is what the HDM does.

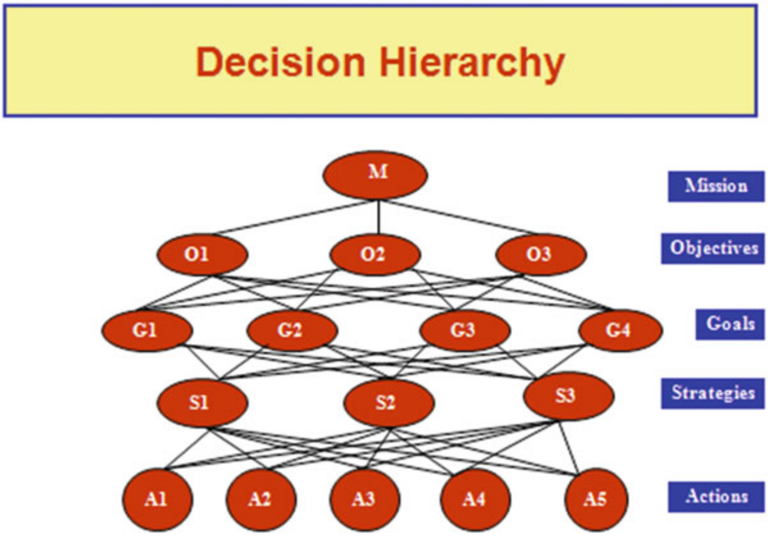


Fig. 1 A typical hierarchical decision model (HDM)

The number of levels in HDM depends upon the logical sequence of the decisions involved. If too many levels are identified, the number of measurements becomes exceedingly large; if too few levels are used, measurements become difficult because of excessive aggregations.

The typical starting point to trigger a decision process is the establishment of the mission and objectives. These are broad statements specifying the overall benefits expected from an organized activity. Because of the abstract nature of objectives and the difficulty of developing a precise measure of effectiveness for the benefits, the objectives need to be disaggregated into specific goals with recognizable targets. Once the goals are defined, the approach to achieve those goals has to be developed. This is done by establishing strategies and identifying specific actions as the components of the strategies.

Each level of such a decision hierarchy consists of multidimensional, often conflicting decision elements. At the top, multicriteria objectives contribute to the fulfillment of the mission. At the bottom, each action becomes a part of one or more of the strategies with varying degrees of contribution to each strategy. Strategies impact multiple goals. The achievement of each goal results in meeting one or more of the objectives. These impact relationships are depicted in a typical HDM Hierarchy in Fig. 1.

When the arcs connecting the nods in Fig. 1 are measured by quantifying expert judgments, a vector at the "Objectives" level and a series of matrices below the Objectives are obtained. Relative value of each decision element at each level of the hierarchy is then determined by performing matrix multiplications among the levels. The final result is a normalized set of values representing the relative contribution of each action to the mission of the organization.

Portland, OR, USA Tugrul U. Daim

Contents

Part I
Technology Assessment

Chapter 1
Technology Assessment: Criteria for Evaluating a Sustainable Energy Portfolio

Dundar F. Kocaoglu, Tugrul U. Daim, Ibrahim Iskin, and Yasser Alizadeh

Abstract Selecting an appropriate portfolio of energy resources is a complicated and multidimensional problem. Affected by numerous factors stemming from multiple perspectives including technical, economic, environmental, social, and political, each energy resource has varying degrees of appropriateness for different regions/energy systems. Although there is significant amount of research attempting to incorporate different pieces of aforementioned considerations in an assessment framework very little has addressed this issue in a complete manner. This research study reviews assessment studies in the energy field and identifies over 50 assessment criteria that fall under aforementioned perspectives. Output of this study is expected to provide a knowledge database for practitioners and scholars for enabling development of more comprehensive assessment frameworks. Ultimately, this study is expected to contribute to energy planning field for development of more sustainable energy portfolios.

1.1 Introduction

Nature of resource planning has changed dramatically since 1970s due to increased diversity in resource options such as renewable alternatives, demand side management, cogeneration of heat and electricity in industrial applications, and deregulation of the energy market. New objectives have been added to the utilities' decision-making processes beyond cost minimization, requiring utilities to address environmental and social issues that may emerge as a result of their operations [1]. Moreover, technological development, instability in fuel markets and government regulations started taking place faster than ever before and as a result, complexity and uncertainty involved in utility decision-making practices have become increasingly significant.

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During the 1970s, nature of decision-making in energy planning was mostly single dimensional, aiming to design energy systems in a least cost manner [2, 3]. In the 1980s, environmental awareness has started to show itself in energy planning considerations. This situation let increasing use of multi-criteria decision-making (MCDM) approaches attempting to address trade-off between environmental and economic decision attributes [4, 5]. One of the most significant reasons behind this situation stems from MCDM methods' ability to address decision issues in the presence of multiple objectives and stakeholders. This feature has been observed to be very important due to complexity of the energy systems where different stakeholders have varying degrees of interest on different decision attributes.

Increasing concerns on peak oil, energy security, global warming; and increasing interest on renewable energy alternatives have drawn significant amount of attention in the energy literature. Although fossil-based resources seem to continue playing a major role in world economy in the short and medium term, development of resource diverse energy portfolios is becoming more and more favorable among researchers and practitioners. Selecting an appropriate energy portfolio is a complex and multivariable problem that requires taking a number of high level perspectives into consideration such as technical, economic, environmental, social, and political. Despite the significant amount of research in the literature, there still needs more research for extending the scope of existing energy technology assessment approaches.

1.2 Assessment Criteria Employed in the Energy Technology Assessment Literature

In this section each assessment factor is going to briefly explained along with a number of reference studies.

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1.1. Power Plant Availability
1.1.1. Technical Availability
1.1.2. Resource Availability
1.2. System Efficiency
1.2.1. Heating Value
1.2.2. Thermal Efficiency
1.3. Capacity factor
1.4. Fuel Logistics
1.5. Supportive Technology Accessibility
1.6. Power Plant Lifetime
1.7. System Compatibility and Integrity
1.8. Operational Flexibility and Modularity
1.9. Technology Maturity

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1.10. Workforce Availability
2. Assessment Factors under Economics Perspective
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2.2. Operational and Maintenance Cost
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2.4. Waste Management Cost
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2.7. Grid Reinforcement Cost
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5.4.4. White Certificates
5.4.5. Subsidies/Grants/Loans
5.4.6. Tax Exemptions
5.4.7. Carbon Tax/Carbon Cap and Trade

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(continued)

5.5. Public R&D Network Infrastructure (Linkage of Industry, Universities, State-owned Labs, Standard Setting Organizations)
5.6. Technology Transfer Availability and Costs
5.7. Current and Future Market Size
5.8. Reserves/Production Ratio (R/P)
5.9. National/International Standards
5.10. Resource Diversity
5.11. Technological Diversity
5.12. Overall Security of the Energy Supply

1. Assessment Factors Under Technical Perspective

1.1. Power Plant Availability

Power plant availability is a ratio defined as the division of amount of time that electricity/heat (energy) production is up by the total amount of time in a specific analysis period [6]. Power plant availability can be approached with respect to a number of factors such as technical and resource availability.

1.1.1. Technical Availability

Technical availability is a ratio defined as the division of amount of time that electricity/heat (energy) production is up by the total amount of time in a specific analysis period—excluding downtime caused by lack of fuel and resources [7–9]. A power plant can be out of service due to maintenance, repairs [9] as well as unsuitable weather conditions [10]. Technical availability is subject to change based on the technology in question and continuously improves due to technological progress. Most steam-electric power plants such as: coal, geothermal, oil, natural gas, biomass as well as nuclear power plants, have 80–96 % availability. Photovoltaic, wind, and hydro power plants have lower availability values ranging between 20 and 50 % [7, 8]. Most studies refer to technical availability [11] in assessment purposes. There are many studies on technical availability of nuclear power plants [12–14].

1.1.2. Resource Availability

Resource availability/reliability refers to degree of reliability in accessing required resources. Fuel availability is defined as the division of the amount of time that electricity/heat (energy) production is up by the amount of total time in that specific period—excluding downtime caused by scheduled maintenance and repair activities. Resource availability is effective specifically on solar, wind, and hydropower plants due to significant direct effects caused by atmospheric and climatic changes [10]. Based on the energy source, measurement of resource reliability is calculated using two different approaches. First approach employs a ratio defined as the division of amount of time that a power plant is able to produce energy over a certain period by the analysis period. This ratio is mostly used for wind, solar, and other renewable sources [15]. Second approach employs reserves to production ratio which refers to number of years that a certain nonrenewable energy source can be supplied in an economically feasible manner [6]. This ratio can be calculated with respect to both increasing and stable demand. Relevant studies in the area include water availability for three types of power plants in Europe [16], gas availability for thermoelectric power plants [17], and forest biomass [18]. Furthermore, there have been studies attempting to explore wind availability in various regions such as Germany, Egypt, Canada, and Taiwan [19–22].

1.2. System Efficiency

System efficiency is a ratio which is defined by division of output energy by input energy. Output energy is the desired form of energy which power plants are using input energy to convert into. Efficiency ratio is always smaller than 100 % as some of the input energy is always lost during the conversion process [7, 8, 23]. Heating value and thermal efficiency are important in assessing fuel economies of different systems [24]. Among different methods of determining a power plant's efficiency, variations of data envelopment analysis (DEA) methods have been used more than any other [25–28].

1.2.1. Heating Value

Heating value of a given fuel type has important impact on overall efficiency of power plants. Heating value or calorific value is defined as the amount of heat released during the combustion of per unit of substance [23, 29]. Heating value becomes particularly important in comparing biofuels with fossil-based fuels. For instance, there has been considerable amount of scholarly research on comparing ethanol with conventional petroleum-based fuels. Although heating value of ethanol is lower than petroleum-based fuels, higher thermal efficiency of ethanol-based fuel makes it a good fuel candidate [24]. Moreover, heating values of bio-based chars are comparable with those of lignite and coke; heating values of liquids are comparable with those of oxygenated fuels such as methanol and ethanol, which are much lower than those of petroleum fuels. Heating values of biogases are also comparable with gasified coal and are much lower than that of natural gas [30].

1.2.2. Thermal Efficiency

Not only the type of fuel but also the combustion processes can significantly affect overall system efficiency. Thermal efficiency is defined as the ratio of heat actually produced in a combustion process compared to total amount of heat that would be released if the combustion process was perfectly complete [31].

1.3. Capacity Factor

Capacity factor is defined as the amount of energy that a power plant produces over a period divided by the amount of energy it could have produced if it had run at full power over the analysis period [7, 8]. Besides the availability and efficiency, power plant capacity plays a key role in decision-making practices. Power plant design, embedded technologies as well as characteristics of energy source have major impact on nominal capacity of power plants. Hence, although high capacity power plants are desirable, it should be noted that they are limited by the geographical limitations such as water potential (flow and head values) for hydroelectric power plants [11], elevation and radiation (kWh/m^2/day) for solar power plants, annual crop production (kton/year) for biofuel-based plants [32], and wind speed for wind farms [32, 33].

At this point, it should be noted that capacity factor should not be confused with plant availability. Accordingly, plant availability refers to time aspect of the efficiency, whereas capacity factor refers to amount of energy that can be generated at full capacity at a given time. For instance, oil, natural gas turbines and natural gas combined cycle plants have 92, 91 and 91 % availability rates, while they have 26.2, 16.6 and 38.2 % capacity factors. Furthermore, wind power plants have greater availability of 38 % as compared to their capacity of 32.1 %, while photovoltaics have less availability of 20 % as compared to their capacity of 22.1 % [7, 8].

1.4. Fuel Logistics

In many cases, energy technologies have particular requirements in terms of transmission and storage of process inputs and energy outputs. Fuel logistics is used to capture level of difficulty in transportation and storage of fuels as well as conservation of undesired process outputs. For example, in the case of biofuel power plants, feedstock has to be delivered to power stations in a limited amount of time due to decomposing of organic matter which decreases the efficiency factor. In the case of nuclear power plants, specially equipped transportation devices are used to deliver radioactive fuel and waste. Moreover, due to intermittency of wind turbines and solar power technologies, utilities invest in storage technologies to increase efficiency levels by storing energy at peak production periods and save it for peak load periods [34]. Current storage technologies vary in terms of technology maturity and capacity, and viability of these investments depend on technological as well as load characteristics. It has been observed that literature regards fuel cell technology as one of the most promising storage alternative in the future. Fuel cells are also favored for their ability to be transferred from one location to another, enabling it to be a promising energy transmission mediator [35].

1.5. Supportive Technology Accessibility

In addition to distribution and storage technologies some power plants require supportive technologies as well. This variable is especially more applicable in case of nuclear power plants where uranium enrichment capability is considered as one of the most important factor in determining the fuel cost of nuclear energy [36].

1.6. Power Plant Lifetime

Power plant lifetime refers to expected effective lifetime of a power plant. Most of the time it is embodied in the internal rate of return or cost–benefit analysis, but essentially lifetime of a power plant is an important technical criterion which has a significant relationship with fatigue of mechanical components, maintenance, downtime occurrences, and even safety risks [37–39]. In the case of photovoltaics, system lifetime, influenced by sudden temperature changes that create deformation on the panel surface, is an important limitation that drives the energy production costs higher [40].

1.7. System Compatibility and Integrity

Most of the renewable energy generation sites reside in remote places which bring out the need to connect newly built generation units with existing transmission grids. Since generation capacity of renewable energy alternatives is less predictable than conventional power plants, this situation might cause failure in another part of the grid due to power congestion [41, 42]. The same risky situations in transmission related challenges are also applicable to generation capacity planning and operations decisions due to increased uncertainty. Accordingly, there is an increasing need for new grids and generation technologies to be more responsive to rapid changes for maintaining reliability.

1.8. Operational Flexibility and Modularity

Operational flexibility is one of the technical metrics which refers to ease and speed of scaling output of a given power plant up and down. Accordingly, base load power plants are operated for supplying continuous demand which is not subject to huge fluctuations whereas peak generation units act as back-up units and are suitable for instances where demand fluctuate at relatively high frequencies. Currently, base loads are mostly supplied by fossil and nuclear-based power plants which perform most efficiently at higher utilization rates, but cannot respond to rapid load fluctuations. Peaking power plants are based on reliable and fast starter capabilities with significant generation capacities such as natural gas turbines and hydropower plants. However, there are also hybrid power plants such as wind-gas [43], solar-gas-storage [44], and geothermal [45] which have been proposed as proper alternatives for peaking power plants.

In the literature, modularity has been assessed in terms of providing support of deregulation of energy markets and accelerating of rural electrification [46]. Solar power panels are good examples of modularity, by adding or removing new panels into the existing system power production can be aligned in a small amount of time [47]. On the more conventional power generation side, modular nuclear reactors with improved safety features became more available after the Three-Mile Island accident. Economics of small modular reactors compared to large light water reactors, whose power output is 10 times higher, is a major issue for market adoption [48]. Modularization has been proposed as a nuclear power plant design-fabrication approach for increasing flexibility [49] and reducing construction costs [50].

1.9. Technology Maturity

A mature technology is defined to have been in use for long enough that most of its initial faults and inherent problems have been removed or reduced by further development. Technical maturity is essential for evaluation of applied technology alternatives [51–54]. Emerging technologies that are more mature have higher rate of reliability and lower costs [55, 56]. As for renewable energy technologies Wang et al. [52] and Wang and Jing et al. [53] suggest four technological development stages for defining maturity level. Accordingly these stages are: technologies that are in laboratory development; technologies that are only performed in pilot tests; technologies that are in the market, but could still be improved; and consolidated technologies which are close to reaching their theoretical limits of efficiency.

1.10. Workforce Availability

Workforce availability variable refers to match between available workforce in the market and level of expertise in required expertise for operation of a particular energy technology. This case applies to nuclear as well as newly established renewable energy alternatives. In the case of large deployments of such technologies there will be a need for qualified people in technology development and operations. Thus, opening new educational programs about related expertise as well as promoting people to follow their career in new fields will be required.

2. Assessment Factors Under Economics Perspective

2.1. Capital Cost

Capital costs include cost of land, cost of facility and required equipment as well as cost of complementary technologies [57]. Cost of labor and any cost item related to maintenance is not considered under this item [6]; however, some research studies address investment costs and O&M cost together [58, 59].

2.1. Operational and Maintenance Cost

Wages of employees, product and services related to plant operation as well as any cost items associated with operations and maintenance is considered under operational and maintenance cost [7, 8, 60]. O&M are divided into two subcategories, namely fixed and variable costs. Fixed O&M costs are yearly costs for operation and maintenance that are not independent from the amount of electricity produced. Variable costs are directly related to the amount of electricity produced [7, 8, 11].

2.2. Fuel Costs

Fuel costs may include extraction, transportation, and fuel processing for use in a power plant [7, 8].

2.4. Waste Management Cost

Clean-up costs refer to cost items related to collecting, transporting, processing, recycling, storing or disposing wastes after energy production process as well as decommissioning costs of facility. This cost item cannot be neglected due to the fact that some energy technologies' process outputs are toxic to the environment and should be disposed or contained safely. Selected literature on the issue covers fossil fuel power plants [61], disposal of materials in nuclear power plants [62], and process outputs [7, 8].

2.5. Land Use

Land use of a given energy technology is the area occupied for producing the energy and where the infrastructure is located. Moreover, apart from infrastructure there may be a need for larger land requirements for extracting and processing process inputs. Literature indicates that both direct and indirect land use should be taken into account as part of the life-cycle in order to enable comprehensive decision-making practices [63]. This variable has been observed to be significant in the case of biofuel technologies, which is also referred to as indirect land use. Accordingly, biodiversity has been negatively influenced by intensive agriculture, forestry and the increase in urban areas [64]. Renewable energy sources often are regarded as dispersed, requiring substantial land resources in comparison to conventional energy sources [63]. Selected studies on the matter cover impacts of biofuel [65] and solar [46] technologies.

2.6. Grid Connection Cost

Renewable energy sources may be located in remote areas and in such cases cost of grid connection plays an important role in economic feasibility. Cost items regarding power grid connection largely depends on the distance between energy source and point of coupling with the grid, voltage level of the connection line and capability of applying standardized equipment such as cables and bulbar [57, 66].

2.7. Grid Reinforcement Cost

Existing power grids are designed to handle supply and demand by considering future load forecasts. Connecting new energy sources to existing grids in order to deliver electricity to larger consumption areas might lead overload in local grids. In the case of renewable energy alternatives, fluctuations in energy supply also affect the reliability of the grid. Thus, weak points in transmission or distribution networks have to be identified and energy flow should be managed by forecasting changes on the external effects. Cost items related to grid reinforcement largely depend on new energy resource's power capacity and existing grids' tolerances, fluctuations in the power flow caused by externalities, managing energy reliability and quality [57, 67].

2.8. Investment Costs into Regulating Power Plants Caused by Integration of Renewables

In the case of renewable energy resources, due to fluctuations in power production demand for reserve power regulation will be increased. Thus, flexible power generation technologies like gas turbines will be necessary to speed up power generation in a small amount of time and storage technologies like pumped hydro or compressed air energy storages will become necessary to compensate losses during excess power generation [67–71]. This variable is going to be measured by using monetary value. This cost item can be replaced under operational and maintenance cost in economical assessments.

2.9. Change of Operational Costs of Conventional Power Plants due to the Integration of Renewables

Large scale integration of renewable energy alternatives lead in significant fluctuations in power generation which not only decrease the utilization of conventional power plants decreases but also reduce plant life time due to improper usage. Moreover, part load utilization decrease conventional power plants' efficiency factor and in turn fuel costs increase [67].

2.10. Private R&D Expenditures

Without institutional support, emerging energy technologies are limited by their financial restraints from penetrating the commercial market. R&D expenditures allocated today will shape the development pathways for energy production methods for decades to come [72, 73]. A measure of commitment to developing new energy technologies is referred to as R&D intensity (defined as R&D as a percentage of net sales). Examining R&D intensity across sectors reinforces concerns about the level of investment in R&D [72].

2.11. Creation of Competitiveness and Supportive Industries

Different types of energy technologies create or expand different industries on the local and national scale. For example, investing in oil or gas energy fosters investment and development in refineries, mining and petrochemical industries, whereas investing in solar or nuclear energies motivates other industries to more development. Therefore, the energy technology selection may determine the development and creation of supportive industries which may be realized as return on investment on local and national scale.

3. Assessment Factors Under Environmental Perspective

Importance of environmental aspect cannot be neglected in case of assessing technologies [74–81]. In the literature there are various studies focusing on assessing each energy technology in terms of impact on water habitants, soil habitants ([82, 89]).

3.1. Air Conservation

Air conservation has been divided into subtopics due to specific emission issues addressed by international agreements as well as other air polluters and gas emissions mentioned in the literature. While calculating amount of emissions released, it is very important to have a system perspective rather than just focusing on one specific aspect. A study conducted by Nguyen et al. [83] assessed emission profile of cassava ethanol for fuel production. Study approached the problem by considering emissions during plantation, harvest, and conversion of raw material into fuel as well as fuel's usage in combustion engines. Such a wide perspective is expected to reduce unexpected long term consequences.

3.1.1. Greenhouse Gas Emissions

According to Kyoto protocol, participant countries agreed to reduce the emissions of six specific green house gases, namely CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide), HFC (hydrofluorocarbons), PFC (perfluorocarbons), and SF_6 (sulfur hexafluoride). Stated level of reduction between 2008 and 2012 is at least 5 % below 1990 levels [60]. Parameter GHG emission is usually one of the important criteria in most of the studies [6, 24, 46, 65, 82–89].

3.1.2. Other Air Polluters

- NO_x
- CO
- SO_2 and its equivalents
- PM_{10}
- Dust

3.2. *Land Conservation*

In general, land degradation refers to reduction in biological productivity of agricultural lands, pastures, rangelands, and woodlands [89–92]. Causes of land degradation is various, so in the name of research scope we are going to be focusing on potential energy related effects of altering hydrology, large dams, vegetation removal, inappropriate agricultural practices, excess mining, and acid deposition [92]. United Nation's Commission on Sustainable Development has developed a list of indicators on sustainable development [172]. In terms of sustaining soil quality this list includes land degradation, pesticide use, and nitrogen balance as important indicators that should be followed up [82]. In our study, these variables are going to be used as indicators of land degradation.

3.2.1. Soil Nutrient Balance

Soil nutrient balance variable becomes an important variable in case of bio crops plantation. Essential nutrient elements mentioned in the literature are carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, boron, chlorine, copper, iron, manganese, molybdenum and zinc [94]. There have been studies in the literature identifying effects of growing bio crops as well as pesticide use and residue burning [24].

3.2.2. Soil Pollution

Its distinctive nature and potential hazard make nuclear waste not only the most dangerous waste ever created by humanity, but also one of the most controversial and regulated with respect to disposal [62]. Soil contamination occurs in many ways such as industrial waste, sewage, emissions from combustion of fuels as well as pesticides used in farming [95]. Contaminants might be pesticides, lead like heavy metals, solvents, petroleum hydrocarbons as well as nuclear wastes. Such contaminants have negative effects on ecosystem and in order to manage the waste and sustain soil quality government organizations set regulations regarding disposal. There are remarkable examples related to soil contamination even for the clean perceived energy technologies. For example, in the case of biofuel production there have been studies identifying negative effects of pesticide as well as fertilizer use in bio crop plantation [24]. In the case of solar power plants there is risk leakage of coolant liquids that contains glycol, nitrites, chromates, sulfites, sulfates, aromatic alcohols, oils, and such potentially harmful matters (OECD/IEA).

3.4 Water Pollution: Impact on Water Resources

Water is another resource that is negatively affected by energy production related activities. Water pollution can be defined as any impurities that are unnatural to water. A study done by Kowalski and his colleagues includes set of pollutants that are proposed to be significant in assessing water quality with respect to energy technologies [89]. As predicted each energy technology has different pollutants that come into play. There are large numbers of water pollutants that have been identified and tracked by US Environmental Protection Agency. To see the complete list of water contaminants you can use US Environmental Protection Agency website [96].

3.4. Noise

The requirements for preventing and mitigating noise pollution are increasingly important subjects [97]. The frequencies of this noise due to steam ejection range from a low frequency region to a very high frequency region [98]. Also, there are some studies on noise and combined cycle power plants [97], gas turbines [99], nuclear power plants [100], wind power plants [101] and solar [46].

3.6. Light Pollution

Animals can experience increased orientation or disorientation from additional illumination and are attracted to or repulsed by glare, which affects foraging, reproduction, communication, and other critical behaviors [102]. For example, light pollution reduces the amplitude of migration of Daphnia (a type of a zooplankton) if light levels are sufficiently high at night [103]. Ecologists have widely studied effects of natural night lighting on species interactions [102].

3.6 Smell

Smell variable refers to disturbance that has negative effect on both human and natural habitat. Smell has been used in assessment of energy technologies by Kowalski and his colleagues [89] by using qualitative methods. In our study smell variable is going to be measured by using utility curve functions.

3.7. Wind Pattern Changes

Wind pattern changes variable refers to decreased speed of wind and its effects on natural balance in the case of using wind turbines to extract energy from wind power. There have been some concerns about negative impacts of decreased wind speed on atmospheric circulation [104]. Effects have not been proven to be significant yet, but potential effects are stated to be abnormal local temperature changes around the wind farm areas. Until claims of such studies are proven this variable is not suitable to use. However, this variable is proposed to be measured by level of temperature changes.

4. Assessment Factors Under Social Perspective

4.1. Visual Impact (Aesthetics)

If a power generation system is built near an area of natural beauty, the visual impact can be significant. In the case of modules integrated into the facade of buildings, there may be positive aesthetic impact on modern buildings in comparison to historic buildings or buildings with cultural value. The ability to be "easily integrated in buildings in an aesthetically pleasant manner" [46] is desirable most of the time, although what is aesthetic is subject to debate. As noted by Tsoutsos et al. [46], solar technologies in buildings are good examples.

4.2. Public Acceptance

Perception and awareness of individuals and societies have influenced the adoption of many technologies, especially the emerging ones. Social perception has often been an obstacle to the development and execution of nuclear policy [105]. Another famous debate is on biofuels, also known as the "food vs. fuel" debate. Some believe that using land for growing crops for biofuel production versus using the land for growing food leads to increased food prices. Although some studies confirm this belief at least in the short run, according to Rathmann et al. [106], "We find that the emergence of agro-energy has altered the land use dynamic, albeit not yet significantly, with a shift of areas traditionally used to grow foods over to crops to produce biofuels. This has been contributing to raise food prices in the short run. However, it is probable that this is not the only factor determining this trend, nor will it last over the long run. The challenge is to conciliate the production of biofuels with the production of foods in sustainable form" [106]. Some researchers reject the validity of this idea: "In recent years the share of bioenergy-based fuels has increased moderately, but continuously, and so did feedstock production, as well as yields. So far, no significant impact of biofuels production on feedstock prices can be observed" [107]. There are many, however, who believe that fuel and food crops can coexist without one being sacrificed or favored over the other. However, success of this equilibrium depends on international policy [108]. Different technologies among different people with different levels of awareness, experiences and training have different levels of opposition or support. As an example, a recent research in Greece regarding biofuel reveals that only 27.3 % believe that priority must be given to biofuels over other renewable energy sources [109]. In the meantime media, governments and NGOs could influence these values and beliefs. Because of this many think the success of any technology depends on the mutual development of society and technology [110].

4.3. Job Creation

Job creation is the extent to which an energy source can create jobs [56]. Numerous authors have mentioned job creation as a criterion for any energy technology selection [6–8, 51, 84, 85, 88, 111–115]. This criterion could include direct or indirect job creation. Since job creation is a quantitative concept, it could be measured by the existing statistics from the current energy source technologies, although this estimation always includes errors due to type of technology, size of power plants, etc. Also, technological changes and innovations are difficult to take into account. Despite this, there are some studies which compare the job creation capability of some energy sources such as refs. [116, 117].

4.4. Impact on Buildings and Historical Monuments

Emissions have impacts on buildings and historical monuments. The emissions taken into consideration are primarily conventional air pollutants, i.e., sulfur dioxide (SO_2), nitrogen oxides (NO_x) and total suspended particulates, as well as GHGs. Fossil fuel power plants if near to historical sites and buildings may cause especially destructive effects, although other energy sources can also lead to such destruction. For instance, construction of a new hydropower plant and dam (Sivand

Dam) in Fars province, Iran, close to The Cyrus tomb (known as "Cyrus the Great", born in 600 BC and the founder of the Achaemenid Empire) and ancient Persian capital of Persepolis, caused a big controversy over the destructive impact of increasing humidity on the this historic structure [118].

4.5. Safety

Public safety is the impact on public health (increases in morbidity and mortality rates). Mortality rate is defined as the death rate; the mortality rate of a disease is the ratio of the number of deaths from a given disease to the total number of cases of that disease. It is measured by the Years of Life Lost (YOLL). Morbidity rate is the number of cases of a given disease occurring in a specified period per unit of population. Nuclear waste issues, related to uncertainties in geologic disposal and long-term protection, combined with potential misuse by terrorist groups, have created uneasiness and fear in the general public and remain stumbling blocks for further development of a nuclear industry in a world that may soon be facing a global energy crisis [62].

5. Assessment Factors Under Political Perspective

5.1. Security

Many authors consider security a very important criterion for energy source selection [41, 46, 83, 89, 119–134]; however, none have addressed the issue from all aspects. Having disrupted by recent oil crisis, effective international and geopolitical forces have been put UK's energy research agenda [41]. From the consumer's perspective, fuel or energy sources have to be reliable and resilient. Reliability means users should be able to access the energy they require, when they require it. Many authors address this as the "security for energy supply" issue and define it as consistent availability of sufficient secure supplies of energy [119]. Several studies argue that energy security is an important criterion for the assessment of renewable energy [121–123, 135] and some have examined energy security for specific energy sources such as solar [46]. Resilience (or invulnerability) is another aspect of energy security and is defined as the ability of the system to cope with shocks and changes. This aspect has been minimally addressed by a few authors such as Markandya and Pemberton [131], Costantini et al. [124], and Jun et al. [130]. Most of the time, however, energy vulnerability is tied to traditional energy sources such as oil and gas. Some authors have proposed methods to estimate the cost of oil dependency [125]. For solving the issue, some propose diversification of the energy portfolio [133], some studies propose that reliance on indigenous resources may increase energy security [126, 128, 133] even if this reduces diversity [128], and some suggest a shift to renewable energies [126, 136].

5.2. IPR (Intellectual Property Right)

Intellectual property (IP) is a term referring to a number of distinct types of creations for which property rights are recognized and the corresponding fields of law. Common types of intellectual property include copyrights, trademarks, pat ents, industrial design rights, and trade secrets in some jurisdictions [137]. IPR can have an impact on technology transfer. Intellectual property rights (IPRs) and the transfer of low carbon technologies to developing countries have been the focus of sustained disagreement between many developed and developing country Parties to the United Nations Framework Convention on Climate Change (UNFCCC) [138].

5.3. Power Market Structure and Regulations

An energy system is driven by a combination of markets and regulations [41], so what motivates private companies to invest in a particular energy source is influenced by market regulations and degree of privatization of the market. Regardless of power market models or power structure, different regulations applied by governments also impact all private and state-owned companies' behavior regarding the selection and investment in energy source technologies [139].

5.4. Incentives/Government Financial Support/Disincentives

Government incentives variable refers to tools that government agencies can take advantage to promote specific energy technologies. There are number of tools available focusing on different aspects of diffusion [41, 140].

5.4.1. Information Campaigns

Information campaign variable refers to government incentives that aim to educate public about new technologies in order to eliminate biases and prejudices [41].

5.4.2. Regulations/Standards

Importance of regulations emerges from the fact that they obligate some certain expectations. For example, many states have set objectives about increasing the percentage of electricity coming from renewable resources in a given amount of time. Specifically, Oregon needs to generate 25 % of its electricity from new renewable energy resources by 2010 [141].

5.4.3. Market-Based Instruments

MBIs are “instruments or regulations that encourage behavior through market signals rather than through explicit directives” [142]. Focus of market-based instruments may vary depending on the matter that needs to be controlled. There have been examples applied on sulfur oxide, lead, nitrous oxides, and chlorofluorocarbon release in the USA [143]. Some of the widely mentioned market instruments related to energy issue are carbon tax and white certificates.

5.4.4. White Certificates

White certificates have been applied by a number of European countries in order to increase use of energy efficient technologies. White certificates have the same logic as carbon tax in terms of creating a demand and supply around a specific issue, but differ with its attribution to energy efficiency rather than carbon emission [144]. White certificates are used to set energy efficiency goals that oblige energy suppliers and distributors to meet over a period. Energy savings are measured and certified at the end of every period [145]. Certified energy savings can be traded via white certificates in order to provide extra income through savings. There have been studies focusing on developing policy frameworks that combines voluntarily agreements with white certificates [140]. This variable is going to be measured by monetary value of electricity savings given a period of time by each energy technology compared to existing alternative. This variable is proposed to be used in economic analyses.

5.4.3. Subsidies/Grants/Loans

Subsidies, grants and loans variable refers to financial aids allocated for helping emerging technologies’ diffusion.

Subsidies/Premium Tariffs

A subsidy is financial assistance, either through direct payments or through indirect means such as price cuts and favorable contracts, to a person or group in order to promote a public objective. Government guaranteed loans: the government acts as an intermediary between the agency and the financial institutions as a guarantee of the loan [146]. Many studies point out that subsidies have a strong impact on motivating generation and application of renewable energies. The present health of the industry, although it is based on a relatively fragile system of government subsidies, is helping to stimulate the introduction of improved manufacturing techniques and technology [147]. On the other hand, some argue that subsidies for fossil fuels indicate that renewable energies have not yet achieved their proper niche in the market. Consumers tend to ignore renewable power systems because they are not given accurate price signals about electricity consumption [148]. The subsidy could be applied to the energy producers, distributors, or consumers. The latter one in renewable energy literature is known as “renewable premium tariff” (RPT) [146].

Grants/Bonus

Governments may increase R&D in universities or any state-owned or private research centers or power generator companies by scholarly grants or financial bonuses. Some researchers have discussed the advantages of different bonus mechanisms such as a “pure bonus model” vs. an “optional bonus model” [149].

5.4.6. Tax Exemptions

As stated by Ekins, there have been tax exemptions on the supply side and corporate investments on the demand side where as households have not received such a relief in the UK [41]. A tax exemption is a full or partial immunity from the requirement of paying taxes. Tax exemptions may increase the motivation for investing in any specific field or technology. This policy can assist a country in improving energy efficiency while innovating [140]. New terms such as tradable certificates for renewable electricity and energy savings have also been discussed in this field [150]. Some researchers have focused on identification of positive and negative interactions between energy efficiency and renewable electricity promotion in order to assess whether the choice of specific instruments and design elements within those instruments affects the results of the interactions [151]. Cansino et al. studied all tax incentives applicable to different types of taxes, from direct taxes (personal income tax, corporate tax, property tax) to indirect taxes (value added tax (VAT), excise duty exemptions) and so forth. Additionally, they studied 27 European members and compared their experiences regarding the implications of tax incentives and exemptions [152]. Other researchers have explored the impact of tax exemption regulations on specific energy sources in specific regions [153, 154]. Renewable energy alternatives are widely supported by tax exemptions in order to increase diffusion rate in the USA [155].

5.4.7. Carbon Tax/Carbon Cap and Trade

A carbon tax is an environmental tax that is levied on the carbon content of fuels [156]. A carbon tax is an indirect tax—a tax on a transaction—as opposed to a direct tax, which taxes income. A carbon tax is also called a price instrument, since it sets a price for carbon dioxide emissions [157]. Some studies have shown the real impact of a carbon tax on the GHG reduction in some regions such as Europe, Indonesia, Taiwan, and Japan [158–161]. Another alternative policy considered is carbon cap and trade. The cap-and-trade strategy is considered a more market-driven approach to handling carbon dioxide output. As the Environmental Protec tion Agency (EPA) explains, under this system the government sets an overall emissions cap while creating allowances that enable businesses to emit a given amount. These allowances can be traded, so companies that reduce their emissions can sell surplus allowances to those who would have to pay to a penalty to EPA. In theory, this method allows companies to achieve their maximum allowable output at the lowest cost (US Environmental Protection Agency n.d.).

5.5. Public R&D Network Infrastructure (Linkage of Industry, Universities, State-Owned Labs, Standard Setting Organizations)

R&D spending and patents, both overall and in the energy sector, have been highly correlated during the past two decades. Declining investments in energy R&D in industrial nations will also adversely impact developing nations that often have limited capacity for energy R&D and rely instead on importing, adapting, or collaborative policies to install new energy systems [72].

5.6. Technology Transfer Availability and Costs

In most of the cases, there are core or supportive technologies related to any energy technology which are not affordable in the domestic market, leading the buyer to purchase or transfer the technology from abroad. Availability of these missed pieces and their prices could have an impact on decision-making when selecting energy technologies. The transfer of technology from industrialized nations to developing countries will play an important role in balancing increasing consumption with the need for reducing emissions from fossil fuels [111]. Intellectual property rights (IPRs) and the transfer of low carbon technologies to developing countries have been the focus of sustained disagreement between many developed and developing country Parties to the United Nations Framework Convention on Climate Change (UNFCCC) [138]. Many developing nations have been left feeling frustrated at the lack of progress that has been made in achieving technology transfer in practice [162]. Also, different technology transfer methods could be appropriate for different technologies and different regions. For instance, Michanek et al. reviewed and analyzed the licensing process for nuclear power plants in Sweden [163].

5.7. Current and Future Market Size

Many countries are looking not only to expand their domestic use of renewable energy but also to develop accompanying local renewable energy industries to meet the demand [164]. As an emerging industry, the potential market size plays an important role in establishing the industrial competitiveness [135, 164, 165]. In order to accomplish the economic goal of stimulating economic growth and increasing employment, the potential market size, including those that are domestic as well as international, should be carefully evaluated [165]. A larger market size attracts more companies that are willing to invest, which is helpful to facilitate the development of related industries [56].

5.8. Reserves/Production Ratio (R/P)

Ratio calculates the availability (in years) of a certain type of fuel according to current consumption and the annual consumption increase/decrease rate of each non-energy source for electric power generation [7, 8]. When evaluating the amount of fuel, only well-known sources that can be truly exploited are considered. Several types of models such as the exponential, harmonic and mechanistic Li–Horne models are used frequently to estimate reserves and to predict the production of oil and gas [166].

5.9. National/International Standards

Standards make technology diffusion simpler. Numerous studies have shown that setting some single standards could increase the market size and consequently firms' motivation to adopt the technology or become active in the market [167].

5.10. Resource Diversity

Resource diversity variable refers to level of diversity in energy production systems in terms of source. This variable can be measured by using Stirling's index with the formula as shown below where p_i represents the proportion of fuel type i in overall energy portfolio [127]. Value of the resource diversity is the payoff between resource diversity and cost of increasing energy source diversity by new energy investments. This issue has been addressed by Awerbuch [120] using a portfolio-based electricity generation planning.

5.11. Technological Diversity

Technological diversity variable refers to number of available technologies that can be used to generate electricity from a particular energy source [127].

5.12. Overall Security of the Energy Supply

Overall security variable refers to supply reliability of each energy resource. Data related to this variable can be found by looking at both region and impact of historical crises [127].

1.3 Conclusions

Results show that majority of the assessment criteria used in the literature have qualitative nature which may or may not necessarily be measures using quantitative metrics. Although financial analysis methods have been established as a widely accepted practice, there have been several issues concerning the limitations of these methods. One of the major drawbacks of these methods emerges in case of adding non-monetary variables into the analyses. Core of the criticism implies that there is no reliable and commonly accepted way of monetizing benefits that derive from qualitative decision attributes that largely stem from environmental, social and political perspectives. It is stated that in order to include non-monetary variables into the calculations, financial analyses are conducted by over simplifying the assumptions which would otherwise prevent these variables from being incorporated into the analyses. As a result, judgments and assumptions behind the calculations are criticized to be too simple and hidden to decision makers which ultimately reduce the reliability of the results [168–171]. Furthermore, due to nature of economic decision analysis methods decision makers are not provided with detailed information to enable decision analysis at the multiple variable level, but rather a single data point. Accordingly, current decision-making approaches, employing economic analysis methods, have been observed to take only the quantifiable variables into consideration and miss taking some of the social and environmental variables that cannot be easily quantified [168].

This research study reviews assessment studies in the energy field and identifies over 50 assessment criteria that fall under aforementioned perspectives. Output of this study is expected to provide a knowledge database for practitioners and scholars for enabling development of more comprehensive assessment frameworks that can address some of the aforementioned weaknesses of current analysis approaches. Ultimately, this study is expected to contribute to energy planning field for development of more sustainable energy portfolios by enabling development of more comprehensive decision analysis practices.

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Chapter 2
Technology Assessment: Energy Efficiency Programs in Pacific Northwest

Ibrahim Iskin and Tugrul U. Daim

Abstract This chapter introduces a hierarchical decision modeling framework for energy efficiency program planning in electric utilities. The proposed approach focuses on assessment of emerging energy efficiency technologies and is proposed to bridge the gap between technology screening and cost/benefit evaluation practices. The proposed approach is expected to identify emerging technology alternatives, which have the highest potential to pass cost/benefit ratio testing procedures, and contribute to effectiveness of decision practices in energy efficiency program planning. Proposed framework also incorporates a sensitivity analysis for testing the robustness of decisions under varying scenarios in an attempt to enable more informed decision-making practices. Proposed framework was applied for the case of Northwest USA, and results of the case application and future research initiatives are presented.

2.1 Introduction

Nature of resource planning has changed dramatically since 1970s due to increased diversity in resource options such as renewable alternatives, demand-side management (DSM), cogeneration of heat and power (CHP) in industrial applications, and deregulation of the energy market. New objectives have been added to the utilities' decision-making processes beyond cost minimization, requiring utilities to address environmental and social issues that may emerge as a result of their operations [1]. Moreover, rapidly changing business conditions caused by technological

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development, instability in fuel markets, and government regulations have significantly increased complexity of and uncertainty involved in utility decision-making practices.

Prior to 1970s, utilities' main strategy in meeting increasing demand mostly consisted of capacity extensions; however due to increasing marginal cost of generation this approach was abandoned and replaced with more efficient use of existing resources. As a result, DSM initiatives were considered as a resource and a part of integrated resource plans. DSM programs have been widely utilized to meet increasing demand until the mid-1990s when the oil prices were again at a relatively lower level. Until this point, electric utilities were required to prove cost-effectiveness of DSM programs within certain definitions imposed by the Public Utilities Commission. These definitions were primarily set in order to ensure that proposed programs would recover cost of investments from a number of stakeholder perspectives. After reduction of oil prices and restructuring of electricity markets in 1990s, new approaches for justifying cost-effectiveness of DSM programs emerged. For instance, feasibility of DSM programs was evaluated by accounting for market externalities that had not been taken into consideration by the preceding assessment approaches. Inclusion of social and environmental externalities led recognition of societal and environmental perspectives which eventually enabled a large number of energy efficiency programs, which were previously infeasible, to be feasible [2]. Although DSM programs have often been characterized as being part of integrated resource planning, their value as a resource has not reached to its full potential due to a number of reasons discussed in the barriers literature.

2.2 Background

A review of existing energy efficiency program management practices reveals that there are four major components associated with energy efficiency program evaluation and deployment. These are program screening, evaluation, characterization, and deployment. Aforementioned process starts with screening of energy efficiency technologies, which have savings potential for a given case. Criteria for screening practices are mostly technical considerations. Following the screening phase, candidate technology applications are defined and evaluated based on their potential benefits. Evaluation phase mostly employs multiple perspectives considering technical, economical, and environmental impacts. Those technology applications, which pass evaluation phase, are moved to characterization phase where field tests are conducted for quantification of costs and benefits associated with them. Based on the quantified data cost/benefit ratio tests are conducted, reimbursement levels are determined for specified cases. Lessons learned are documented and used as input for creating measure implementation procedures for ensuring reliable energy savings. Those measures, which pass cost/benefit ratio tests, are moved to deployment phase where energy efficiency measures are officially released and marketed through various channels.

Energy efficiency has been traditionally a significant part of Pacific Northwest's energy portfolio and its increasing contribution is expected to continue in the future. In the last 30 years, energy conservation programs in the Pacific Northwest have achieved 4,000 average megawatts of electricity savings, meeting the half of the region's demand growth between 1980 and 2008. Conserved amount of electricity is expressed as being enough to power the states of Idaho, Western Montana, and city of Eugene for 1 year, avoiding 8–10 new coal- or gas-fired power plants and saving ratepayers $1.8 billion. Energy efficiency savings have been contributing to the region's power system in a number of ways by keeping electricity rates low, avoiding new construction projects, reducing environmental footprint, and contributing to regional economic growth. Recent increases in cost of energy resources, increasing electricity demand and straining the limits of the existing power system, potential carbon policies have increased the importance of energy conservation more than ever before. Accordingly, region's resource plan demands 80 % of the load growth in the next 20 years to be met by energy efficiency efforts.

Management of technology has been critical to Northwest's historical success in utilizing energy efficiency as a resource. It has been asserted that many of today's successfully diffused energy efficiency technologies, compact fluorescent lamps (CFLs), resource-efficient cloth washers, super-efficient windows, and premium efficiency motors, were results of research projects initiated in the 1980s and 1990s. Due to deregulations taken place in mid-1990s, utility-driven technology development efforts have halted significantly and its impacts are felt today in a way that there is no portfolio of technologies that can enable significant savings potential for the future. In order to meet the aggressive energy efficiency goals of Pacific Northwest's public power, investor-owned utilities and other energy efficiency organizations have restarted technology management initiatives in 2008.

Considering its background in energy efficiency investments and future plans, Pacific Northwest USA has been identified as a potential case application for this chapter.

2.3 Research Methodology

Methodology employed in this research is hierarchical decision modeling (HDM), which is one of the widely used multi-variable decision-making methodologies. HDM breaks down complex decision problems into smaller subproblems and provides decision makers a systematic way to evaluate multiple decision alternatives. HDM can be used for decision analysis problems with multiple stakeholders and provides basis for group decision making. Its ability to make use of qualitative and quantitative decision variables makes it very flexible and applicable to a wide range of application areas. For instance, HDM has been applied in a number of energy-related applications such as policy development and analysis [3, 4], electricity generation planning [5, 6], technology evaluation [7–11], R&D portfolio management [12], site selection [13, 14], integrated resource planning [15–18], evaluation of DSM implementation strategies [19, 20], evaluation of lighting efficiency measures [21], and prioritization of energy efficiency barriers in SMEs [22]. Further information about the mechanics of the methodology can be obtained from studies published by Dundar F. Kocaoglu and Thomas L. Saaty, who are the leading contributors to development of this methodology.

Case application of this research consisted of multiple phases, which include model development, model validation, and data collection. In the following sections you will be provided with further detail on aforementioned phases.

Model development process was initiated by constructing a preliminary assessment model based on findings from a comprehensive literature review on energy efficiency program assessment. It was observed that energy efficiency programs are utilized to accomplish a number of power system objectives and goals. Parallel to that a large body of assessment literature was observed to utilize utility objectives and goals as a measure for evaluation purposes. See Table 2.1 below for breakdown of the current literature with respect to assessment perspectives, utility objectives, and goals.

Preliminary assessment model was presented to a group of five experts, whose participants had at least 15+ years of experience in the area of emerging energy efficiency technologies. Based on the focus group feedback it was observed that the preliminary model would be suitable for post-evaluation of energy efficiency programs at government level. However, for the case of emerging energy efficiency programs it was emphasized that it would be difficult for experts to provide judgment for each utility value stream due to lack of data and complexity of the system. It was further noted that value of programs varies depending on different parts of the system; thus it would be difficult for experts to account for all sub-systems and come up with a value for the whole system. Accordingly, use of variables that could combine all value streams was suggested being more practical and accurate. Another important suggestion referred to the notion that program selection should not be limited to value potential only, but also address program development and market diffusion considerations. Within the evaluation of value streams, it was communicated that non-energy savings are important, and however should be separated from energy savings. Based on the focus group feedback preliminary model was revised.

Total of 26 subject matter experts with various backgrounds, 15 utility, 7 nonprofit organization, 2 research lab, 1 university, and 1 consulting, and positions participated in judgment quantification process. Experts had experience in the areas of management, planning, engineering, and economics. A large number of energy efficiency organizations, 5 utilities, 4 nonprofit organizations, 2 research labs, 1 university, and 1 consulting company, from the Pacific Northwest region were represented.

Judgment quantification was conducted through six expert panels, which were focused on quantifying different parts of the assessment model. Each panel required different types of expertise and experts were assigned to panels accordingly. See Table 2.2 below for focus of each expert panel and required expertise.

Judgment quantifications for panels 1 through 5 were performed by using pairwise comparison method. Response with inconsistencies greater than a predetermined threshold value was communicated back to its owner for further

Table 2.1 Taxonomy of energy efficiency program assessment literature

Objectives	Goals	References
Promoting regional development	Creating or retaining job opportunities	[15, 16, 21, 23, 24]
	Keeping local industry competitive	[16, 21, 23, 24]
	Improving life standards (non-energy benefits)	[16, 21, 24–26]
Reducing environmental impacts	Reducing GHG emissions	[15, 16, 21, 24–32]
	Reducing emission of soil, air, and water contaminants	[15, 16, 21, 23–28, 30]
	Avoiding flora and fauna habitat loss	[15, 16, 24, 30]
Increasing operating flexibility and reliability	Reducing need for critical resources	[15, 16, 21, 23, 24, 26–30, 32–39]
	Increasing power system reliability	[15, 16, 21, 24, 28–30, 32, 33, 36, 37, 39, 40]
	Increasing transmission and distribution system reliability	[15, 16, 21, 24, 28–30, 32, 33, 36–42]
Reducing system cost	Reducing/postponing capital investments	[15, 16, 21, 23–31, 34, 35, 37, 38, 42–45]
	Reducing operating costs	[15, 16, 21, 23, 24, 26, 27, 29–32, 34, 35, 37, 42, 45]
Reducing adverse effects on public	Avoiding noise and odor	[16, 24]
	Avoiding visual impacts	[16, 24]
	Avoiding property damage and impact on lifestyles	[16, 21, 24, 25]

Table 2.2 Focus and required expertise per expert panel

Panels	Focus	Required expertise
Panel 1	Energy efficiency program management considerations	Executive management
Panel 2	Variables under energy savings potential	Program planning and evaluation
Panel 3	Variables under ancillary benefits potential	Program planning and evaluation, market transformation
Panel 4	Variables under program development and implementation potential	Project and program management, measurement and verification
Panel 5	Variables under market dissemination potential	Market research and market transformation

treatment. Expert panels with disagreements greater than a predetermined threshold value were further analyzed. Subgroups with similar opinions were identified by using hierarchical clustering method. Rank order analysis was conducted for identified subgroups in order to determine whether differences in opinions would have significant impact on end results. All experts demonstrated acceptable degree of consistency in their judgments; however there were significant group disagreements in panels 2 and 3.

2.4 Results and Data Analysis

Results and data analysis section is divided into three major threads. Synthesis of priorities section provides relative importance of model variables and decision alternatives derived from aggregation of expert judgments. The following section provides results of rank order analysis based on expert disagreements that were identified. Finally, sensitivity analysis section provides allowable perturbations on relative importance of program management considerations before a given incumbent program alternative would lose its current ranking to a given challenger program alternative. Based on panel results, synthesis of priorities is calculated for different levels of the decision hierarchy. For instance, relative importance of sub-factors with respect to mission, relative importance of program alternatives with respect to program management considerations, and overall importance of decision alternatives with respect to mission are presented in this section. See Fig. 2.1 below for overall importance of model variables with respect to mission.

Peak savings potential (0.166), base load (off-peak) savings potential (0.146), and end-use adoption potential (0.115) are the highest; whereas equity considerations (0.021), promotion of regional development (0.026), ease of compliance with codes and standards (0.039), and reduction of environmental footprint (0.039) are the lowest weighted sub-factors. The rest of the sub-factors, direct impact on power system operations (0.075), intensity of market barriers and availability of leverage points (0.074), ease of savings measurement and verification (0.070), supply chain acceptance potential (0.068), ease of measure deployment (0.061), ease of maintaining measure persistence (0.055), and degree of rebound effects (0.044), have relatively closer weights.

2.5 Conclusions

Energy efficiency program planning is performed considering long-term needs, which may be up to 20 years of time horizon. Since planning periods are significantly long, it is very likely that priorities will change in an attempt to adapt to new business environments. This research approach integrated a sensitivity analysis with the assessment model and enabled decision makers to observe how optimum decisions could change in different future scenarios. Integration of sensitivity analysis through the proposed approach was observed to provide decision makers more insight, enabling better decision-making practices.

Overall, proposed improvements contributed to existing level of knowledge by enabling a more accurate energy efficiency program evaluation and planning approach that can provide better understanding of the potential implications of the strategic decisions.

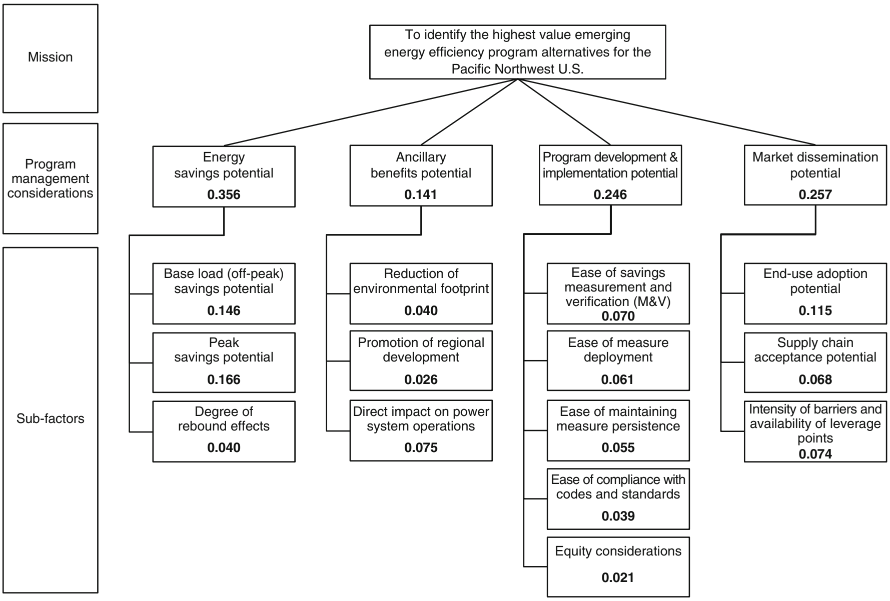

Fig. 2.1 Overall importance of model variables with respect to mission

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Chapter 3
Technology Assessment: Washington Public Power Supply System (WPPSS)

Nasir Sheikh

Abstract The Washington Public Power Supply System (WPPSS) is remembered as the largest bond default in the history of the USA. WPPSS was an ambitious program for the construction of multiple nuclear power plants to augment hydroelectric power and instead became known as the WPPSS (or "Woops") debacle. WPPSS was started as a small municipal corporation in the mid-1950s to meet future electric power needs of the residential, industrial, and commercial sectors in the Northwest region of the United States. The WPPSS charter was to enable electric public utilities to combine their resources to build large power generation plants and benefit from economies of scale. WPPSS initially consisted of 17 utilities including Seattle City Light, Washington State's largest public utility.

3.1 Introduction

The energy planners forecasted an increase in demand of about 7 % per year or doubling in 10 years [1]. The existing hydroelectric power would not be sufficient to support the long-term demand. Officials believed that nuclear power was the best way to provide clean and inexpensive electricity. It should be noted that, "coincidently," WPPSS was located near the US Department of Energy's Hanford Nuclear Site which processed plutonium. This site had been built in 1943 for atomic weapons related to the national defense program during World War II.

Not one but five nuclear power plants were proposed in the early 1970s. Certain events occurred at that time to make this decision even more reasonable. Low snowfall in 1972–1973 resulted in electricity shortage from hydroelectric power and the Arab oil embargo in 1973 caused gas shortages and general public panic.

WPPSS was a small agency and this was its first attempt at such a large-scale project. The program was wrought with major problems which caused huge delays

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and cost overruns. Based on Daniel Pope's definitive work on the WPPSS debacle, the author came to the conclusion that the main causes were [2, 3]:

- WPPSS's ambitions greatly exceeding its capabilities
- Poor decisions and lack of management, financial, and construction/technical expertise
- Changes in government regulation related to nuclear safety
- Constant design changes
- Construction delays
- Cost overruns
- Inflation
- Public suspicion
- Citizens and environmentalists joining the decision-making process (and opposing nuclear power)
- Declining demand for electrical power

The causes fed off of each other and had a cascading effect of escalating the problems.

The project costs are summarized in Table 3.1 for the five nuclear power plants WNP-1, WNP-2, WNP-3, WNP-4, and WNP-5 (WNP-i: WPPSS Nuclear Project i).

The WPPSS management explained the causes and cost overruns as listed in Table 3.2 below [3].

Finally, in 1982, due to cost overruns and other problems WPPSS was forced to stop construction for all the nuclear plant projects. Since no revenue had been generated, WPPSS defaulted on $2.25 billion in bonds. This left the member utilities and ratepayers with the debt obligations. For ordinary citizens this translated to about $12,000 per customer. The 75,000 bondholders sued and after 13 years in litigation a settlement of $753 million was reached which meant that they received back less than 40 % of their investment. Furthermore, the courts ruled that the member utilities were also liable because of inappropriate financial management by WPPSS. For example, Seattle City Light was held responsible for an additional $50 million.

Only one plant, Plant 2 or WNP-2, was completed in 1984 and changed its name to "Columbia Generation Station." It is viable and produces 12 % of BPA's power; however it still makes the news due to recurring problems [4]. In 1998, WPPSS also changed its name to "Energy Northwest." The Hanford site and location of Energy Northwest are depicted Fig. 3.1. The Hanford site itself has had environmental problems due to hazardous waste and even today it is part of an immense environmental cleanup project.

Table 3.1 WPPSS nuclear projects (WNPs) summary (*source*: [3])

	WNP-1	WNP-2	WNP-3	WNP-4	WNP-5
Location (Washington State)	Hanford Reservation	Hanford Reservation	Satsop	Hanford Reservation	Satsop
Financing	Net Billed[a]	Net Billed[a]	Net Billed[a]	88 participating utilities' shares of "project capability"	88 participating utilities' shares of "project capability"
Completion target date	Sept. 1980	Sept. 1977	March 1982	March 1983	Jan. 1985
Initial cost estimates[b]	$1.2 billion	$0.5 billion	$1 billion	$3.4 billion	
Date	Sept. 1975	June 1973	Dec. 1975	Feb. 1977	
New cost estimates	$4.3 billion	$3.2 billion	$4.5 billion	$5.5 billion	$6.3 billion
New date	May 1981	May 1981	May 1981	May 1981	May 1981
Final status	Constructions halted April 1982	Project completed Dec. 1984	Constructions halted May 1983	Constructions halted May 1981	Constructions halted May 1981
	Project terminated May 1994		Project terminated May 1994	Project terminated Jan. 1982	Project terminated Jan. 1982

WNP-i: WPPSS Nuclear Project I, i = 1–5
[a]"Net Billing" was a complex process that allowed Bonneville Power Administration to assist with the financing [3]
[b]Costs are approximate in billions of dollars

Table 3.2 Causes of cost overruns (1977–1981) as explained by WPPSS (*source*: [3])

WPPSS: causes of cost overruns 1977–1981	Percent of total cost	Amount (billion)
Regulatory requirements	50	$4.2
Strikes/schedule extensions	15	$1.3
Inflation/estimating and design refinements	30	$2.5
Nuclear fuel	4	$0.3
Other authorized costs	1	$0.1
	100	$8.4

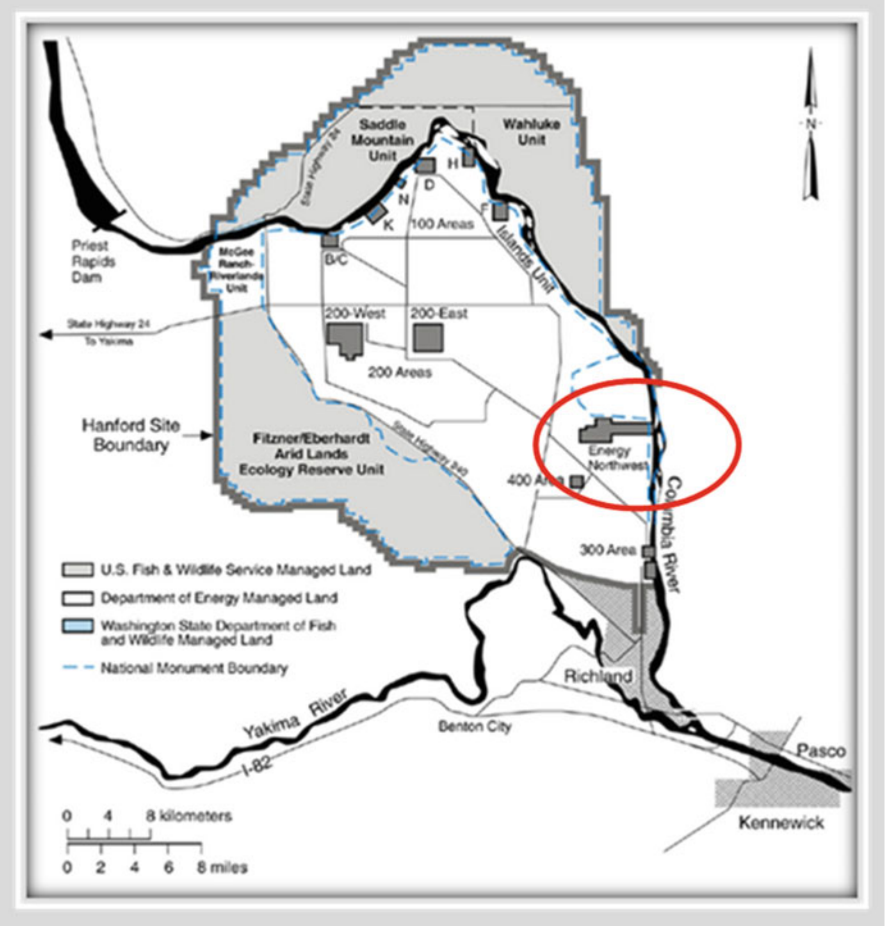

Fig. 3.1 Location of energy northwest and the Hanford nuclear site (*source*: http://en.wikipedia.org/wiki/Hanford_Site)

3.2 Multiple Criteria Decision Making for Energy Planning

Energy planning has improved significantly in the last decade and improved methods and models are being used for capital projects related to electrical power generation. These include integrated energy planning, decentralized planning, energy forecasting, and energy conservation [5]. The cost of new energy programs is becoming extremely high—in the hundreds of millions or billions of dollars range—and decision mistakes can have immense negative effects from multiple perspectives—social, technical, economic, environmental, and political. Hence, multiple criteria decision-making models are becoming popular for new energy projects, programs, and policies [6, 7]. Furthermore, it is important to use a decision model that takes into consideration the judgment or input from multiple actors or stakeholders and several leading alternative solutions [8].

As a counterexample to the WPPSS scenario, in 1988, the Finnish Parliament commissioned the use of a hierarchical decision model AHP (which is similar to HDM) and sensitivity analysis to help shape public policy for nuclear energy [9, 10]. There had been a strong debate and controversy over the use of nuclear power in Finland and the Parliament needed a rational decision model to help resolve the debate. The situation was best stated as:

> The controversial information and opinions about nuclear power are among the main reasons for the great difficulties found today in energy policy decision making. The simultaneous consideration of quantitative, qualitative and purely intuitive aspects of a problem like this is usually a difficult task for an unaided human mind. In such an environment individuals, including experts, are liable to a number of cognitive biases. For example, an individual making up his mind may easily escape the difficult problem of value trade-offs by focusing exclusively on part of the information which is new, easy to understand or compatible with his earlier preferences and knowledge. In energy policy debates this can explain the emergence of pressure groups concentrating on just one of the relevant factors [10].

The situation in Finland was similar to the US Northwest in that it had hydroelectric power and needed to expand its future capacity. For the national decision-making process, three perspectives were considered: (1) national economy; (2) health, safety, and environment; and (3) political factors. The objective was "society's overall benefit" and not just "increasing the supply of electric power." Each perspective had three criteria as shown in Table 3.3 below.

At that time the three competing energy alternatives were (1) no big power plant (i.e., decentralized power), (2) coal-fired plant (i.e., low-cost traditional power), and (3) nuclear plant (i.e., large-scale centralized power). The HDM framework is shown in Fig. 3.2 below.

Even though this was a simplistic decision model, it enabled the stakeholders to have a thoughtful structured approach that considered not just energy economics but also other perspectives—with competing criteria—as well. The policy makers were willing and capable to use a decision aid that multiple stakeholders/actors could collectively frame and value the outcomes. Since then, Finland has refined its

Table 3.3 Three perspectives for Finnish nuclear policy decision making (*source*: [9])

National economy	Health, safety, and environment	Political factors
Cheap electricity	Natural resources	Energy independence
Foreign trade	Unavoidable pollution	Centralization
Capital resources	Accidents and long-term risk	Political cooperativeness

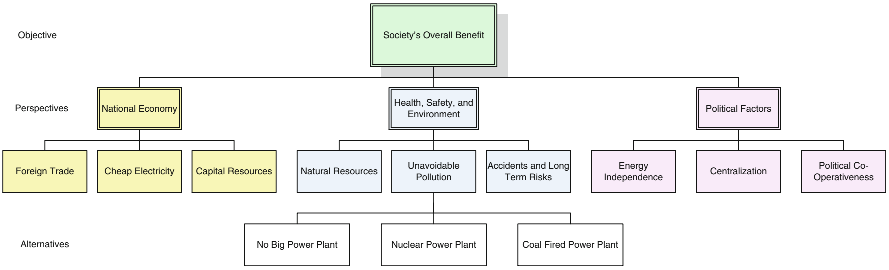

Fig. 3.2 The energy hierarchical decision model for the Finnish Parliament (*source*: [9])

decision-making approach and as of December 2011 boasts the following ("Nuclear Power in Finland," [11]):

- Four nuclear power plants providing about 30 % of the nation's electricity.
- A fifth nuclear plant under construction and two more are planned.
- Radioactive waste disposal is well managed.
- The power plants have been uprated—capacity increased and lifetime extended—since they were built. This is a remarkable feat since power plants are typically downrated over time.

3.3 Application of Sheikh Proposal to WPPSS: A Decision Analysis Framework

3.3.1 Consideration of Multiple Perspectives

In a similar approach to the Finnish case study above the Sheikh proposal uses five perspectives—social, technical, economic, environmental, and political (STEEP)—to develop an HDM framework for decision making. One potential set of criteria to be considered under the STEEP perspectives is shown in Table 3.4 and then summarized below. [The reader is also referred to the Sheikh Proposal and associated appendices [12]].

Table 3.4 STEEP perspectives and associated criteria for selecting new power generation source

Social	Technical	Economic	Environmental	Political
Public participation and perception	Energy capacity planning	Financing	Pollution/negative impact	Policies
Employment	Technology/know-how maturity	Start-up costs	Environmental benefits/positive impact	Regulations
Health and safety	Deployment	Levelized cost of energy (electricity generation costs $/kWhr)	End of life/disposal	Codes/standards—compliance
Local infrastructure development	Operations	Economic value (cost/benefit, IRR, profit, risk analysis, energy payback time, inflation)	Consumption of resources	Security (supply, pricing)
	Maintenance	Cost mitigation	Waste management	
	Resources/materials required	Market demand		
	Technology roadmap	Impact on local economy		

3.3.1.1 Social Perspective

Public Participation and Perception

The social phenomenon known as public perception may be viewed as a virtual truth or aspect of the truth that is shaped by popular opinion, media coverage, impact on social norms or livelihood, or reputation. It may consist of such factors as aesthetics, impact on lifestyle, social benefits, and social acceptance. An important aspect of perception management for energy projects is to have the affected public and industry participate in the decision-making process. This is now referred to as "participatory decision making and analysis" and is an effective way to the capture the perceived values of the stakeholders. [It is important to draw out their concerns early to avoid potential catastrophic public backlash.]

Employment

Essentially, employment is all about jobs. It is related to such factors as job creation, availability of workforce, and poverty alleviation.

Health and Safety

Health and safety is the protection of safety, health, and welfare of the individuals, society, and workplace by governments and society. It includes public safety, work safety, fail-safe mechanisms to prevent accidents, and prevention of long-term hazardous health effects and is an investment in the long-term health of society.

Local Infrastructure Development

Typically, infrastructure development is a long-term benefit to the locality and region. It consists of infrastructure improvements and promotion of related industry, and empowers the region to improve productivity and quality of life.

3.3.1.2 Technical Perspective

Energy Capacity Planning

Traditional energy planning was focused on building up energy supply capacity (power generation) while minimizing cost. This is also referred to as "supply-side planning."

Technology/Know-How Maturity

A technology is considered mature if it has been in use for a long time and many of the associated problems and defects have been dealt with. Technology maturity refers to the stage of the technology and is associated with trends and its persistence ability. It includes factors such as density and maturity of patents, flexibility, scalability, modularity, and obsolescence resistance.

Production/Operations

In this context production refers to manufacturing of renewable energy sources. Operations also refer to manufacturing operations. This can include production capacity, production process complexity, ability to leverage well-known processes, production waste management, line breakage, and production maturity.

Resources/Materials Required

Availability and management of raw materials in the manufacturing process are important for the evaluation of renewable energy sources. Factors key for this criterion include availability of resources, access to resources, avoiding the use of rare metals and hazardous materials, and chemicals and gases used.

Deployment

Deployment of the renewable energy source has many forms, considerations, and components. These factors may include large-scale installations, field performance, service availability, effect of power purchase agreements (PPAs), impact on meeting important national and international energy targets, suitability for transmission and distribution.

Maintenance

Maintenance periods are closely aligned with installation and deployment. Important factors in this criterion are low maintenance, long lifetime, and prevention of annual power production degradation.

Codes/Standards: Compliance

It is an accepted fact that most energy deployments must be compliant with local, regional, national, and/or international standards to some extent. For the USA such standards include the United States Code, building safety standards, and environmental safety standards.

Technology Roadmap (2010–2030)

Besides the current state of the energy technology, its trajectory or roadmap must also be assessed to gain a fuller understanding of the technology direction for the next few decades. This criterion would contain technology-specific factors.

3.3.1.3 Economic Perspective

Financing

Funding is an important aspect of any capital project. The funding types and sources such as issuance of bonds, investors, government, and ratepayers are the underlying factors.

Start-Up Costs

Planning for start-up costs for project success is fundamental to the energy planning process. These include factors such as construction costs, licensing, zoning approvals, capital equipment, nonrecurring engineering (NRE), and funding costs.

Electricity Generation Costs: LCOE

The total cost of electricity generation over the life of the energy source assists in deciding the equivalent operating cost per kilowatt-hour (kWh). It has traditionally been calculated as standardized or levelized cost of energy (LCOE) over the life cycle of the product or energy source. However, this formula did not typically include the end-of-life disposal costs. For a comprehensive assessment of technology another calculation should be made and included as a factor to reflect the true cost.

Economic Value

In this context engineering economic value has been defined as the financial analysis related to the viability of energy investments and benefits derived and includes factors such as cost/benefit analysis for public projects, return on investment (ROI), projected savings to power utilities, energy portfolio costs to utilities (to supply power vis-à-vis renewable energy sources), and a roadmap of costs over the next two decades. This criterion provides a long-term landscape for investment purposes and enables experts or decision makers to compare to other important economic criteria.

Cost Mitigation

One aspect or criterion of the economic perspective is cost mitigation or how an energy technology or source can help to alleviate overall costs. There are multiple factors that positively affect cost mitigation and include independence from economies of scale (implying that building a higher capacity power plant will increase costs exponentially with size due to complexity of larger systems), energy supply chain advantage (since fossil fuels require costly distribution and the supply chain is extensive), reduction in government administrative costs (involving imported fuels), and better use of hard currency (for developing countries that need to use hard currencies for fuel imports).

Market Demand

Forecasting and planning for energy demand from end-user sectors such as residential, commercial, industrial, and transportation is another important criterion.

Positive Impact on Local Economy

Local economies can be impacted through the deployment of energy technologies. Besides the social quality-of-life gains the economic gain may include a mix of factors related to higher wage jobs, new job creation, creation of an insourcing trend (and in direct opposition to outsourcing), and creation or expansion of economic clusters. Michael E. Porter defined economic clusters as a local concentration of specialized companies and institutions that increase productivity. Cluster development initiatives are an important agenda for many governments as they are seen to improve economic activity. For example, the installation of a local PV manufacturing or system integration plant can be at the heart of a cluster of other related companies and activities that feed off of the PV product sales and installations. Plus local universities may increase R&D activity to support the PV plant.

3.3.1.4 Environmental Perspective

Pollution or Negative Impact

From an environmental perspective pollution is the first thing that comes to people's minds and is an important criteria to use for the assessment of an energy technology. The factors that make up this criterion and imply different types of pollution—during the production or deployment phase of the technology—may include greenhouse gases (GHG), smoke or dust particles, vapor, glare (visual pollution), water, soil, noise, solid waste, water resources (used in production), stratospheric ozone, natural habitat, water temperature change, wind pattern change, forest and ecosystem, ecological footprints (crops, woods, marshes, etc.), and accidental release of chemicals.

Environmental Benefits or Positive Impact

There can be a positive impact on the environment due to renewable energy. The factors that comprise this criterion may include better land utilization, climate change mitigation, environmental sustainability, low land (real estate) requirements, energy conservation improvement, better consumption of natural resources, reduced fossil fuel imports (or dependence), and better use of rooftops (for PV and wind energy).

Disposal and End of Life

An environmental criterion that is gaining importance is the advanced planning for waste and end-of-life disposal (or dismantling) of renewable energy sources. Factors to be considered for this are related to biodegradability, ease in recycling, and proper disposal of chemicals and gases used in production or deployment. Another factor might be leveraging waste disposal management know-how from existing mature production processes (such as from semiconductor manufacturing). [It should be noted that the dismantling and cleanup aspect of a nuclear power plant may make such projects unfeasible.]

Consumption of Resources

Considering that most natural resources are finite, their use especially during manufacturing needs to be part of the technology assessment process. There are three main factors: land, water, and raw materials.

3.3.1.5 Political Perspective

Policies

Renewable energy policies are typically at national or local levels and can mark the success or failure of a renewable energy source. Policy factors include security, support for certain types of energy (such as renewable energy), national energy independence (from fossil fuels), financing option with government backing, local sourcing, stipulated 5- or 10-year plans for certain types of energy or energy efficiency, workforce training on new energy sources, and integration with/or replacement of existing power plants.

Regulations

The power markets can be managed in many different ways through the political process. Regulation can include factors such as renewable portfolio standard, incentives, energy price controls through rate structures, subsidies (such as tax credits, tax exemptions), carbon tax, cap and trade, and promotion of centralized or decentralized power.

Codes/Standards: Compliance

This criterion includes factors such as the United States Code (for the USA), national and international standards, and building and environmental safety standards. (These factors imply that the policies enact the standards and enforce them.)

Security

Security is the responsibility of the government and is a public policy issue. Security consists of both energy supply stability and energy price stability. (These are the two factors that comprise the security criterion.) Even if governments cannot control the supply (especially in the case of fossil fuels) they may need to control the price through subsidies because history has proven that energy price escalation can lead to civil unrest.

3.3.1.6 Framing the Problem, Decision Modeling, and Desirability Functions

The WPPSS objective was to build a "nuclear energy supply for the US Northwest's future needs." If WPPSS had considered their objective as "new energy supply to provide the maximum benefit to the US Northwest," this would have enabled WPPSS to have a broader scope of the challenge at hand and also included other stakeholders such as the public and regulators. It would also have forced WPPSS to consider nuclear energy in comparison to other alternatives such as utility-scale renewable energy—wind or solar, traditional coal-firing power plants, and hydroelectric power plants—small or large, and gas-firing power plant. Hence a rational decision model could be built; judgments from experts, stakeholders, and decision makers elicited; and sensitivity analysis applied for what-if scenarios. This, at least, would have revealed potential major issues during the initial evaluation and feasibility process. Clearly, the energy planners had thought of the other options but the author believes that they may have dismissed them based on their own experiential knowledge. They may have thought that they knew "what is best." A decision model framework applicable to WPPSS is shown below in Fig. 3.3.

With the aid of desirability functions WPPSS may have had a chance to review areas of big gaps to "best desirability." For example, building desirability functions with respect to specific regulations should have indicated that nuclear power plants had big gaps that needed to be addressed before construction started.

3.3.1.7 Interviews: Robert Ferguson and Daniel Pope

The author was privileged to interview Robert Ferguson and Daniel Pope to obtain their expert opinion. The objective was to determine if such an approach of decision

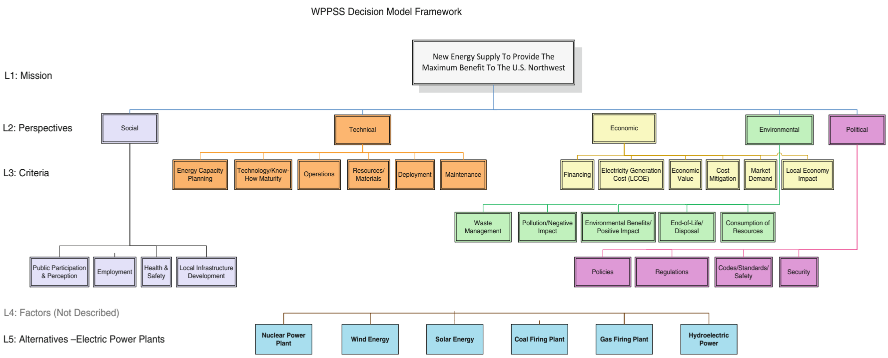

Fig. 3.3 Proposed WPPSS decision model framework

modeling and including the judgments of experts and decision makers could have improved the WPPSS outcome. Robert Ferguson was the Managing Director of WPPSS during its final days. Robert is now retired and lives in Lake Oswego, Oregon. He was brought in from the Department of Energy to help salvage the program. Daniel Pope, is a professor at the University of Oregon, Department of History, and has written the definitive work on WPPSS entitled "Nuclear Implosions: The Rise and Fall of the Washington Public Power Supply System" [3]. In general, both agreed that such a decision modeling approach would have been very useful. Some of the insights gained from the interviews include the following:

- Although Daniel Pope in his book listed major reasons for the WPPSS failure [3], according to Robert Ferguson, the main cause was poor planning and the other causes were secondary.
- The parties involved with the decision making and modeling must also be able and willing to act on the decision.
- Use of forecasting models for electricity demand could not be relied upon.
- In the late 1970s wind technology was not developed enough to be an option.
- For base load energy production (i.e., power always available) the only other feasible option was coal.
- Regional criteria—such as managing and balancing issues of energy, fisheries (for example protecting salmon runs), and agriculture; the needs of local industry that buys wholesale electricity (for example aluminum plants); and local abundance of resources (for example sunlight or wind)—should also be included in the modeling.
- In the case of WPPSS, initially it had public support but that changed (reversed) over time.
- It was realized that factors such as debt payment (i.e., interest on the loans) and project delays became more important than building nuclear facilities and production capabilities.

- Politics and legal constraints were major reasons for WPPSS to default on its bonds. The restrictions caused WPPSS to take no action to mitigate the deteriorating situation—"WPPSS defaulted by default."

The above insights could be useful in decision modeling and comparative assessment of utility-scale power systems based on different energy sources such as nuclear, hydroelectric, coal, and gas (also refer to Fig. 3.3).

In the end the WPPSS program became entangled in legal and political issues resulting in only one nuclear power plant. A decision model in the beginning (i.e., in the initial planning phase) could have helped but its utility is questionable towards the end when the situation had deteriorated to a crisis level.

3.4 Concluding Remarks

If the Sheikh proposal and modeling had been adopted by WPPSS it would have helped in avoiding being blindsided by perspectives and criteria not considered earlier in the planning cycle such as changing regulations and stay orders (and lawsuits) by the public and environmentalists. (This was a very complex project and a decision model may not have been able to capture and anticipate every criterion and the changes over time.) It should be noted that good decision making alone does not make a project successful. It is, however, a necessary condition. The decision makers and the parties in charge must be willing and able to develop and execute strategies that result in total program success. Large public works and construction projects are complex and costly and, hence, the aid of the best known methods of decision making and problem solving is needed to realize them. Decision modeling and HDM's power lie in the ability to make judgments—of experts and decision makers with different values, preferences, and expertise—explicit. Hence it provides the ability for a structured analysis—for current and future reference and for understanding the effect of underlying judgment criteria and factor changes.

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Chapter 4
Technology Assessment: Evaluating Personal Transportation Technologies

Kevin van Blommestein, Tugrul U. Daim, Ritu Bidasaria, Jared Nambwenya, and Matt Nickeson

Abstract A hierarchical decision model was applied to the problem of consumer choice among single-person transportation technologies. Criteria and sub-criteria were pulled from literature and similar studies to objectively compare the vehicles. Pairwise comparison was used to rank the weights of each criteria and sub-criteria across four different cultural states: the USA, South Africa, India, and Kenya. For the USA the highest ranked criteria were economic and practicality, for South Africa safety and economic, for India safety, and for Kenya practicality. The lowest weight for all countries was for public use regulations. All countries preferred the simple human-powered bicycle to any more advanced technology. This data could be used to inform product development or marketing decisions within each country.

4.1 Introduction/Problem Statement

As the world's population continues to increase, transportation continues to be a significant source of energy consumption [1]. The transportation of people has greatly contributed to the shape of the modern world; as rural populations have gradually moved to urban environments their logistical needs have evolved as well. For instance, in 2009 the average American wasted 25 entire hours simply waiting in traffic, along with a corresponding increase in fossil fuel consumption and pollution [2]. Recent technological advances such as the Segway [3, 4], as well as more commonplace, "low-tech" devices such as the simple bicycle, are at the forefront of this technological shift.

Our paper sets out to use a hierarchical decision model (HDM) model to analyze consumer preferences concerning single-person transportation options. By

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analyzing the preferences of a small panel of consumers between several independent criteria and factors we hope to develop a model which can be used not only to predict which vehicles are preferred but also to address which criteria are most important to the consumer and so influence future product development.

4.2 Literature Review

4.2.1 Introduction to HDM Model

We opted to use an HDM model, which is used to break down a complex decision problem into smaller, less complex, subproblems [5]. HDM models have been used by many authors to compare between multiple technological options [6–8].

A hierarchical decision model has a goal, criteria that are evaluated for their importance to the goal, and alternatives that are evaluated for how preferred they are with respect to each criterion [5]. The goal, the criteria, and the alternatives are all elements in the decision problem, or nodes in the model. Depending on the complexity of the problem more levels can be added in a tree between goal and alternatives. The lines connecting the goal to each criterion mean that the criteria must be compared pairwise for their importance with respect to the goal. Similarly, the lines connecting each criterion to the alternatives mean that the alternatives are compared pairwise as to which is more preferred for that criterion.

An abstract view of such a hierarchy is shown in Fig. 4.1.

To identify the best alternative which will most satisfy the goal, the first step is to identify the criteria, sub-criteria, and alternatives. The second step is to create the hierarchical model and identify the relative priorities using pairwise comparisons. The third step is to determine the best alternative and analyze the weight. The steps are described in more detail below.

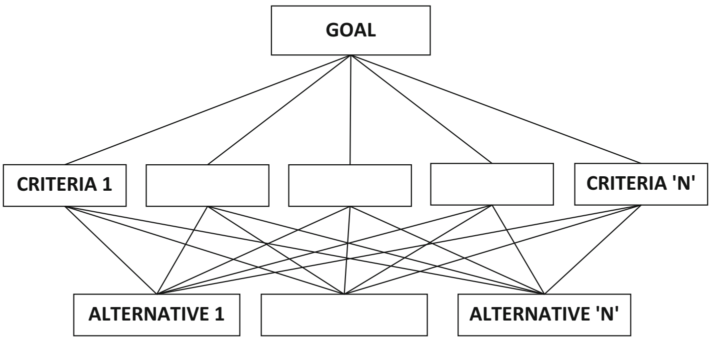

Fig. 4.1 HDM in abstract

4.2.1.1 Identify Criteria, Sub-criteria, and Alternatives

In this step different criteria, the technological factors (sub-criteria) under each criteria, and different alternatives are identified which specifically satisfies organization's objective. Technological factors can be either quantitative or qualitative. Brainstorming, interview, group discussion, and Delphi technique are some of the methods which can be used for identifying criteria and factors under each criterion.

4.2.1.2 Hierarchical Modeling

In this step a hierarchical model is developed by identifying the relative priority of each criteria and determining the relative importance of factors by calculating weights.

4.2.1.3 Weight Evaluation

In this step the best alternative is identified which contributes most to the organization's goal after evaluating the weight of all the technologies.

4.3 Hierarchical Decision Model

4.3.1 Criteria and Sub Criteria

To identify the criteria and sub-criteria, we searched many websites and discussed within our team in order to understand the important aspects that one should consider in comparing different types of single-person transportation vehicle. Since it was difficult to obtain quantitative objective values for some subcriteria, a 5-point scale was used. Other criteria needed to be inverted to reflect their appropriate value; for instance a high-cost score is a negative thing; these criteria are shown along with their proportional weighted curves. The criteria and sub-criteria used in our model are the following:

Safety [6]

1. Safety features: This is the safety equipment installed on the vehicle (e.g., braking system). The 5-point scale used for this sub-criterion is described in Appendix 2.
2. Stability: This is how steady the vehicle is when operating (i.e., turning corners, changing between different surfaces). The 5-point scale used for this sub-criterion is described in Appendix 2.

3. Weight restriction: This is the maximum weight of the person operating the vehicle that is specified by the manufacturer.
4. Recommended age: This is the lowest recommended age for a person operating the vehicle, as specified by the Department of Motor Vehicles or equivalent.
5. Maximum speed: This is the absolute maximum speed at which the vehicle can travel.

Practicality [6, 8]

1. Equipment weight: This is the weight of the vehicle (e.g., how heavy it is to pick up in the train, into your car).
2. Equipment size: This is the length of the longest dimension of the vehicle.
3. Charge time: This is how long an electric vehicle takes to fully charge before it can be used. The linear curve for charge time is shown in Fig. 4.2, which ranged from the best case (zero hours) for charging to the worst case (12 h). Twelve hours and above was seen as an unacceptable charging time since it is no longer practical for everyday use.
4. Maximum speed: This is the maximum speed at which an average user can travel using the vehicle. The sub-criterion is not just repeated; however, it is looking at how practical it is to use the vehicle and not the safety as under the safety criteria.
5. Range per charge: This is the maximum distance that the vehicle can travel on one charge. This assumes that the vehicle is being used economically and not at maximum performance.

Economics [6–9]

1. Purchase cost: This is the initial cost to purchase the vehicle. The linear curve shown in Fig. 4.3 was used, which ranged from the best case ($0) to the worst case ($7,000). To calibrate the scale, one dollar above the Segway price was

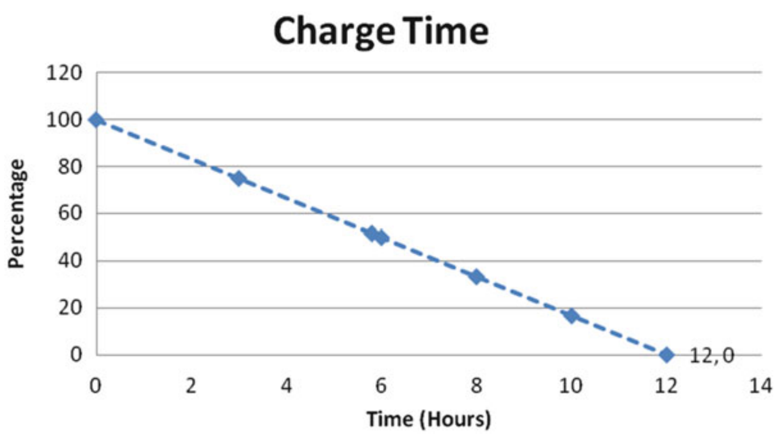

Fig. 4.2 Linear curve (charge time)

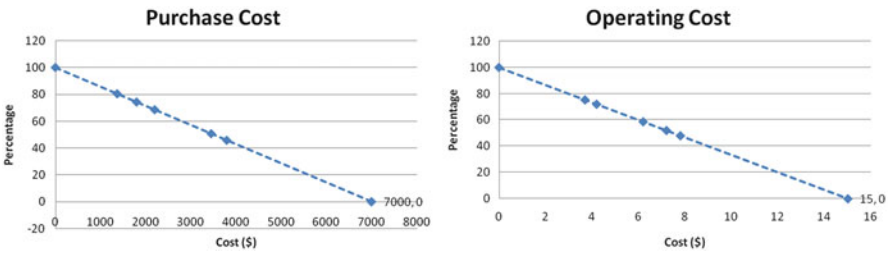

Fig. 4.3 Linear curves (purchase cost and operating cost)

chosen as the limit to the purchase cost, with any amount above this making the purchase impractical.

2. Operating (charging) cost: This is the cost to use the vehicle per month (i.e., charging cost for an electric vehicle). The linear curve shown in Fig. 4.3 was used, which ranged from the best case ($0) to the worst case ($15). The charging cost was calculated using the kWh usage per charge of the vehicle and a $0.2 per kWh rate, multiplied by 30 days of the month. This assumes that the vehicle will be charged once per day. The Segway for example uses 1.04 kWh per charge [8]; therefore taking 1.04 kWh per day multiplied by 30 days per month, multiplied by $0.2 per kWh, results in $6.24 per month. Although different countries have different kWh rates, this will not affect the outcome since all alternatives will be adjusted equally.
3. Maintenance cost: This is the cost to maintain the vehicle (e.g., replacing tires, batteries). The 5-point scale used for this sub-criterion is described in Appendix 2.

Service and Support [6, 8]

1. Warranty: This is the length of the warranty for the vehicle in years.
2. Ease of maintenance: This is how easy the vehicle is to maintain yourself. The 5-point scale used for this sub-criterion is described in Appendix 2.
3. Reliability: This is how reliable the vehicle is generally perceived to be. The 5-point scale used for this sub-criterion is described in Appendix 2.

Ease of Use

1. Physical exertion: This is how much effort goes into using the vehicle. The 5-point scale used for this sub-criterion is described in Appendix 2.
2. Comfort: This is how comfortable the vehicle is (e.g., standing vs. sitting, seat comfort). The 5-point scale for this sub-criterion is described in Appendix 2.
3. Storage: This is how practical the vehicle is to store away (e.g., in a cupboard). The 5-point scale for this sub-criterion is described in Appendix 2.
4. Handling: This is how easy the vehicle is to operate (e.g., turning, balancing). The 5-point scale for this sub-criterion is described in Appendix 2.
5. Appearance: This is the general perception on what the vehicle looks like. The 5-point scale for this sub-criterion is described in Appendix 2.

Public Use Regulations [10]

1. Sidewalk restrictions: This is whether the vehicle is allowed to be used on sidewalks or not. A binary "Yes or No" is used to quantify this sub-criterion.
2. Road restrictions: This is whether the vehicle is allowed to be used on the road or not. A binary "Yes or No" is used to quantify this sub-criterion.
3. License/permit requirements: This is whether you require a license or permit to use the vehicle on public roads and sidewalks. A binary "Yes or No" is used to quantify this sub-criterion.

4.3.2 Alternatives (Technologies)

Our team decided to choose technologies which are used as single-person transportation vehicles, with an average speed less than 30 miles per hour, which leads us to evaluate the following six technologies (the values for the sub-criteria of these technologies can be found in Appendix 3):

1. Human-powered (standard) bicycle: This is a standard bicycle with the highest physical exertion and lowest price among all the technologies selected. The bicycle is easy and inexpensive to maintain, has no public use restrictions, and has no charge time and cost. The bicycle used in the model was the Trek Soho Deluxe [9, 10].
2. Electric-assisted bicycle: This is a bicycle with an additional electric motor to assist the user when he/she pedals. The electric-assisted bicycle is considered as a standard bicycle with respect to public use regulations, except with an additional restriction for use on sidewalks. The bicycle has much less physical exertion than the standard bicycle with a relatively low charge time and cost; however the price is more than double. The bicycle used in the model was the Kalkhoff Sahel Pro [11–13].
3. Electric Trikke: This is a three-wheeled vehicle that is propelled by the user shifting his/her body weight, with assistance from an electric motor. The Trikke has a low charge time and cost, has relatively low purchase cost, and is foldable and easy to store away. The vehicle used in the model was the Trikke Tribred Pon-e 48V [14, 15].
4. Electric kick scooter: This is a two-wheeled vehicle with a small platform to stand on and propelled by an electric motor. It is approximately the same price as the electric-assisted bicycle (for similar performance to the other technologies), has a relatively low charge time and cost, and is also foldable and easy to store away. However the safety features and stability of the vehicle are considered to be poor. The vehicle used in the model was the Go-Ped ESR750 Li-ion 32 [16–18].
5. Segway: This is a two-wheeled self-balancing electric vehicle. The Segway has a very high cost and lower speed compared to the other technologies, but has

good safety features and is relatively easy to store away. The vehicle used in the model was the Segway i2 [19–21].

6. Electric scooter: This is a type of motorcycle with an electric motor for propulsion. The vehicle is heavy with a low speed, is not easy to maintain, and has high maintenance costs. The vehicle used in the model was the X-Treme XB-420M Electric Scooter [22–24].

4.3.3 Decision Model

The HDM model shown in Fig. 4.4 is structured with an objective, criteria, sub-criteria, and alternatives. The model attempts to include as many objective sub-criteria that could be obtained from the manufacturers' websites, manuals, and alternative sources. Some subjective sub-criteria however were included that were quantified by a 5-point scale, as described in Appendix 2. The alternative technologies were chosen all with a maximum average speed below 30 mph, over a varying price range, and with different benefits, however all performing the same purpose of single-person transportation.

4.3.4 Expert Responses

The experts for the model were the consumers, the people who would be making the decision of which vehicle to purchase for single-person transportation. The survey shown in Appendix 1 was sent out to possible consumers in four countries, namely India, Kenya, South Africa, and the USA. In total 16 complete responses were received, consisting of 5 from the USA, 4 from India, 4 from South Africa, and finally 3 from Kenya.

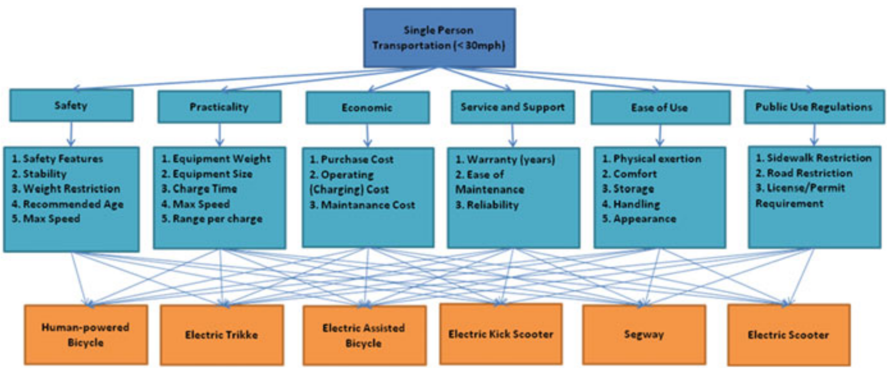

Fig. 4.4 Hierarchical decision model

4.3.5 *Calculating Weights*

The survey in Appendix 1 was used to obtain the pairwise comparisons from the consumers in the different countries. The comparisons were manually entered into the Pairwise Comparison Method (PCM) software [25] and the respective weights for the criteria and sub-criteria were obtained. The technology rankings were then obtained using these weights and the objective values per vehicle.

4.4 Results

The weights for the criteria and sub-criteria per country are shown in Appendix 4, with very few inconsistencies above 0.1. Using these weights the technology rankings per country were obtained.

4.4.1 *Criteria and Sub-criteria Weights*

Figure 4.5 illustrates the weights for the six criteria per country. It can be seen that the criteria with the highest weights for the USA was economic and practicality, for South Africa was safety and economic, for India was safety, and for Kenya was practicality. The lowest weight for all countries was for public use regulations.

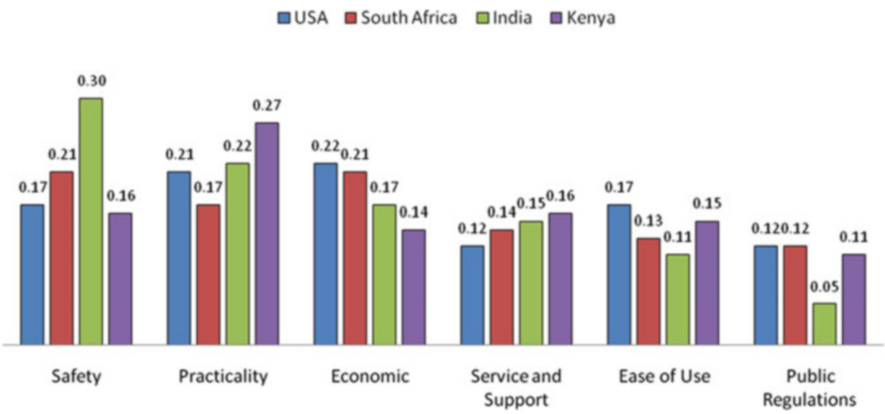

Fig. 4.5 Criteria weights per country

4.4.2 *Sub-criteria Weights*

4.4.2.1 Sub-criteria Weights Under Criteria

The weights for the sub-criteria per country under each criterion can be found in Appendix 4. These weights can be used to evaluate the importance of each sub-criterion to each criterion; however it was determined that it would be more beneficial to evaluate the sub-criteria to the overall objective.

4.4.2.2 Sub-criteria Weights to Objective

The weights for the sub-criteria to the objective (i.e., criteria weight multiplied by the sub-criteria weight) are shown under Appendix 5. The results are summarized in Table 4.1, which includes the highest and lowest weights for each country.

4.4.3 *Technology Ranking*

Figure 4.6 illustrates the outcome of the decision model, showing the rankings of each technology per country. The human-powered bicycle was ranked the highest for all four countries, while the electric scooter was ranked the lowest. The ranking of devices from all countries is in the same order.

Table 4.1 Sub-criteria weights to objective

Country	Highest weights	Lowest weights
USA	• Equipment weight • Purchase cost • Operating cost • Maintenance cost • Road restrictions	• Weight restriction • Sidewalk restriction
South Africa	• Purchase cost • Operating cost • Stability	• Weight restriction • Recommended age • Equipment weight • Equipment size • Storage • Appearance
India	• Safety features	• License/permit requirement
Kenya	• Range per charge	• Recommended age • Physical exertion • Storage • Appearance

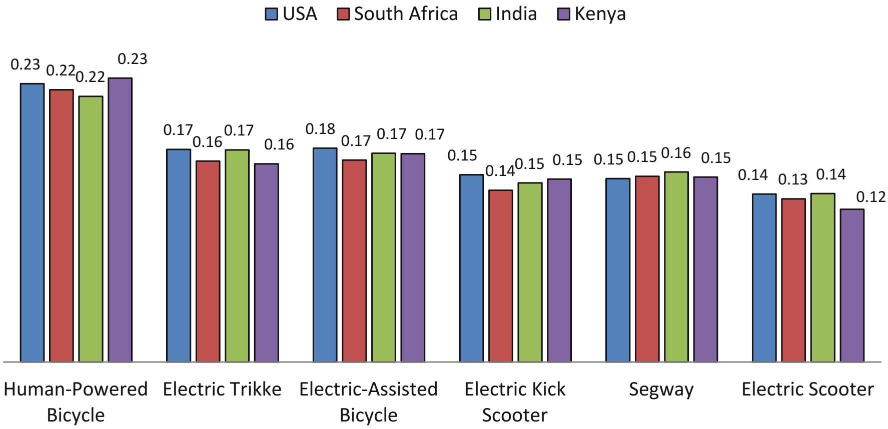

Fig. 4.6 Technology ranking per country

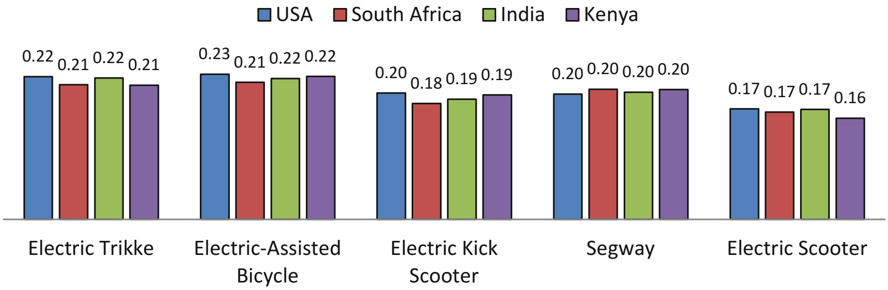

Fig. 4.7 Technology ranking per country (without human-powered bicycle)

Figure 4.7 illustrates the technology ranking with the human-powered bicycle removed. The ranking order remains the same among the electric vehicles. The electric Trikke and electric-assisted bicycle are ranked slightly higher than the remaining vehicles.

4.5 Discussion

As shown in Fig. 4.5, each country roughly agreed in terms of overall criteria, with a few exceptions. Indian respondents gave more emphasis to safety factors than the other countries, and less importance to regulations. Kenya ranked practicality the highest, while the USA and South Africa spread their weights across safety, practicality, economics, and ease of use.

We felt that this response made sense because of the perception of heavy traffic conditions in India which lead people to fear for their personal safety when using transportation in public. It was also noted that there are no strict rules regarding vehicle licensing and no significant punishment for infractions which explains the low rank given to the regulation criteria.

For South Africa one of the highest weights was for purchase cost, which may be due to the fact that products in South Africa are generally more expensive, and the general income is lower. As an example, the Segway i2 is approximately 16 % more expensive than in the USA [26]. Additionally, the operating (charging) cost may have one of the highest weights because of the high increase in electricity costs over the previous years [27]. The lower weights (equipment weight, size, and storage) could be because bicycles are generally used for recreational or sporting activities in South Africa and lifting the vehicle is not a common requirement, neither is storing it away an issue.

For the Kenyan responses, practicality rose to the top largely due to the "range per charge" factor which makes sense given the local infrastructure and relative lack of urban development. One surprise was that the USA gave such a high ranking to economic concerns, being the richest country surveyed. There was also widespread agreement on the service and support criteria.

As shown in Table 4.1, each country also applied factor weights differently within each criteria group. It can be seen that for the USA the economic factors are the highest overall although there were other factors which achieved equal weight. It is also easy to see the rank of safety for Indian respondents, with "safety features" having the highest individual weight across all countries overall.

One surprising aspect of this table is the relatively low weight applied to "appearance." It is known that vehicle appearance can be quite important to consumers, but the team believes that the placement of this factor within the criterion of practicality may have led to its being overlooked by our survey respondents. Despite the different weights applied across all the criteria and factors, each country chose the simple human-powered bicycle as the best technology for transporting a single person. The actual scores are shown in Fig. 4.6. However, it appeared that, due to overwhelming weights applied such categories as "range per charge," "cost per charge," and "time to recharge," the bicycle was masking the differences between the other electric vehicles. Therefore we ran the weights again without the bicycle and achieved the answer shown in Fig. 4.6. The next preferred vehicle is the electric-assist bicycle followed closely by the Trikke and Segway. The least preferred vehicle was the electric scooter in all cases.

4.6 Future Work

As mentioned earlier, this chapter used a simple HDM model to compare across different transportation alternatives. However, when we began this project we attempted to apply a more advanced model using technology valuation (TV) factors to further refine the weights of each technological attribute. However, upon discussion with our advisor we opted to forgo this step since it would be too time consuming to obtain appropriate desirability information from each respondent country. Future work could look into this TV methodology and attempt to refine the scores of our vehicle alternatives.

We hope that this methodology could also apply across different transportation sectors beyond single-person and low speed. For instance, knowing that safety is so important to Indian consumers could inform the marketing or even product development of transportation projects in that country. To further this research it would be good to offer the same survey to both consumers and product development personnel in each country to compare and contrast the weights applied by each group.

4.7 Conclusion

We have used a simple HDM model to compare consumer preferences for transportation alternatives across four very different countries and shown that while each country has preferred characteristics, they all prefer the common bicycle to any newer, more highly featured alternatives.

Appendix 1: Survey

Single-Person Transportation Survey

The purpose of this survey is to establish the importance of different criteria and factors that a person takes into account when deciding to purchase a vehicle for single-person transportation. These are devices such as bicycles, electric-assisted bicycles, and electric scooters. A full list of vehicles can be seen at the end of this survey. Throughout this survey "vehicle" refers to any one of these options.

Section 1: Comparisons

Introduction

The comparisons in this section are done by a method called pairwise comparison. This is when you have 100 points available and you assign them between two options. For example, the following is comparing safety against practicality:

Pairwise comparison			
Safety	70	30	Practicality

Since I see safety as more important than practicality I assign more points to safety than practicality. If I see them as equal I assign 50 to practicality and 50 to safety. If I see safety as substantially more important than practicality I assign 99 points to safety and 1 point to practicality. Do not assign 100 points to one option only. Also make sure that the values add up to 100 points for each comparison.

Comparison 1

The first comparison is between the following criteria when purchasing a vehicle for single-person transportation:

1. Safety—This is how safe the vehicle is to use (e.g., safety features, stability, weight restriction, maximum speed).
2. Practicality—This is how convenient the vehicle is to use (e.g., the weight and size of the vehicle, charging time, distance per charge).
3. Economic—This is the costs involved with purchasing, operating, and maintaining the vehicle.
4. Service and support—This is the length of the warranty and the reliability of the vehicle.
5. Ease of use—This is how much effort goes into using the vehicle (e.g., physical exertion, comfort, storage,).

6. Public use regulations—This is the restriction when using the vehicle (e.g., license requirements, sidewalk and road restrictions).

   Please complete the comparison below:

Pairwise comparison			
Safety			Practicality
Safety			Economic
Safety			Service and support
Safety			Ease of use
Safety			Public use regulations
Practicality			Economic
Practicality			Service and support
Practicality			Ease of use
Practicality			Public use regulations
Economic			Service and support
Economic			Ease of use
Economic			Public use regulations
Service and support			Ease of use
Service and support			Public use regulations
Ease of use			Public use regulations

Comparison 2

The second comparison is between factors under safety, which are as follows:

1. Safety features—This is the safety equipment installed on the vehicle (e.g., braking system).
2. Stability—This is how steady the vehicle is when operating (i.e., turning corners, changing between different surfaces).
3. User weight restriction—This is the maximum weight of the person operating the vehicle.
4. User recommended age—This is the youngest recommended age for a person operating the vehicle.
5. Max speed—This is the maximum speed at which the vehicle can travel.

   Please complete the comparison below:

Pairwise comparison (safety)			
Safety features			Stability
Safety features			User weight restriction
Safety features			User recommended age
Safety features			Max speed
Stability			User weight restriction

(continued)

Pairwise comparison (safety)			
Stability			User recommended age
Stability			Max speed
User weight restriction			User recommended age
User weight restriction			Max speed
User recommended age			Max speed

Comparison 3

The third comparison is between factors under practicality, which are as follows:

1. Equipment weight—This is the weight of the vehicle (e.g., how heavy it is to pick up in the train, into your car).
2. Equipment size—This is the longest length of the vehicle.
3. Charge time—This is how long an electric vehicle takes to fully charge before it can be used.
4. Max speed—This is the maximum speed at which the vehicle can travel.
5. Range per charge—This is the distance that the vehicle can travel on one charge.

Please complete the comparison below:

Pairwise comparison (practicality)			
Equipment weight			Equipment size
Equipment weight			Charge time
Equipment weight			Max speed
Equipment weight			Range per charge
Equipment size			Charge time
Equipment size			Max speed
Equipment size			Range per charge
Charge time			Max speed
Charge time			Range per charge
Max speed			Range per charge

Comparison 4

The fourth comparison is between factors under economic, which are as follows:

1. Purchase cost—This is the initial cost to purchase the vehicle.
2. Operating cost—This is the cost to use the vehicle (e.g., charging cost for electric vehicle).
3. Maintenance cost—This is the cost to maintain the vehicle (e.g., replacing tires, batteries).

Please complete the comparison below:

Pairwise comparison (economic)			
Purchase cost			Operating cost
Purchase cost			Maintenance cost
Operating cost			Maintenance cost

Comparison 5

The fifth comparison is between factors under service and support, which are as follows:

1. Warranty length—This is the length of the warranty for the vehicle.
2. Ease of maintenance—This is how easy the vehicle is to maintain yourself.
3. Reliability—This is how reliable the vehicle is perceived to be.

Please complete the comparison below:

Pairwise comparison (service and support)			
Warranty length			Ease of maintenance
Warranty length			Reliability
Ease of maintenance			Reliability

Comparison 6

The sixth comparison is between factors under ease of use, which are as follows:

1. Physical exertion—This is how much effort goes into using the vehicle.
2. Comfort—This is how comfortable the vehicle is (e.g., standing vs. sitting, seat comfort).
3. Storage—This is how practical the vehicle is to store away (e.g., in a cupboard).
4. Handling—This is how easy the vehicle is to operate (e.g., turning, balancing).
5. Appearance—This is your perception on what the vehicle looks like.

Please complete the comparison below:

Pairwise comparison (ease of use)			
Physical exertion			Comfort
Physical exertion			Storage
Physical exertion			Handling
Physical exertion			Appearance
Comfort			Storage
Comfort			Handling

(continued)

Pairwise comparison (ease of use)			
Comfort			Appearance
Storage			Handling
Storage			Appearance
Handling			Appearance

Comparison 7

The seventh comparison is between factors under public use regulations, which are as follows:

1. Sidewalk restrictions—This is whether the vehicle is allowed to be used on sidewalks or not.
2. Road restrictions—This is whether the vehicle is allowed to be used on the road or not.
3. License requirement—This is whether you require a license or permit to use the vehicle on public roads and sidewalks.

   Please complete the comparison below:

Pairwise comparison (public use regulations)			
Sidewalk restrictions			Road restrictions
Sidewalk restrictions			License requirement
Road restrictions			License requirement

Thank you for your patience and time for completing this survey!!!!

Section 2: Single-Person Transportation Vehicles

Human-powered bicycle
- Price—$1,369
- Shimano mechanical disc front brakes

(continued)

	Electric Trikke • Price—$2,200 • Weight—46 lb • Range—24 miles per charge • Max speed—16 mph • Foldable • Dual disk brakes • Charge time—3 h
	Electric-assisted bicycle • Price—$3,449 • Weight—47 lb • Range—40 miles per charge • Warranty—2 years • Shimano hydraulic disk brakes
	Electric kick scooter • Price—$3,795 • Weight—46 lb • Range—28 miles per charge (econ) • Max speed—20 mph • Foldable • Mad Dog Disc braking system
	Segway i2 • Price—$6,999 • Weight—105 lb • Range—24 miles per charge • Max speed—12.5 mph

(continued)

	Electric scooter • Price—$1,799 • Weight—265 lb • Range—15 miles per charge • Max speed—15 mph • Warranty—6 months • Charge time—8 h • Front and rear drum brakes

Appendix 2: Description of 5-Point Scale for Sub-criteria

Table 4.2 Sub-criteria 5-point scale description

Factor	5-point scale	Description
Factor 11: Safety features	Excellent (E)	Safety features are above all other vehicles in the same category.
	Good (G)	Safety features are equivalent to the leading vehicles in the same category.
	Average (A)	Safety features are equivalent to competing products in the same category.
	Poor (P)	Very basic safety features installed that are not up to the standards of competing vehicles in the same category.
	Unacceptable (UA)	No safety features installed on the vehicle.
Factor 21: Stability	Excellent (E)	The vehicle can handle corners and changes in surface safely at the maximum speed.
	Good (G)	The vehicle can handle corners and changes in surface safely at the average speed of the vehicle.
	Average (A)	The vehicle handles corner sufficiently, and can handle changes in surface; however there is still a possibility of the vehicle losing control.
	Poor (P)	The vehicle turns corners with difficulty or unsafely. It is recommended to turn corners at very low speeds.
	Unacceptable (UA)	The vehicle cannot turn corners or handle changes in surface; it can basically not be used for any purpose.
Factor 33: Mainte-nance cost	Very Low (VL)	The cost to maintain the vehicle is less than 10 % of the purchase cost of the vehicle.
	Low (L)	The cost to maintain the vehicle is between 10 and 30 % of the purchase cost of the vehicle.
	Acceptable (A)	The cost to maintain the vehicle is between 30 and 60 % of the purchase cost of the vehicle.
	High (H)	The cost to maintain the vehicle is between 60 and 90 % of the purchase cost of the vehicle.
	Very High (VH)	The cost to maintain the vehicle is above 90 % of the purchase cost of the vehicle.
Factor 24: Ease of maintenance	Excellent (E)	It is possible to maintain all parts of the vehicle without assistance.
	Good (G)	It is possible to maintain small parts (tires, chains, etc.) and medium parts (batteries, wheels, etc.) without assistance.
	Average (A)	It is possible to maintain small parts (tires, chains, etc.) and medium parts (batteries, wheels, etc.) with assistance.
	Poor (P)	It is possible to maintain small parts (tires, chains, etc.) of the vehicle with assistance.
	Unacceptable (UA)	It is impossible to maintain the vehicle. The vehicle needs to be sent into the repair shop.

(continued)

Table 4.2 (continued)

Factor	5-point scale	Description
Factor 34: Reliability	Excellent (E)	The vehicle is reliable 100 % of the time.
	Good (G)	The vehicle operated acceptably with a very small possibility of failure.
	Average (A)	The vehicle operates acceptably with a small possibility of failure.
	Poor (P)	The vehicle is operational but there is a consistent possibility of failure.
	Unacceptable (UA)	The vehicle cannot be operated without a failure occurring.
Factor 15: Physical exertion	Very low (VL)	No effort is required when operating the vehicle.
	Low (L)	Slight amount of effort is required while operating the vehicle (e.g., standing).
	Acceptable (A)	Some effort is required while operating the vehicle (e.g., pushing, assisted cycling).
	High (H)	Equivalent effort to the average pace of walking is required while operating the vehicle.
	Very high (VH)	Equivalent effort to the average pace of running or cycling is required to operate the vehicle.
Factor 25: Comfort	Excellent (E)	The vehicle has no discomfort and can be used continuously without any issues.
	Good (G)	The vehicle is comfortable to operate for the duration of a long daily commute.
	Average (A)	The vehicle is comfortable to operate for the duration of an average daily commute.
	Poor (P)	The vehicle is uncomfortable to operate but can still be used for short durations.
	Unacceptable (UA)	The vehicle is extremely uncomfortable to operate. The vehicle should not be used.
Factor 35: Storage	Excellent (E)	The vehicle can be stored in a small-size closet, trunk of a car, etc.
	Good (G)	The vehicle can be stored in a standard-size storage closest.
	Average (A)	The vehicle can be stored in a small open area (e.g., balcony, storage room).
	Poor (P)	The vehicle can be stored in an open area such as a garage and small yard.
	Unacceptable (UA)	The vehicle cannot be stored anywhere except in a large open area.
Factor 45: Handling	Excellent (E)	The vehicle can handle all possible conditions
	Good (G)	The vehicle can handle different road surfaces and most weather conditions and is extremely easy to maintain balance on.
	Average (A)	The vehicle can handle slight changes in weather conditions and road conditions and is easy to maintain balance on.
	Poor (P)	The vehicle can only operate in standard weather conditions and flat paved roads.
	Unacceptable (UA)	The vehicle is very difficult to balance on, and does not handle any conditions and cannot be used.

(continued)

Table 4.2 (continued)

Factor	5-point scale	Description
Factor 55: Appearance	Excellent (E)	The vehicle would be appealing to all consumers in the market.
	Good (G)	The vehicle would be appealing to the current market of single-person transportation vehicles and will attract current motor vehicle users.
	Average (A)	The vehicle would be appealing to the current market of single-person transportation vehicles.
	Poor (P)	The vehicle would be acceptable to a very small amount of consumers in the market.
	Unacceptable (UA)	The vehicle is not appealing to any consumer and will not be purchased.

Appendix 3: Technologies

Table 4.3 Technology data

		Units	Limiting values		Human-powered bicycle	Electric Trikke	Electric-assisted bicycle	Electric kick scooter	Segway i2	Electric scooter
			Worst	Best						
Criteria 1: Safety										
Factor 11	Safety features	5-point scale	UA	E	G	A	G	A	E	G
Factor 21	Stability	5-point scale	UA	E	A	A	A	P	G	A
Factor 31	Weight restriction	lb	0	300	300	250	300	250	260	350
Factor 41	Recommended age	Years	0	21	8	16	16	16	16	16
Factor 51	Max speed	mph	30	0	40	12	20	20	12.5	15
Criteria 2: Practicality										
Factor 12	Equipment weight	lb	100	0	30	46	47	49	105	265
Factor 22	Equipment size	Inches	80	0	70	55	70	48	51	63
Factor 32	Charge time	Hours	12	0	0	3	6	5.8	10	8
Factor 42	Max speed	mph	0	30	25	12	25	20	12.5	15
Factor 52	Range per charge	Miles	0	100	100	24	40	28	24	15

(continued)

Table 4.3 (continued)

		Units	Limiting values		Human-powered bicycle	Electric Trikke	Electric-assisted bicycle	Electric kick scooter	Segway i2	Electric scooter
			Worst	Best						
Criteria 3: Economic										
Factor 13	Purchase cost	$	7,000	0	1,369	2,200	3,449	3,795	6,999	1,799
Factor 23	Operating (charg-ing) cost	$/month	15	0	0	4.2	3.7	7.2	6.2	7.8
Factor 33	Maintenance cost	5-point scale	VL	VH	L	A	A	A	H	H
Criteria 4: Service and support										
Factor 14	Warranty	Years	0	10	2	1	2	2	1	0.5
Factor 24	Ease of maintenance	5-point scale	UA	E	G	A	A	A	P	P
Factor 34	Reliability	5-point scale	UA	E	E	G	G	A	G	A
Criteria 5: Ease of use										
	Physical exertion		VL	VH	VH	A	A	L	L	L

(continued)

Table 4.3 (continued)

		Units	Limiting values		Human-powered bicycle	Electric Trikke	Electric-assisted bicycle	Electric kick scooter	Segway i2	Electric scooter
			Worst	Best						
Factor 15		5-point scale								
Factor 25	Comfort	5-point scale	UA	E	A	P	A	P	P	G
Factor 35	Storage	5-point scale	UA	E	A	E	A	E	G	P
Factor 45	Handling	5-point scale	UA	E	G	A	G	P	G	G
Factor 55	Appearance	5-point scale	UA	E	A	P	A	P	A	A
Criteria 6: Public regulations										
Factor 16	Sidewalk restriction	Y/N	Y	N	N	Y	Y	Y	N	Y
Factor 26	Road restriction	Y/N	Y	N	N	N	N	N	N	N
Factor 36	License/permit requirement	Y/N	Y	N	N	N	N	N	N	Y

Appendix 4: Criteria and Sub-criteria Weights

1. India

Table 4.4 Criteria and sub-criteria weights (India)

	Person 1	Person 2	Person 3	Person 4	Mean
Criteria					
Safety	**0.19**	**0.43**	**0.31**	**0.26**	**0.30**
Practicability	0.16	0.24	0.26	0.22	0.22
Economic	0.23	0.11	0.15	0.19	0.17
Service and support	0.2	0.12	0.1	0.17	0.15
Ease of use	0.12	0.07	0.14	0.11	0.11
Public use regulations	0.1	0.03	0.04	0.04	0.05
Inconsistency	0.053	0.11	0.049	0.086	0.056
Safety sub criteria					
Safety features	**0.25**	**0.26**	**0.51**	**0.41**	**0.36**
Stability	0.37	0.29	0.18	0.21	0.26
Weight restriction	0.11	0.14	0.08	0.11	0.11
Recommended age	0.13	0.14	0.05	0.1	0.10
Max speed	0.15	0.17	0.18	0.17	0.17
Inconsistency	0.041	0.017	0.039	0.039	0.069
Practicability sub-criteria					
Equipment weight	0.17	0.19	0.15	0.18	0.17
Equipment size	0.25	0.18	0.17	0.14	0.19
Charge time	**0.2**	**0.29**	**0.23**	**0.23**	**0.24**
Max speed	0.23	0.13	0.21	0.18	0.19
Range per charge	0.15	0.21	0.23	0.27	0.22
Inconsistency	0.048	0.063	0.014	0.038	0.041
Economic sub-criteria					
Purchase cost	**0.43**	**0.33**	**0.25**	**0.33**	**0.34**
Operating cost	0.29	0.33	0.38	0.33	0.33
Maintenance cost	0.29	0.33	0.38	0.33	0.33
Inconsistency	0.000	0.000	0.000	0.000	0.052
Service and support sub-criteria					
Warranty length	0.65	0.17	0.09	0.16	0.27
Ease of maintenance	0.24	0.3	0.3	0.3	0.28
Reliability	**0.11**	**0.53**	**0.61**	**0.54**	**0.45**
Inconsistency	0.032	0.022	0.026	0.01	**0.198**
Ease of use sub-criteria					
Physical exertion	0.17	0.39	0.14	0.25	0.23
Comfort	**0.27**	**0.18**	**0.31**	**0.2**	**0.24**
Storage	0.2	0.08	0.21	0.21	0.17
Handling	0.18	0.21	0.21	0.2	0.20
Appearance	0.18	0.15	0.14	0.14	0.15

(continued)

Table 4.4 (continued)

	Person 1	Person 2	Person 3	Person 4	Mean
Inconsistency	0.003	0.015	0.072	0.024	0.065
Public use regulations sub-criteria					
Sidewalk restrictions	0.49	0.41	0.08	0.36	0.33
Road restrictions	**0.31**	**0.41**	**0.52**	**0.47**	**0.43**
License requirement	0.2	0.18	0.4	0.18	0.24
Inconsistency	0.059	0.000	0.021	0.005	**0.132**

2. Kenya

Table 4.5 Criteria and sub-criteria weights (Kenya)

	Person 1	Person 2	Person 3	Mean
Criteria				
Safety	0.16	0.16	0.16	0.16
Practicality	**0.24**	**0.25**	**0.33**	**0.27**
Economic	0.21	0.11	0.11	0.14
Service and support	0.12	0.18	0.17	0.16
Ease of use	0.14	0.19	0.12	0.15
Public use regulations	0.12	0.11	0.09	0.11
Inconsistency	0.081	0.076	0.05	0.038
Safety sub-criteria				
Safety features	**0.31**	**0.34**	**0.3**	**0.32**
Stability	0.26	0.21	0.26	0.25
Weight restriction	0.11	0.19	0.2	0.17
Recommended age	0.11	0.1	0.09	0.10
Max speed	0.21	0.16	0.14	0.17
Inconsistency	0.035	0.07	0.016	0.032
Practicality sub-criteria				
Equipment weight	0.15	0.13	0.14	0.14
Equipment size	0.2	0.2	0.2	0.20
Charge time	0.19	0.19	0.19	0.19
Max speed	0.19	0.21	0.2	0.19
Range per charge	**0.27**	**0.27**	**0.27**	**0.27**
Inconsistency	**0.102**	0.08	0.09	0.006
Economic sub-criteria				
Purchase cost	0.33	0.33	0.24	0.30
Operating cost	0.33	0.29	0.28	0.30
Maintenance cost	**0.33**	**0.38**	**0.48**	**0.40**
Inconsistency	0.000	0.021	0.006	0.056
Service and support sub-criteria				
Warranty length	0.18	0.33	0.38	0.30
Ease of maintenance	**0.41**	**0.33**	**0.37**	**0.37**

(continued)

Table 4.5 (continued)

	Person 1	Person 2	Person 3	Mean
Reliability	0.41	0.33	0.25	0.33
Inconsistency	0.000	0.000	0.05	0.081
Ease of use sub-criteria				
Physical exertion	0.16	0.15	0.15	0.16
Comfort	0.33	0.24	0.32	0.30
Storage	0.11	0.13	0.13	0.12
Handling	**0.3**	**0.33**	**0.3**	**0.31**
Appearance	0.11	0.15	0.1	0.12
Inconsistency	0.034	**0.108**	**0.182**	0.062
Public use regulations sub-criteria				
Sidewalk restrictions	0.32	0.29	0.26	0.29
Road restrictions	0.24	0.28	0.19	0.24
License requirement	**0.43**	**0.43**	**0.55**	**0.47**
Inconsistency	0.023	0.049	0.029	0.05

3. South Africa

Table 4.6 Criteria and sub-criteria weights (South Africa)

	Person 1	Person 2	Person 3	Person 4	Mean
Criteria					
Safety	**0.18**	**0.26**	**0.29**	**0.13**	**0.21**
Practicability	0.16	0.13	0.14	0.26	0.17
Economic	**0.24**	**0.19**	**0.19**	**0.23**	**0.21**
Service and support	0.23	0.08	0.19	0.07	0.14
Ease of use	0.11	0.13	0.1	0.2	0.13
Public use regulations	0.07	0.21	0.09	0.12	0.12
Inconsistency	0.051	0.005	0.016	0.059	0.06
Safety sub-criteria					
Safety features	0.23	0.36	0.41	0.11	0.28
Stability	**0.3**	**0.38**	**0.33**	**0.23**	**0.31**
Weight restriction	0.12	0.09	0.04	0.16	0.10
Recommended age	0.1	0.05	0.12	0.17	0.11
Max speed	0.25	0.13	0.09	0.34	0.20
Inconsistency	0.053	0.005	0.073	0.065	0.09
Practicability sub-criteria					
Equipment weight	0.1	0.16	0.2	0.12	0.14
Equipment size	0.09	0.06	0.1	0.12	0.09
Charge time	0.33	0.17	0.23	0.2	0.23
Max speed	0.21	0.22	0.13	0.34	0.22
Range per charge	**0.27**	**0.4**	**0.34**	**0.22**	**0.31**

(continued)

Table 4.6 (continued)

	Person 1	Person 2	Person 3	Person 4	Mean
Inconsistency	0.068	0.013	0.028	0.017	0.064
Economic sub-criteria					
Purchase cost	**0.38**	**0.5**	**0.25**	**0.38**	**0.38**
Operating cost	0.33	0.33	0.38	0.33	0.34
Maintenance cost	0.29	0.17	0.38	0.29	0.28
Inconsistency	0.021	0.000	0.000	0.005	0.078
Service and support sub-criteria					
Warranty length	0.21	0.42	0.36	0.14	0.28
Ease of maintenance	0.37	0.21	0.18	0.41	0.29
Reliability	**0.42**	**0.37**	**0.47**	**0.45**	**0.43**
Inconsistency	0.006	0.006	0.005	0.029	**0.103**
Ease of use sub-criteria					
Physical exertion	0.26	0.35	0.15	0.08	0.21
Comfort	**0.24**	**0.19**	**0.23**	**0.35**	**0.25**
Storage	0.1	0.12	0.13	0.11	0.12
Handling	**0.15**	**0.29**	**0.27**	**0.3**	**0.25**
Appearance	0.24	0.04	0.23	0.16	0.17
Inconsistency	0.021	0.008	0.023	0.017	0.078
Public use regulations sub-criteria					
Sidewalk restrictions	0.26	0.38	0.33	0.25	0.3
Road restrictions	**0.54**	**0.38**	**0.33**	**0.43**	**0.42**
License requirement	0.2	0.25	0.33	0.33	0.28
Inconsistency	0.005	0	0	0.005	0.071

4. USA

Table 4.7 Criteria and sub-criteria weights (USA)

	Person 1	Person 2	Person 3	Person 4	Person 5	Mean
Criteria						
Safety	0.22	0.23	0.19	0.1	0.13	0.17
Practicality	0.18	0.14	0.23	0.35	0.14	0.21
Economic	**0.17**	**0.17**	**0.26**	**0.16**	**0.31**	**0.22**
Service and support	0.18	0.2	0.07	0.05	0.08	0.12
Ease of use	0.17	0.12	0.22	0.15	0.18	0.17
Public use regulations	0.08	0.14	0.04	0.18	0.15	0.12
Inconsistency	0.026	0.05	0.033	**0.156**	0.049	0.065
Safety sub-criteria						
Safety features	0.37	0.27	0.25	0.1	0.3	0.26
Stability	**0.37**	**0.25**	**0.25**	**0.31**	**0.21**	**0.28**
Weight restriction	0.05	0.16	0.06	0.26	0.06	0.12

(continued)

Table 4.7 (continued)

	Person 1	Person 2	Person 3	Person 4	Person 5	Mean
Recommended age	0.09	0.15	0.25	0.14	0.14	0.16
Max speed	0.13	0.16	0.18	0.19	0.28	0.19
Inconsistency	0.015	0.023	0.003	0.01	0.101	0.075
Practicality sub-criteria						
Equipment weight	**0.27**	**0.19**	**0.09**	**0.26**	**0.77**	**0.32**
Equipment size	0.25	0.13	0.06	0.19	0.08	0.14
Charge time	0.15	0.22	0.26	0.14	0.02	0.16
Max speed	0.18	0.12	0.26	0.27	0.11	0.19
Range per charge	0.15	0.34	0.34	0.14	0.03	0.20
Inconsistency	0.006	0.016	0.019	0.056	0.068	**0.147**
Economic sub-criteria						
Purchase cost	0.29	0.38	0.27	0.23	0.46	0.33
Operating cost	**0.43**	**0.29**	**0.57**	**0.23**	**0.17**	**0.34**
Maintenance cost	**0.29**	**0.33**	**0.16**	**0.54**	**0.36**	**0.34**
Inconsistency	0	0.005	0.004	0	0.038	**0.133**
Service and support sub-criteria						
Warranty length	0.38	0.38	0.09	0.11	0.14	0.22
Ease of maintenance	0.25	0.29	0.55	0.5	0.28	0.38
Reliability	**0.38**	**0.33**	**0.36**	**0.39**	**0.58**	**0.41**
Inconsistency	0	0.005	**0.186**	0.005	0.035	**0.131**
Ease of use sub-criteria						
Physical exertion	0.11	0.14	0.09	0.17	0.28	0.16
Comfort	0.27	0.34	0.15	0.25	0.15	0.23
Storage	0.16	0.17	0.17	0.22	0.06	0.16
Handling	**0.25**	**0.22**	**0.43**	**0.19**	**0.33**	**0.28**
Appearance	0.2	0.13	0.17	0.18	0.17	0.17
Inconsistency	0.024	0.035	0.014	0.054	0.03	0.071
Public use regulations sub-criteria						
Sidewalk restrictions	0.31	0.38	0.05	0.12	0.02	0.18
Road restrictions	**0.21**	**0.38**	**0.68**	**0.66**	**0.85**	**0.55**
License requirement	0.48	0.25	0.27	0.22	0.14	0.27
Inconsistency	0	0	0.051	0.019	**0.123**	**0.19**

Appendix 5: Sub-criteria Weights to Objective

		USA	South Africa	India	Kenya
Criteria 1: Safety					
Factor 11	Safety Features	0.04	0.06	0.11	0.05
Factor 21	Stability	0.05	0.07	0.08	0.04
Factor 31	Weight Restriction	0.02	0.02	0.03	0.03
Factor 41	Recommended Age	0.03	0.02	0.03	0.02
Factor 51	Max Speed	0.03	0.04	0.05	0.03
Criteria 2: Practicality					
Factor 12	Equipment Weight	0.07	0.02	0.04	0.04
Factor 22	Equipment Size	0.03	0.02	0.04	0.05
Factor 32	Charge Time	0.03	0.04	0.05	0.05
Factor 42	Max Speed	0.04	0.04	0.04	0.05
Factor 52	Range per charge	0.04	0.05	0.05	0.07
Criteria 3: Economic					
Factor 13	Purchase Cost	0.07	0.08	0.06	0.04
Factor 23	Operating (Charging) Cost	0.07	0.07	0.06	0.04
Factor 33	Maintenance Cost	0.07	0.06	0.06	0.06
Criteria 4: Service and Support					
Factor 14	Warranty	0.03	0.04	0.04	0.05
Factor 24	Ease of Maintenance	0.05	0.04	0.04	0.06
Factor 34	Reliability	0.05	0.06	0.07	0.05
Criteria 5: Ease of Use					
Factor 15	Physical exertion	0.03	0.03	0.03	0.02
Factor 25	Comfort	0.04	0.03	0.03	0.05
Factor 35	Storage	0.03	0.02	0.02	0.02
Factor 45	Handling	0.05	0.03	0.02	0.05
Factor 55	Appearance	0.03	0.02	0.02	0.02
Criteria 6: Public Regulations					
Factor 16	Sidewalk Restriction	0.02	0.04	0.02	0.03
Factor 26	Road Restriction	0.07	0.05	0.02	0.03
Factor 36	License/Permit Requirement	0.03	0.03	0.01	0.05

Fig. 4.8 Overall factor weights per country

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Part II
Strategic Planning

Chapter 5
Strategic Planning: A Quantitative Model for the Strategic Evaluation of Emerging Technologies

Nathasit Gerdsri

Abstract This chapter presents a quantitative model used for evaluating the impact of emerging technologies on a company's objective. The hierarchical model with four levels (objective–criteria–factors–technology alternatives) is structured to decompose the complex decision problems and incorporate quantitative and qualitative aspects into the evaluation process. A new approach on applying a semi-absolute scale to quantify the values of technologies is proposed in conjunction with the determination of criteria priorities and the relative importance of factors under each criterion. The impact of technologies on a company's objective is calculated as a composite index called technology value. The improvement gap and improvement priority of each technology are also determined to identify the characteristics of the emerging technologies on which technology-driven companies would focus in order to maximize the impact of those technologies on the company's strategic objectives. A case study is included in this chapter to illustrate the applicability and computations of the proposed model.

5.1 Introduction

Increasing global market competition is making a strong impact on the design and development of new products [1, 2]. To survive under this intense pressure, companies are seeking for the better way to exploit the uses of technologies [3–5]. Choosing the right technologies would help companies supporting the future development of their new products.

In today's environment, technologies are changing faster than ever. Companies have to keep an eye on the development of emerging technologies as they constantly monitor the development of existing technologies. The success of

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implementing technologies to new products would open windows of opportunity for companies to gain competitiveness [6]. However, managers of technology development divisions in companies often struggle with finding a proper way to analytically evaluate the impacts of those emerging technologies on a company's objective.

Despite the fact that there is an abundance of literature on decision-support models for the evaluation of technologies, only a few studies specifically address to emerging technologies. The development processes of a decision-support model for emerging technology tend to be more sophisticated than those of existing technologies due to the higher degree of uncertainty and the limited amount of data available.

Theoretically, the concept of hierarchical modeling (also known as analytical hierarchy process—AHP) can be applied to structurally decompose the complex problems as well as incorporate quantitative and qualitative aspects into consideration [7, 8]. There have been several studies done on applying AHP approach to the evaluation or assessment of technologies: for example, Technological Choice in the Less Developed Countries: An Analytical Hierarchy Approach, Ramanujan [9]; The Analytical Hierarchy Process for Choice of technologies, Prasad [10]; The Prioritization of Technologies in a Research Laboratory, Melachrinoudis [11]; Prioritizing Telecommunications Technologies for Long-Range R&D Planning to the Year 2006, Suh [12]; and Justification of New Manufacturing Technology: A Strategic Approach Using the AHP, Albayrakoglu [13].

In those studies, the hierarchical model for the evaluation and assessment of technologies is constructed with either three levels (objective–criteria–technology alternatives) or four levels (objective–criteria–subcriteria–technology alternatives). The series of comparative judgments are analyzed to determine the relative impact of technologies on the objective.

However, obtaining the direct comparison of technologies with respect to each criterion may pose the problems on the aggregation of comparative judgments [14]. These issues really become the limitations on the application of the model to emerging technologies.

To unleash the limitations and enhance the robustness of a model, this chapter proposes a new approach by replacing the technologies with their measures of effectiveness. Thus, the impact of emerging technologies can be evaluated through the semi-absolute values instead of the relative values.

5.2 Model Development

The development of proposed model for the evaluation of emerging technologies is achieved in three steps: (1) technology characterization, (2) hierarchical modeling, and (3) technology evaluation. Figure 5.1 represents the flow of information within the model from Step 1 to Step 3 as well as the integration of strategic information used as inputs to the model. The strategic information presents the list of potential

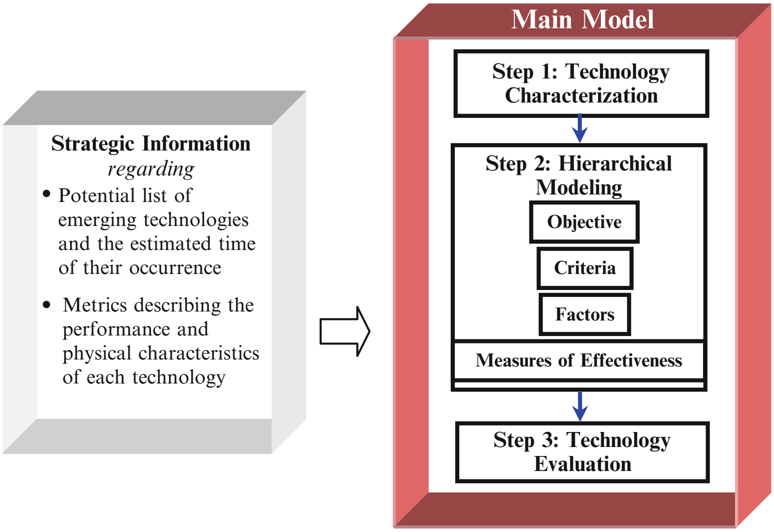


Fig. 5.1 Information flow to and within the model

emerging technologies and the estimated time of their occurrence along with the metrics describing the performance and physical characteristics of each technology.

To obtain the strategic information on emerging technologies, it is always challenging due to the limited data availability inherent in emerging technologies. Gerdsri and Kocaoglu applied Delphi method to obtain this strategic information by gathering expert opinions [15].

For the main technology evaluation model, the concept of hierarchical decision modeling is applied to decompose the structure of complex issues into hierarchies and then apply the comparative judgments to synthesize the relative priorities of components in each hierarchy.

The identification of components in each hierarchy as well as the quantification of their relative priorities need to be specifically determined for a company. An expert panel is formed for this purpose. Members of the panel are all involved in the implementation technologies in the company.

5.2.1 Step 1: Technology Characterization

The experts are first asked to define and verify the company's objective for evaluating technologies. It is important to align the objective with the company's strategy. After that the experts are asked to decompose the decision complexity by identifying criteria and technological factors which contribute to the satisfaction of the company's objective.

A set of technological factors is specifically defined under each area of criteria so that the contribution of technology can be directly measured. For example, under economic criterion, at least three factors, cost of fabrication, cost of operation, and cost of service and maintenance, should be considered on affecting the importance of economic criterion. Technological factors can be either quantitative or qualitative parameters depending on the means used in measuring the contribution of technologies toward factors.

The identification of components placed in the criteria and technological factor level is accomplished based on the focus of their preferential independence even though some components may share their technical dependency.

Many methods such as brainstorming, interview, nominal group discussion, and Delphi technique can be applied to establish a set of criteria and factors through the use of expert opinions.

5.2.2 Step 2: Hierarchical Modeling for the Evaluation of Emerging Technologies

Through conceptual thinking, a generalized hierarchical model can be constructed with a four-level hierarchy: objective, criteria, factors, and technologies, as shown in Fig. 5.2. This model represents the hierarchical structure in which the relative contributions of technologies to the objective are calculated by determining the priorities of the criteria, the relative importance of factors on each criterion, and the relative impact of technologies on each factor. The relative values of components in a given level are determined through a series of pairwise judgment quantifications with respect to the elements in the next higher level.

The aggregation of comparative judgments on technologies with respect to each factor poses two disadvantages. First, the judgment quantification approach becomes very difficult when the number of technologies increases. Second, the whole series of comparative judgments need to be repeatedly quantified every time a new technology is added to the list.

To overcome these difficulties, a composite index called “technology value” is developed to quantify the impact of each technology on the objective based on the semi-absolute values instead of the relative values.

With the new approach of quantifying the technology value, the generalized model has to be transformed to an operational model by replacing the technologies with their measures of effectiveness as shown in Fig. 5.3. A set of measures of effectiveness (metrics) is defined for each technological factor so that the performance and physical characteristics of emerging technologies could be directly evaluated. The impact relationships of measures of effectiveness associated with each factor are determined through the quantification of judgments for the desirability of each measure of effectiveness.

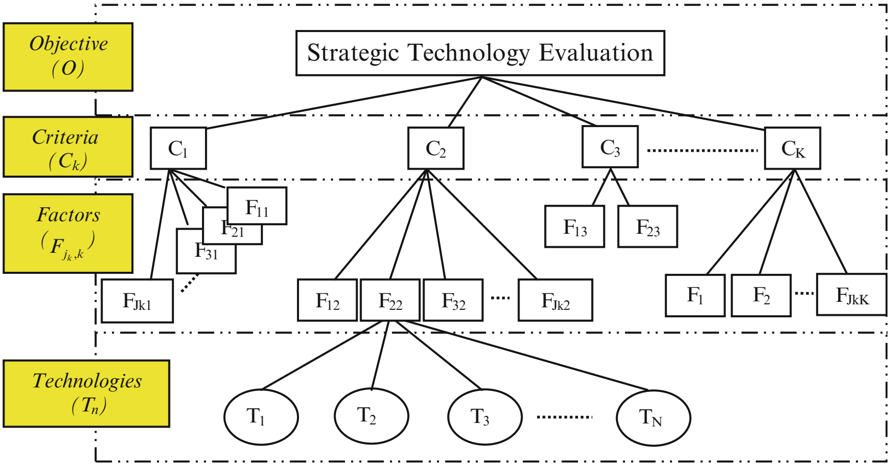


Fig. 5.2 The generalized hierarchical model developed for evaluating emerging technologies

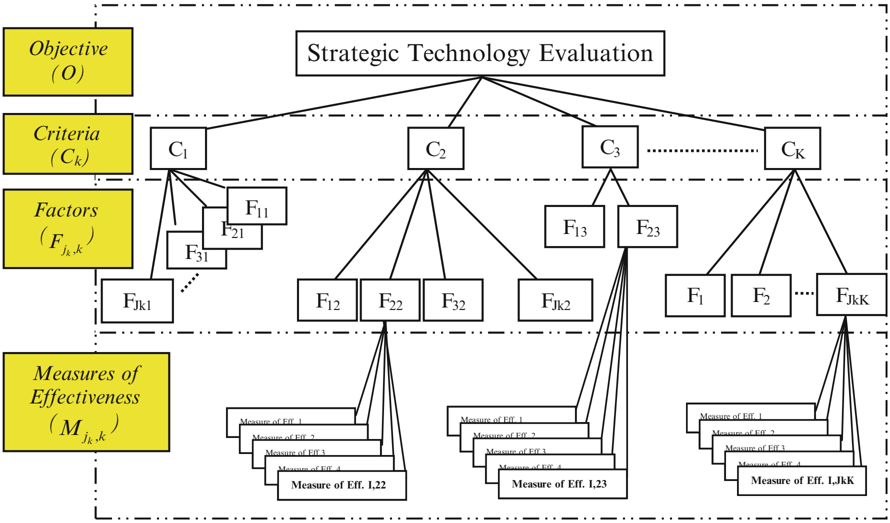


Fig. 5.3 The operational hierarchical model developed for evaluating emerging technologies

5.2.3 Step 3: Technology Evaluation

Referring to the operational hierarchical model in Fig. 5.3, the technology value of an emerging technology (TV_n) can be computed as shown in Eq. (5.1):

$$\boxed{TV_n = \sum_{k=1}^{K} \sum_{j_k}^{J_k} w_k \cdot f_{j_k,k} \cdot V\left(t_{n,j_k,k}\right)} \tag{5.1}$$

where

TV_n: Technology value of technology (n) determined according to a company's objective
w_k: Relative priority of criterion (k) with respect to the company's objective
$f_{j_k,k}$: Relative importance of factor (j_k) with respect to criterion (k)
$t_{n,j_k,k}$: Performance and physical characteristics of technology (n) along with factor (j_k) for criterion (k)
$V\left(t_{n,j_k,k}\right)$: Desirability value of the performance and physical characteristics of technology (n) along factor (j_k) for criterion (k)

The computational process is described through five measurements as follows:

Measurement 1: Determination of [w_k], the relative priority of criterion (k), with respect to the objective:

$$\boxed{\sum_{k=1}^{K} w_k = 1.0; \quad \text{where } w_k > 0} \tag{5.2}$$

The series of comparative judgments are obtained from each expert through the allocation of 100 points between two criteria at a time (applying the constant-sum method) [16, 17]. The judgments are converted to a normalized measure of relative priority values in ration scale for the criteria.

The group values for the relative priority of criteria are calculated as the mean of the priority values obtained from individual experts.

Measurement 2: Determination of [$f_{j_k,k}$], the relative impact of factors (j_k), associated with each criterion (k):

$$\boxed{\sum_{j_k=1}^{J_k} f_{j_k,k} = 1.0 \quad \text{for each criterion (k); where } f_{j_k,k} > 0} \tag{5.3}$$

The series of comparative judgments on technological factors with respect to each criterion are obtained and the relative importance of those factors under each criterion is calculated by following the same approach described in measurement 1.

Measurement 3: Determination of [$V\left(m_{j_k,k}\right)$], the relative desirability of measures of effectiveness (metrics), under each factor (j_k) and criterion (k)

This process is conducted through four steps.

Step a: Identify the best and worst desirable limiting metrics that each factor can take on.
Step b: Verify the measures of effectiveness whose desirability value is linearly proportional to their numerical value between the two limits.
Step c: Develop a semi-absolute scale by assigning 0 point to the worst and 100 points to the best desirable limiting metrics under each factor.
Step d: Calculate the relative desirability of the intermediate values between the two limits by following one of the two approaches described below:

Approach 1: If a characteristic of a factor can be verified as a linearly proportional function, the relative desirability of the measures of effectiveness between the worst and best metrics is determined as linearly proportional to its numerical values between the limits.
Approach 2: If a characteristic of a factor cannot be verified as a linearly proportional function, the nonlinear functional relationships between the numerical values of the metric and their desirability value need to be developed:

$$\boxed{0 \leq V\left(m_{j_k,k}\right) \leq 100 \quad \text{for each factor } (\mathrm{j_k}) \text{ and criterion } (\mathrm{k})} \tag{5.4}$$

The relative desirability values of metrics under each factor can be graphically presented as a desirability curve by arranging the range of metrics value on X-axis and the desirability value on Y-axis.

Measurement 4: Mapping of technological metrics [$t_{n,\,j_k,k}$] to the desirability values [$V\left(t_{n,\,j_k,k}\right)$]

For each technology, the mapping of technological metrics [$t_{n,\,j_k,k}$] to the desirability values [$V\left(t_{n,\,j_k,k}\right)$] is completed through the relative desirability of the measures of effectiveness [$V\left(m_{j_k,k}\right)$] computed in Measurement 3:

$$\boxed{t_{n,\,j_k,k} \overset{V\left(m_{j_k,k}\right)}{\longrightarrow} V\left(t_{n,\,j_k,k}\right) \quad \text{for technology } (\mathrm{n})} \tag{5.5}$$

Measurement 5: Quantification for [$\mathrm{TV_n}$], technology value

By applying Eq. (5.1), the technology value is calculated through the matrix computations among the criteria priorities (Measurement 1), the relative importance of factors on each criterion (Measurement 2), and the desirability value of technologies to factors (Measurement 4). The outcomes are the technology values of emerging technologies according to a company's objective. The ideal technology from a company's point of view would represent the technology value of 100.

5.3 Application of the Model

For the purpose of illustration, the proposed model is applied to the strategic evaluation of emerging electronic cooling technologies. The outcomes of technology value will indicate which cooling technology a company should consider for R&D investment in developing thermal platforms to support new computer servers.

5.3.1 Problem Statement

A group of experts in a company concerns that the current thermal platform using air cooling technology may not be efficient enough to support new computer server which is planned to launch in 2006–2007 even though the performance and physical characteristics of air cooling technology will continue to improve.

With the strategic information about emerging electronic cooling technologies, the experts identify that there will be three potential candidates for R&D investment. The three technologies are channel flow boiling, spray cooling, and mechanically pumped single-phase liquid cooling (MPS-LP). The estimation of metrics of these technologies is presented in Table 5.1.

A company will determine its R&D investment in cooling technology according to the technology value of four different alternatives (including the three emerging technologies and the incremental improved air cooling technology).

All relevant data are obtained from the ongoing research on Building a Technology Development Envelope (TDE) for Roadmapping of Emerging Electronic Cooling Technologies [15].

5.3.2 Literature Review of the Current Situation of Thermal Management

The thermal management issues in electronics systems have become crucial because future products including high-density desktop computers, multiprocessor rack-mounted servers, and telecommunications cabinets are reaching volumetric thermal densities beyond the limits of the current technology, direct air cooling [18, 19].

There is enough evidence showing that the demands for more functionality, faster performance, lighter weight, smaller size, lower price, and more reliable product cause ever-serious challenges to electronic packaging density and thermal management [20–22]. By managing these challenges, companies can develop competitive advantage in their new electronic product development.

Table 5.1 Metrics and desirability values of potential cooling technologies estimated for 2006–2007

			Technological Metrics ($t_{n,j_k,k}$) →				Desirability Values $V(t_{n,j_k,k})$			
Criterion	Factors	Measurement Unit	Air Cooling (T_1)	Channel Flow Boiling (T_2)	Spray Cooling (T_3)	MPS-LC* (T_4)	Air Cooling (T_1)	Channel Flow Boiling (T_2)	Spray Cooling (T_3)	MPS-LC* (T_4)
C1: Performance	F11: Heat removal flux	W/cm^2	120	120	200	200	12	12	20	20
	F21: Thermal resistance	°C/Watt	0.2	0.03	0.04	0.08	0	90	88	72
	F31: Temperature controllability	Temperature swing (°C)	10	10	4	2	0	0	62	82
C2: Geometric	F12: Height	inches	4	0.3	0.4	2	0	95	92	67
	F22: Footing space	cm^2	6	2	4	4.5	60	88	75	72
	F32: Weight	lbs	2	0.2	1.5	6	0	90	25	0
	F42: Distance of heat transportation	inches	4	1	100	20	50	12.5	100	100
C3: Reliability	F13: Continuous operation	hours	2000	10000	10000	5000	10	40	40	24
	F23: Durability under adverse environment conditions	5-point scale	VG	G	G	G	90	71	71	71
	F33: % of performance drop overtime	%	10	30	5	5	90	70	95	95
	F43: Length of the warming up period at start	seconds	0	10	30	300	100	90	75	0
	F53: Longevity	years	7	5	3	5	90	75	50	75
C4: Economic	F14: Power consumption for cooling system	Watts	5	10	50	15	95	90	50	85
	F24: Cost of fabrication	$	10	150	80	75	97	50	73	75
	F34: Cost for recharging, servicing and reclamation	$	5	100	80	75	99	65	73	75
C5: Environmental Compatibility, Safety, and Regulation	F15: Toxic control of cooling media and combustion products	5-point scale	E	VG	G	VG	100	80	60	80
	F25: Temperature control of exhaust coolant (air/gas/liquid)	°F	55	5	0	0	75	97	100	100
C6: Serviceability & Maintenance	F16: Installation & maintenance Complexity	5-point scale	E	A	G	G	100	40	60	60
	F26: Interchangeability of components	5-point scale	E	A	P	A	100	50	25	50
C7: Flexibility	F17: Physical Moldability	5-point scale	A	A	P	G	27	27	8	50
	F27: Scalability	5-point scale	G	G	G	VG	58	58	58	82
	F37: Upgrade ability	5-point scale	A	G	P	G	33	55	12	55

As a result of continuously increasing power dissipation, electronic cooling technologies will experience a major evolution from air to liquid to possibly cryogenics in the future, as shown in the electronic cooling technology mapping.

5.3.3 Model for the Evaluation of Emerging Electronic Cooling Technologies

A panel of six experts was formed in thermal management division of a technology-driven company. Each expert was involved in some aspects of implementing new electronic cooling technologies to computer servers such as R&D, technology enabling, product design, and manufacturing.

5.3.3.1 The Identification of Technology Characterization (Step 1)

All experts verified their company's objective for the evaluation of emerging electronic cooling technologies as "*To achieve technological competitiveness through the new thermal platform development for computer servers*." Then, they identified seven criteria and a set of factors associated with each criterion along with the limiting values of the measures of effectiveness applied for each factor as shown in Table 5.2.

Table 5.2 List of criteria and factors associated with each criterion along with their limiting values on measures of effectiveness

	Measurement unit	Measure of effectiveness (limiting values)	
		Worst	Best
Criteria 1: Performance			
Factor 11: Heat removal flux	[Watts/cm^2]	0	1,000 or higher
Factor 21: Thermal resistance	[°C/Watts]	0.2 or higher	0
Factor 31: Temperature controllability	[Δ°C]	10 or higher	0
Criteria 2: Geometric (form factor)			
Factor 12: Height	[inches]	4 or higher	0
Factor 22: Footing area	[sq. cm]	16 or larger	0
Factor 32: Weight	[grams]	2 or more	0
Factor 42: Distance of heat transportation	[inches]	0	8 or longer
Criteria 3: Reliability			
Factor 13: Continuous operation	[hours]	0	25,000 or higher
Factor 23: Compatibility and durability to various operating environment conditions	[5-point scale]*	UA	E
Factor 33: % of Performance drop over time	[%]	100	0
Factor 43: Length of warming or starting up	[seconds]	120 or longer	0
Factor 53: Longevity	[years]	0	8 or longer
Criteria 4: Economic			
Factor 14: Cost of operation	[Watts]	100 or higher	0
Factor 24: Cost of fabrication	[$]	300 or higher	0
Factor 34: Cost of recharging and reclamation	[$]	300 or higher	0

(continued)

Table 5.2 (continued)

	Measurement unit	Measure of effectiveness (limiting values)	
		Worst	Best
Criteria 5: Environmental compatibility, safety, and regulation			
Factor 15: Toxic control of cooling media and combustion products	[5-point scale][a]	UA	E
Factor 25: Temperature control of exhaust coolant	[°F]	150	0
Criteria 6: Service and maintenance			
Factor 16: Ease of installation and maintenance	[5-point scale][a]	UA	E
Factor 26: Interchangeability	[5-point scale][a]	UA	E
Criteria 7: Flexibility			
Factor 17: Physical moldability	[5-point scale][a]	UA	E
Factor 27: Scalability	[5-point scale][a]	UA	E
Factor 37: Upgradeability	[5-point scale][a]	UA	E

[a]The description of all 5-point scales is specifically defined for each factor (see Appendix 1)

5.3.3.2 The Construction of Hierarchical Modeling (Step 2) (Fig. 5.4)

5.3.3.3 The Quantification of the Technology Value (Step 3)

Measurement 1: Determination of [w_k], the relative priority of criteria (k), with respect to the objective

The constant-sum values representing comparative judgment on each pair of criteria were obtained from each expert to determine the relative priority of the seven criteria. Table 5.3 represents the 21 comparisons provided by experts.

Using PCM software,[1] the relative priority of the seven criteria to which this expert assigned can be determined as C1:0.26, C2:0.09, C3:0.20, C4:0.21, C5:0.07, C6:0.10, and C7:0.09.

[1] PCM software is developed by Dundar F. Kocaoglu and coded by Bruce J. Bailey. The software is used to facilitate the computation process of constant-sum pairwise comparison method by converting judgments into numerical values [23].

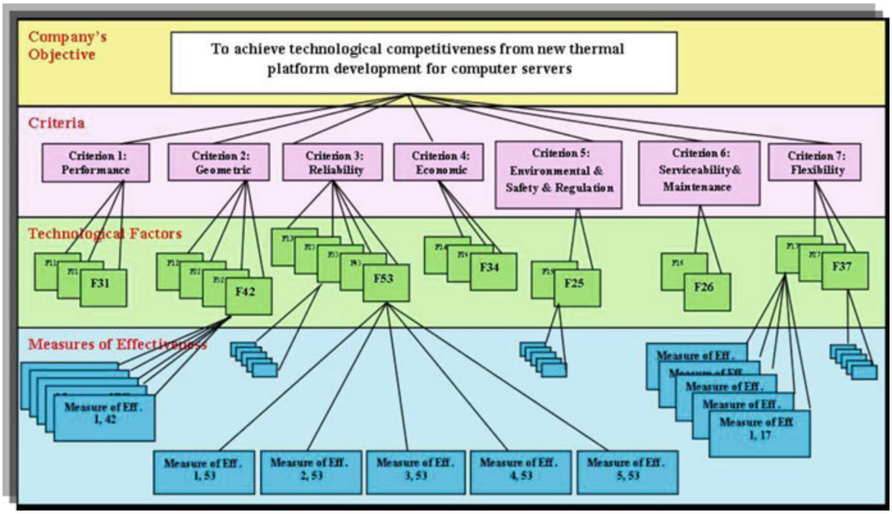


Fig. 5.4 Hierarchical model for the evaluation of emerging electronic cooling technologies with respect to a company's objective

Table 5.3 Example of the constant-sum values in comparative judgments provided by one expert

C1: *75* / C2: *25*	C1: *60* / C3: *40*	C1: *50* / C4: *50*	C1: *80* / C5: *20*	C1: *70* / C6: *30*	C1: *75* / C7: *25*	C2: *30* / C3: *70*
C2: *30* / C4: *70*	C2: *50* / C5: *50*	C2: *50* / C6: *50*	C2: *50* / C7: *50*	C3: *50* / C4: *50*	C3: *75* / C5: *25*	C3: *70* / C6: *30*
C3: *70* / C7: *30*	C4: *70* / C5: *30*	C4: *70* / C6: *30*	C4: *70* / C7: *30*	C5: *40* / C6: *60*	C5: *40* / C7: *60*	C6: *60* / C7: *40*

Table 5.4 The relative priority of the seven criteria, $[w_k]$

Criteria WRT objective	C1	C2	C3	C4	C5	C6	C7	Σ
Rel. importance $[w_k]$ →	*0.27*	*0.12*	*0.20*	*0.15*	*0.09*	*0.09*	*0.08*	**1.00**

By combining the relative priority values given by all experts, the mean value was calculated to represent the group decision on the relative priority of the seven criteria. The final result is shown in Table 5.4.

Measurement 2: Determination of $[f_{j_k,k}]$, the relative impact of factors (j_k), associated with each criterion (k)

The constant-sum values representing comparative judgments on the set of factors associated with each criterion were obtained from all experts. The relative importance of factors with respect to the criterion with which they are associated

Table 5.5 The relative importance of factors under each criterion, $[f_{j_k,k}]$

Factors under C1	F11	F21	F31	**Σ**		
Rel. importance →	*0.34*	*0.46*	*0.20*	**1.00**		
Factors under C2	F12	F22	F32	F42	**Σ**	
Rel. importance →	*0.33*	*0.35*	*0.16*	*0.16*	**1.00**	
Factors under C3	F13	F23	F33	F43	F53	**Σ**
Rel. importance →	*0.22*	*0.20*	*0.22*	*0.14*	*0.22*	**1.00**
Factors under C4	F14	F24	F34	**Σ**		
Rel. importance →	*0.52*	*0.23*	*0.25*	**1.00**		
Factors under C5	F15	F25	**Σ**			
Rel. importance →	*0.54*	*0.46*	**1.00**			
Factors under C6	F16	F26	**Σ**			
Rel. importance →	*0.45*	*0.55*	**1.00**			
Factors under C7	F17	F27	F37	**Σ**		
Rel. importance →	*0.24*	*0.40*	*0.36*	**1.00**		

was calculated by following the same approach as Measurement 1 above. The final results representing the group mean for the normalized relative importance of factors under each criterion are shown in Table 5.5.

Measurement 3: Determination of $[V(m_{j_k,k})]$, the relative desirability of measures of effectiveness (metrics), under each combination of factor (j_k) and criterion (k)

Each expert assigned a value between 0 and 100 representing his/her judgment on the relative desirability of each measure of effectiveness as a ratio of the desirability of the "best" limiting metric. The mean values were calculated among the relative values given by each expert to represent the group decision. As a result, 22 desirability curves were developed.

Figure 5.5 shows some examples of desirability curves developed for heat removal flux, longevity, cost of fabrication, and upgradeability factors. The desirability curves for the other 18 factors are shown in Appendix 2.

Measurement 4: Mapping of technological metrics $[t_{n,j_k,k}]$ to the desirability values $[V(t_{n,j_k,k})]$ using the relative desirability value of measures of effectiveness $[V(m_{j_k,k})]$ resulting from Measurement 3 as presented in Fig. 5.5 and Appendix 2.

Measurement 5: Quantification for the technology value $[TV_n]$

The technology value of each of the four technologies is determined by applying Eq. (5.1) along with the substitution of values obtained from Measurements 1, 2, and 3 as presented in Tables 5.4, 5.5, and Appendix 2, respectively.

For example, the technology value of air cooling technology (T_1) is determined as shown in Table 5.6.

From the computation, the technology value of air cooling technology (T_1) is equal to 54.1. Similarly, the technology values of the three emerging technologies, T_2, T_3, and T_4, are 62.3, 60.7, and 64.4, respectively.

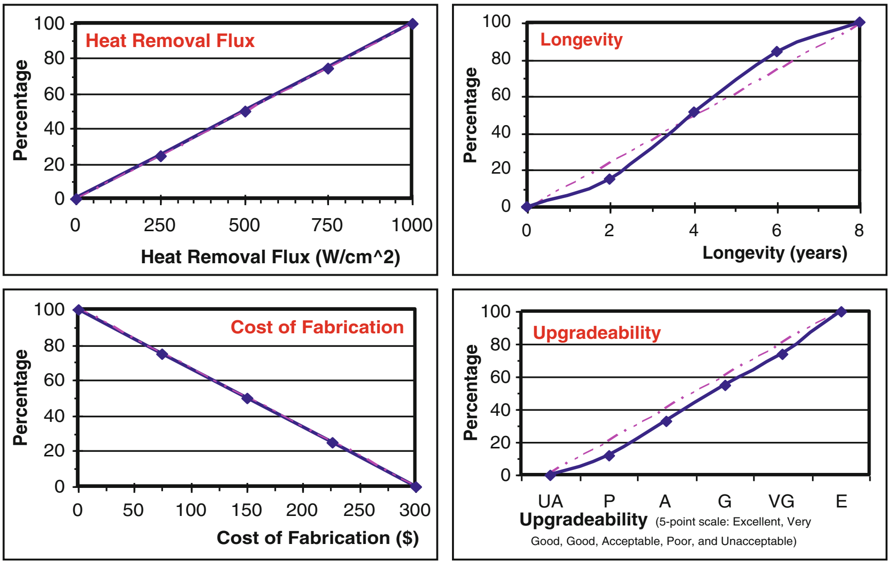


Fig. 5.5 Desirability curves

5.3.3.4 Interpretation of Results

- Air cooling, channel flow boiling, spray cooling, and MPS-LP technology represent the value of 54.1 %, 62.4 %, 60.7 %, and 64.4 % of the ideal technology alternative according to a company's preference.
- The company perceives the value of MPS-LP, channel flow boiling, and spray cooling as 1.19, 1.15, and 1.12 times as preferable as air cooling technology.

5.3.3.5 Discussion of Results

A comparison of the technology values of four different cooling technology alternatives indicates that air cooling technology will no longer be satisfying the company's objective. The computation of the technology value of air cooling technology as shown in Table 5.6 indicates that further improvements of economic, environmental compatibility, and serviceability and maintenance aspects would not yield any greater contribution to its technology value since the desirability values of the factors associated with those three criteria are already approaching the full scores. This situation can also be explained as the phenomenon of overshooting market expectation as Christensen described the difference on expected trajectory between existing and disruptive technologies [24]. Without any breakthrough improvements on performance and geometric limitations, air cooling technology would be replaced by one of the three emerging cooling technologies.

Table 5.6 Computation of technology value of air cooling technology

Criterion	Factors	Desirability value	Technology value
C1: Performance (0.27)	F11 (0.34)	$V(t_{1,11})$ (12)	1.10
	F21 (0.46)	$V(t_{1,21})$ (0)	0.00
	F31 (0.20)	$V(t_{1,31})$ (0)	0.00
C2: Geometric (0.12)	F12 (0.33)	$V(t_{1,12})$ (0)	0.00
	F22 (0.35)	$V(t_{1,22})$ (60)	2.52
	F32 (0.16)	$V(t_{1,32})$ (0)	0.00
	F42 (0.16)	$V(t_{1,42})$ (50)	0.96
C3: Reliability (0.20)	F13 (0.22)	$V(t_{1,13})$ (10)	0.44
	F23 (0.20)	$V(t_{1,23})$ (90)	3.60
	F33 (0.22)	$V(t_{1,33})$ (90)	3.96
	F43 (0.14)	$V(t_{1,43})$ (100)	2.80
	F53 (0.22)	$V(t_{1,53})$ (90)	3.96
C4: Economic (0.15)	F14 (0.52)	$V(t_{1,14})$ (95)	7.41
	F24 (0.23)	$V(t_{1,24})$ (97)	3.35
	F34 (0.25)	$V(t_{1,34})$ (99)	3.71
C5: Environmental compatibility (0.09)	F15 (0.54)	$V(t_{1,15})$ (100)	4.86
	F25 (0.46)	$V(t_{1,25})$ (75)	3.11
C6: Serviceability and maintenance (0.09)	F16 (0.45)	$V(t_{1,16})$ (100)	4.05
	F26 (0.55)	$V(t_{1,26})$ (100)	4.95
C7: Flexibility (0.08)	F17 (0.24)	$V(t_{1,17})$ (27)	0.52
	F27 (0.40)	$V(t_{1,27})$ (58)	1.86
	F37 (0.36)	$V(t_{1,37})$ (33)	0.95
			54.10

5.4 Improvement Gap and Improvement Priority

These two measures are developed to determine which of the technologies to focus on as well as which of the factors to improve.

5.4.1 Improvement Gap

Improvement gap (IG) is the weighted gap between the performance of each technology along a factor and the upper bound for the ideal technology along that factor as calculated from the expert judgments. It is defined as

$$\boxed{IG_n = \sum_{k=1}^{K} \sum_{j_k=1}^{J_k} w_k \cdot f_{j_k,k} \cdot \left[100 - V\left(t_{n,\,j_k,k}\right)\right]} \tag{5.6}$$

The performance gap along factor (j_k), [100-$V\left(t_{n,\,j_k,k}\right)$], is weighted by the product of the relative value of the criterion (k) and the factor (j_k).

5.4.2 Improvement Priority

Improvement priority (IP) is the rank order of the factors according to the IG value of the technologies determined along those factors.

Analysis of IG and IP in the case study
The technology values of channel flow boiling, spray cooling, and MPS-LP technologies are close to each other (62.3, 60.7, and 64.4, respectively). Table 5.7 represents the improvement gap and improvement priority of each of these technologies along 22 factors.

Calculation of IG
Channel flow boiling has the desirability value of 12 out of 100 on the factor of heat removal flux (F11). The improvement gap on this factor is equal to $0.27 \times 0.34 \times (100 - 12) = 8.08$. The IG values along all other factors are calculated in the same way.

Determination of IP
The IP is shown for the top five factors for each of the three technologies in Table 5.7.

The decision on which technology should be selected will significantly depend on successful improvement of heat removal flux (F11) in one of the three technologies. As seen in Table 5.7, the IG value of this factor has the highest IP for all three technologies.

Table 5.7 Improvement gap (IG) and improvement priority (IP) of the three emerging technologies along 22 factors

		Channel flow boiling (T2)			Spray cooling (T3)			MPS-LC[a] (T4)		
Criterion	Factors	Desirability Value V $(t_{2,jk})$	IG[a]	IP[b]	Desirability value $V(t_{3,jk})$	IG[a]	IP[b]	Desirability Value $V(t_{4,jk})$	IG[a]	IP[b]
C1: Performance (0.27)	F11 (0.34)	12	8.08	***1st***	20	7.34	***1st***	20	7.34	***1st***
	F21 (0.46)	90	1.24		88	1.49		72	3.48	*2nd*
	F31 (0.20)	0	5.40	*2nd*	62	2.05		82	0.97	
C2: Geometric (0.12)	F12 (0.33)	95	0.20		92	0.32		67	1.31	
	F22 (0.35)	88	0.50		75	1.05		72	1.18	
	F32 (0.16)	90	0.19		25	1.44		0	1.92	
	F42 (0.16)	13	1.68		100	0.00		100	0.00	
C3: Reliability (0.20)	F13 (0.22)	40	2.64	*3rd*	40	2.64	*4th*	24	3.34	*3rd*
	F23 (0.20)	71	1.16		71	1.16		71	1.16	
	F33 (0.22)	70	1.32		95	0.22		95	0.22	
	F43 (0.14)	90	0.28		75	0.70		0	2.80	*4th*
	F53 (0.22)	75	1.10		50	2.20		75	1.10	

(continued)

Table 5.7 (continued)

		Channel flow boiling (T2)			Spray cooling (T3)			MPS-LC[a] (T4)		
Criterion	Factors	Desirability Value V $(t_{2,jk})$	IG[a]	IP[b]	Desirability value $V(t_{3,jk})$	IG[a]	IP[b]	Desirability Value $V(t_{4,jk})$	IG[a]	IP[b]
C4: Economic (0.15)	F14 (0.52)	90	0.78		50	3.90	*2nd*	85	1.17	
	F24 (0.23)	50	1.73		73	0.93		75	0.86	
	F34 (0.25)	65	1.31		73	1.01		75	0.94	
C5: Environmental compatibility (0.09)	F15 (0.54)	80	0.97		60	1.94		80	0.97	
	F25 (0.46)	97	0.12		100	0.00		100	0.00	
C6: Serviceability and maintenance (0.09)	F16 (0.45)	40	2.43	*4th*	60	1.62		60	1.62	
	F26 (0.55)	50	2.48	*5th*	25	3.71	*3rd*	50	2.48	*5th*
C7: Flexibility (0.08)	F17 (0.24)	27	1.40		8	1.77		50	0.96	
	F27 (0.40)	58	1.34		58	1.34		82	0.58	
	F37 (0.36)	55	1.30		12	2.53	*5th*	55	1.30	

[a]IG represents improvement gap
[b]IP represents improvement priority

5.5 Conclusion

This chapter presents a robust quantitative model for evaluating the impact of emerging technologies on a company's objective. The technology value [TV_n] can be determined for any technology (n) whose performance metrics (measures of effectiveness) are available under (j_k) factors for (k) criteria. Once the technology value is known, then technology can readily be incorporated into the model and compared with all other available and emerging technologies. The model also provides a measure for the relative value of improvements in technical characteristics of each technology and the factors on which a company has to focus in order to maximize that technology's impact on the company's objective.

Appendix 1: Description of 5-Point Scale Specifically Defined For Each Qualitative Factor

Factors	5-point scale	Description
Factor 23: Durability under adverse environmental conditions	*Excellent (E)*	Cooling systems are durable to operate under all three adverse conditions.
	Very Good (VG)	Cooling systems are durable to operate under two out of three adverse conditions.
	Good (G)	Cooling systems are durable to operate under one adverse condition only.
	Acceptable *(A)*	Cooling systems are durable to operate under normal office environment.
	Poor (P)	Cooling systems are required to operate under special environment like clean room.
	Unacceptable (UA)	Hypothetically, cooling system could not be operated under any environment.
Factor 15: Toxicity of cooling media and combustion products	*Excellent (E)*	Totally clean; no toxic treatment needed.
	Very Good (VG)	Low toxicity but still well below the safety allowance limits; no treatment needed.
	Good (G)	Toxicity within the safety allowance but close to the limit; no treatment needed.
	Acceptable *(A)*	Protective measures such as thicker tank walls are needed to meet the safety allowance but no specific toxic treatment is required.
	Poor (P)	Toxic treatment is required, for example, an ammonia cooling system, which requires an ammonia tank surrounded by water.
	Unacceptable (UA)	No toxic treatment is available to make cooling systems useable.

(continued)

(continued)

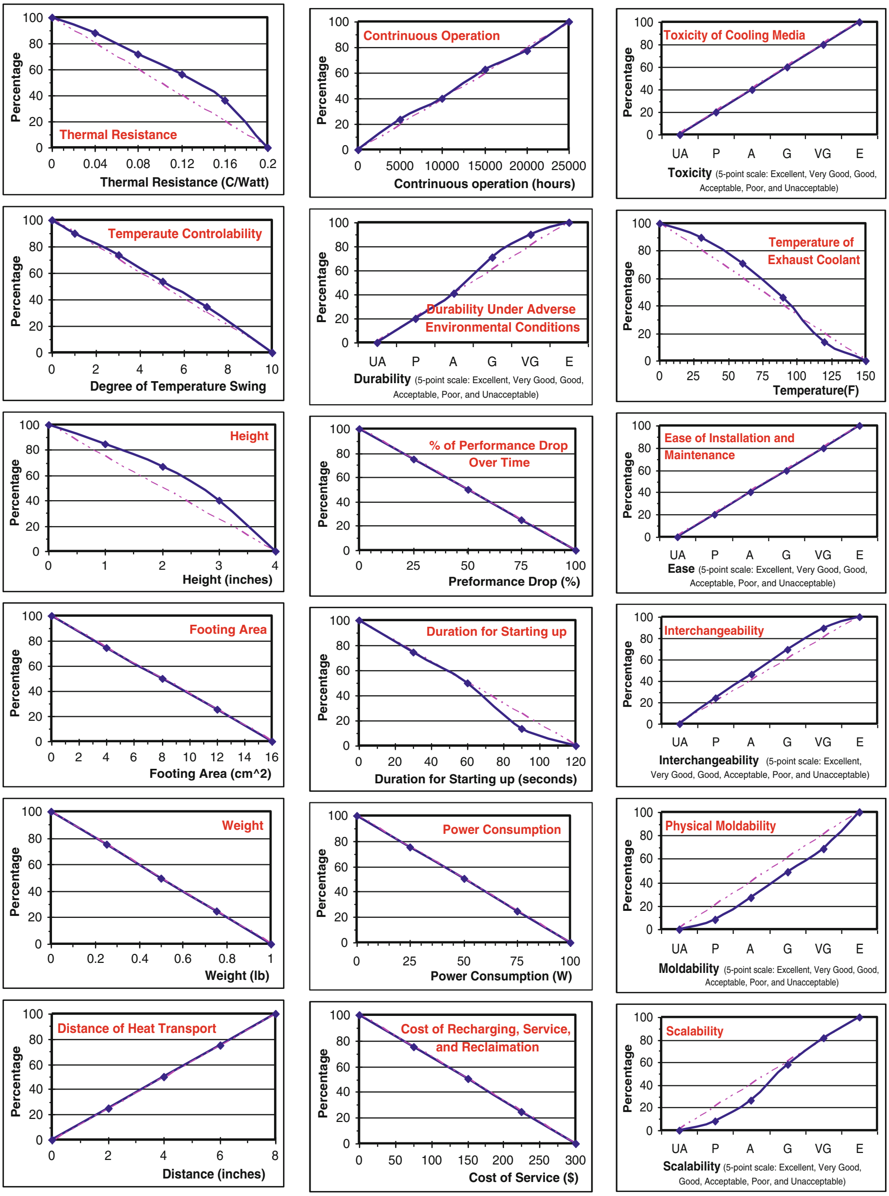
Factors	5-point scale	Description
Factor 16: Ease of installation and maintenance	*Excellent (E)*	Just plug-in.
	Very Good (VG)	Only a screwdriver needed; no skills required.
	Good (G)	Basic handyman skills with a set of tools required.
	Acceptable *(A)*	Some technical skills with a box full of tools required.
	Poor (P)	Extensive technical skills with a box full of tools required.
	Unacceptable (UA)	Cooling systems could not be installed or maintained on-site, so systems need to be replaced when maintenance is needed.
Factor 26: Interchangeability	*Excellent (E)*	System components are interchangeable with same/similar components made by numerous manufacturers commonly available in electronic stores.
	Very Good (VG)	System components are interchangeable with same/similar components made by few manufacturers and commonly available in electronic stores.
	Good (G)	System components are interchangeable with same/similar components made by few manufacturers and available only in specialized stores.
	Acceptable *(A)*	System components are interchangeable only with same/similar components made by the original manufacturer available only in specialized stores.
	Poor (P)	System components are made to order by the original manufacturer.
	Unacceptable (UA)	System components have to be specifically redesigned.
Factor 17: Physical moldability	*Excellent (E)*	Easy to reshape; no tools are needed.
	Very Good (VG)	Reshaping requires specific hand tools.
	Good (G)	Difficult to reshape but it can be done without going through a machine shop process.
	Acceptable *(A)*	Re-shapeable but it has to go through machine shop process.
	Poor (P)	Very difficult to reshape even when going through manufacturing processes.
	Unacceptable (UA)	Components could not be reshaped.

(continued)

(continued)

Factors	5-point scale	Description
Factor 27: Scalability	*Excellent (E)*	Cooling system can adjust itself automatically according to the change of heat dissipation amount.
	Very Good (VG)	Cooling system can adjust itself automatically when the certain limits of changes in heat dissipation amount are reached.
	Good (G)	The cooling capacity can be adjusted manually (such as opening valve or throttle wider)
	Acceptable *(A)*	Some components need to be replaced to respond to any change of heat dissipation amount.
	Poor (P)	The whole cooling system has to be replaced.
	Unacceptable (UA)	Cooling system is not scaleable.
Factor 37: Upgradeability	*Excellent (E)*	Just remove the existing components and plug the new ones in; no additional adjustment or hardware modification required.
	Very Good (VG)	Some adjustments are needed; no hardware modification required.
	Good (G)	Some adjustments are needed along with some hardware modification.
	Acceptable *(A)*	The whole cooling system needs to be adjusted along with hardware modification.
	Poor (P)	The whole cooling system needs to be replaced.
	Unacceptable (UA)	Cooling systems could not be upgraded.

Appendix 2: Desirability Curves



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Chapter 6
Strategic Planning: An Analytical Approach to Building a Technology Development Envelope (TDE) for Roadmapping of Emerging Technologies

Nathasit Gerdsri

Abstract This chapter presents the research on the development of a new concept and methodology called technology development envelope (TDE). TDE approach is applied for identifying the optimum path in developing a technology roadmap in which technology strategies and business strategies are combined. TDE allows the executive-level decision makers in corporations as well as the policy-level decision makers in governments to incorporate disruptive technologies and radical innovations in the development of technology strategies. The combination of Delphi method and hierarchical decision (AHP) is used as a foundation for building the TDE concept. The judgments from technology developers and technology implementers are utilized in the process to assure that the technology strategies are in full support of corporate goals and objectives.

6.1 Introduction

In order to survive in today's fast-changing business environment and intense market competition, technology-based companies look for R&D investment in emerging technologies as a key solution [1–5]. Successful implementation of technologies can strongly enhance a company's competitiveness. However, due to funding constraints, companies must cautiously evaluate technologies before they should invest.

An analytical model was developed in this research to help managers understand how technologies are evolving and how well different technologies fit their

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corporate strategy. The model combines technology forecasting, identification, assessment, evaluation, and selection.

The Delphi method for obtaining expert opinion is applied to generate strategic information regarding potential emerging technologies including their estimated introduction date and their characteristics.

Emerging technologies are then evaluated using a hierarchical decision model with four levels: objective, criteria, factors, and technology alternatives. Comparative judgments provided by experts are analyzed to determine the relative priorities of the components in each level of the hierarchy. A new method for applying a semi-absolute scale to quantify the value of each technology is proposed. The overall impact of each technology on the company's strategic objective is calculated as a composite index called technology value.

Technology development paths are specified by connecting technologies from one period to the next. The path connecting technologies with the highest value in each time period is defined as the "technology development envelope (TDE)." By investing in technologies following the TDE path, a company's technological benefits will be maximized. The TDE and the various technology development paths serve as strategic inputs to the company's technology roadmapping process.

Determining the value of emerging technologies with respect to a company's strategic objective is a valuable process in its own right. However, the results of this research go beyond that. They show that the proposed method leads to a technology development envelope and suggestions for possible technology development paths where none had existed previously. This method was developed using a systematic approach, and was subjected to various tests to show that the method is robust with respect to the variations in the company's priorities.

To demonstrate the process, a specific case study is presented for the development of a TDE on emerging electronic cooling technologies for one of the leading computer server developers. Currently, this industry is in a technological transition period due to the volumetric thermal density limitation of the current electronic cooling technology—direct air cooling.

6.2 Literature Review

To lay out a fundamental understanding of this research, an extensive literature search was conducted on topics including emerging/disruptive technologies, technology forecasting, Delphi method, technology identification, technology assessment, technology evaluation, technology selection, analytical hierarchy process (AHP), and technology roadmapping. The major emphases and potential gaps in the existing literatures are summarized below:

- A wide range of research is available on technology forecasting and assessment methods such as statistical technology forecasting, trend analysis, and judgmental methods [6–12]. Yet, there is a limited number of studies combining expert opinions and analytical models for forecasting the impact of technologies on corporate objective [13–19].

- Most of the technology forecasting applications are applied to the extension of existing technologies, *not* emerging technologies [20–25].
- Despite an abundance of literature on decision-support models and applications for identifying or selecting technologies, only a few studies specifically address emerging technologies. The development of a decision-support model for emerging technology applications tends to be more sophisticated than the ones for existing technologies. This results from the fact that not only both quantitative and qualitative measures must be taken into consideration, but also the limitation on historical data availability of emerging technology has to be overcome [26–31].
- Generally, decisions for technology evaluation are exclusively made by a group of technology managers in companies. It is rare that decisions are made in the environment which technology developers and technology implementers interactively participate [32–37].
- Although the use of technology roadmaps as a technology forecasting technique is spreading among industries, a systematic approach for building a roadmap and keeping it alive is not well defined in the literature [38–43].
- Technology roadmapping processes are carried out either internally within a company or externally among peer technology developers across industries. The linkage between external researchers/developers and corporate decision makers in roadmapping is weak [44–47].
- Strategic management of technology is practiced by applying tools, concepts, and processes in different companies. Therefore, there is an opportunity to develop an operationalizable model to guide the entire process.

6.3 Research Objective, Goals, and Questions

The objective of this research was to develop an analytical approach to build a strategic TDE for roadmapping of emerging technologies. The approach involves forecasting, identification, assessment, evaluation, and selection of emerging technologies. The combination of the Delphi method and hierarchical decision modeling is applied in this research [35, 48–54].

The research objective was achieved by fulfilling five research goals. One or more research questions needed to be answered for each goal. The research goals and questions are summarized below (Table 6.1).

Table 6.1 Research goals and research questions

Research goals	Research questions
RG1: Develop a forecasting model using Delphi for identifying the trends of emerging technologies.	RQ1: What is the trend of emerging technology development in the industry?
RG2: Develop a judgment quantification model for evaluating the value of emerging technologies on a company's objective.	RQ2: What are the significant criteria and technological factors associated with each criterion to satisfy the objective? What should be the measures of effectiveness applied for each factor?
	RQ3: What is the relative priority of each influencing criterion?
	RQ4: What is the relative importance of influencing technological factors on each criterion?
	RQ5: How should the measures of effectiveness be evaluated in terms of their relative desirability for the objective?
RG3: Assess technological characteristics of each emerging technology along the identified factors.	RQ6: How should the characteristics of emerging technologies be assessed based on their technological metrics?
RG4: Evaluate emerging technologies.	RQ7: How should the value of emerging technologies be evaluated in terms of the relative desirability of their technological metrics for the objective?
RG5: Construct the technology development envelope and paths by sequentially connecting one technology to another over time.	RQ8: What is the technology development envelope? How can it be determined?
	RQ9: How can the possible paths of technology development be identified?

6.4 Research Approach

The research consisted of six steps: technology forecasting, technology characterization, technology assessment, technology evaluation, hierarchical modeling, and formation of a TDE as shown in Fig. 6.1. Each step was designed to accomplish a specific research goal as summarized in Table 6.1.

Step 1	*Technology forecasting*: Develop a forecasting model using Delphi for identifying the trend of emerging technologies. (RQ1)
Step 2	*Technology characterization*: Identify criteria and technological factors satisfying a company's objective. (RQ2)
Step 3	*Technology assessment*: Assess emerging technologies based on the measures of effectiveness (metrics). (RQ6)
Step 4	*Hierarchical modeling*: Develop a hierarchical model to determine the relative importance of criteria, the relative impact of factors under each criterion, and the relative desirability of measures of effectiveness on each factor. (RQ3–5)

(continued)

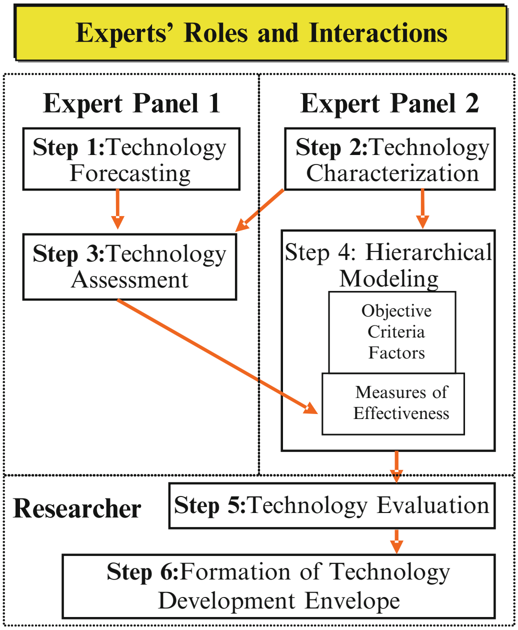


Fig. 6.1 Six-step TDE development

(continued)

Step 5	*Technology evaluation*: Evaluate the semi-absolute impact value of emerging technologies on a company's objective. (RQ7)
Step 6	*Formation of TDE*: Construct the TDE and technology development paths. (RQ8 and RQ9)

Due to limited data availability inherent in emerging technologies, and complex issues in combining qualitative and quantitative aspects into decision-making process, it is always challenging for any organization to understand how emerging technologies are evolving over time and how the development of those technologies impacts an organization's objective.

To overcome these challenges, two expert panels, technology developers (EP-1) and technology implementers (EP-2), were formed to provide inputs and complete specific requirements in each process. The flow of strategic information through these six steps as well as the interaction between the two expert panels are shown in Fig. 6.1.

6.5 Expert Panels

Each panel is a group of experts who have expertise in a particular area. Members of each expert panel are required to provide balanced representation of ideas/backgrounds and have little or no bias regarding the outcomes of the study. Also, they must be in a position to understand the overall scope of the issues and to influence the decision process. The description and role of each expert panel are described below:

Expert panel 1 (EP-1) is a group of "technology developers" widely chosen from the industry. This group of experts is a *technology-dependent source of knowledge*. EP-1's responsibilities are to identify a list of emerging technologies with the expected time of their occurrence and to provide the measures of effectiveness of each emerging technology.

Expert panel 2 (EP-2) is a group of "technology implementers" in an organization who design and develop technologies into products. This group of experts is an *organization-dependent source of knowledge*. EP-2's responsibilities are to identify a set of criteria and technological factors associated with each criterion for satisfying the organization's objective of achieving technological competitiveness. They determine the relative importance of criteria, the relative impact of technological factors on each criterion, and the relative desirability of measures of effectiveness on each technological factor.

6.6 TDE Model Development

The list of potential emerging technologies, the estimated time of their occurrence (resulting from Step 1), and the metrics describing the performance and physical characteristics of each technology (resulting from Step 3) were obtained from the expert group of technology developers through Delphi process. The evaluation model was constructed in a hierarchal format with four levels: objective, criteria, factors, and characteristic metrics (resulting from Step 2). The comparative judgments to determine the relative priorities of components at each level of the hierarchy were provided by the expert group of technology implementers (resulting from Step 4). The characteristic metrics of each technology were evaluated according to the organization's judgments on the desirability of each metric, the relative impact of factors associated with each criterion, and the relative priority of criteria on the objective. The computational results of the technology evaluation are presented as a composite value called technology value indicating the overall impact of each technology on the company's strategic objective (resulting from Step 5). The mathematical model for the technology evaluation was developed as shown in the section below. A technology evaluated with the highest value in each time period represents the technology for which a company has the highest preference compared with other technologies. The path connecting technologies from one period to another is a technology development path. The path connecting technologies that have the highest value in each time period is defined as the "TDE" (resulting from Step 6) (Figs. 6.2 and 6.3).

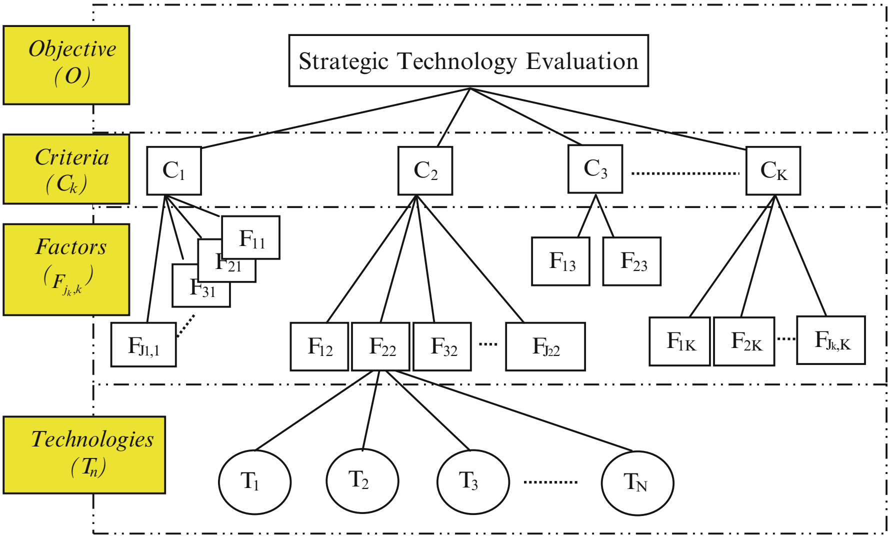


Fig. 6.2 Hierarchical model for evaluating emerging technologies

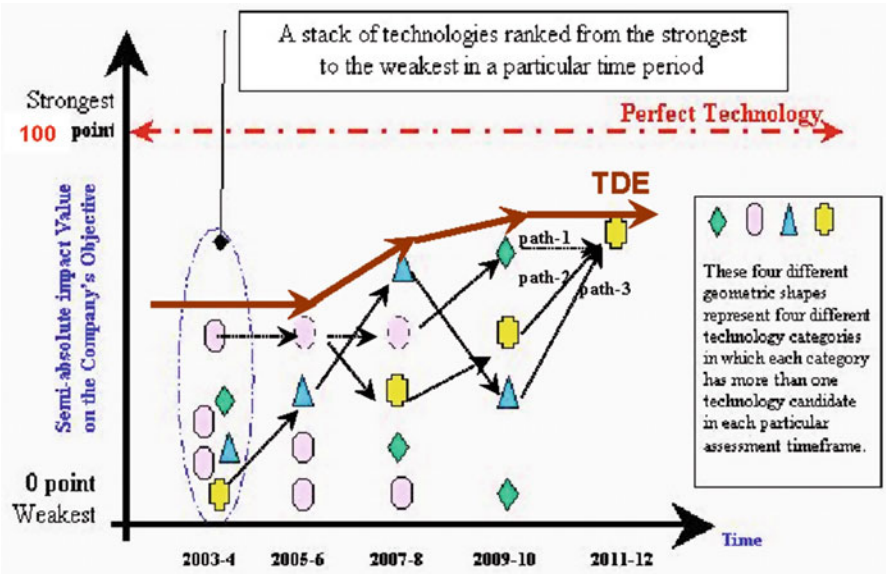


Fig. 6.3 TDE diagram

6.7 Mathematical Model

The mathematic model for the evaluation of emerging technologies is shown below:

$$\boxed{TV_n = \sum_{k=1}^{K} \sum_{j_k=1}^{J_k} w_k \cdot f_{j_k,k} \cdot V\left(t_{n,\, j_k,k}\right)}$$

where

TVn: Technology value of technology (n) determined according to a company's objective
w_k: Relative priority of criterion (k) with respect to the company objective
$f_{j_k,k}$: Relative importance of factor (j_k) with respect to criterion (k)
$\sum_{j_k=1}^{J_k} w_k \cdot f_{j_k,k}$: Relative importance of factor (j_k) with respect to the objective
$t_{n,\, j_k,k}$: Performance and physical characteristics of technology (n) along with factor (j_k) for criterion (k)
$V\left(t_{n,\, j_k,k}\right)$: Desirability value of the performance and physical characteristics of technology (n) along factor (j_k) for criterion (k)

The technology value is calculated through matrix computations among the criteria priorities [w_k], the relative importance of factors on each criterion [$f_{j_k,k}$], and the desirability of technologies for each factor [$V\left(t_{n,\, j_k,k}\right)$]. See Appendix 1 for the measurement procedure of desirability values.

This value indicates the level of company's appreciation on the development of any specific technology over time compared with a company's perception of an ideal technology.

6.8 Research Instruments

The research instruments were specifically designed to capture information about the future development of emerging technologies and the measurement of impacts of technologies on a company's objective. The structure of research instruments facilitates Delphi feedbacks and judgment quantifications as well as the collection of anonymous opinions.

Internet tools were applied as the backbone architecture of all research instruments. This way, the demographic limitations due to the widespread locations of experts in this research were overcome at no cost. In addition, the use of an Internet-based survey alleviated the research participants' time constraints and encouraged them to provide immediate responses.

6.9 Data Analysis

Data analysis was conducted in three areas: Delphi outputs on technology forecasting and assessment, judgment quantification for the evaluation of emerging technologies, and formation of a TDE.

Delphi study: The outputs include the list of emerging technologies and the time of their occurrence. Descriptive statistics are applied to analyze the distribution of expert opinions. The stability between successive Delphi rounds is tested to statistically verify when the Delphi study can be stopped. The chi-square test is applied for this purpose to determine whether there is a significant difference between individual responses in different rounds. See Appendix 2 for the Delphi stopping rule.

Judgment quantification: The relative priority of the criteria and the relative importance of factors associated with each criterion are determined through a series of comparative judgments provided by each expert. Experts' judgments are expressed by allocating a total of 100 points between two elements at a time (applying the constant-sum method). The judgments are converted to a normalized measure of relative values in ratio scale. The level of agreement among the group of experts is tested to determine the degree to which experts are in agreement with one another according to their judgments. The expert agreement on the judgment values and rankings of elements is measured by interclass correlation coefficient and Kendall's coefficient of concordance. F-test and chi-square test are applied, respectively, to statistically verify the significant level of agreement. See Appendix 3 for the group agreement tests.

Formation of TDE: Technologies are arranged according to their technology value in each time period, and the lines serially connecting one technology to another technology in the later time periods represent paths of technology development. The path connecting technologies whose values are highest in each time period is considered the TDE.

6.10 Research Validation

Three tests were conducted to validate this research for: content validity, construct validity, and criterion-related validity.

Content validity was tested in the research preparation phase and the development of research instrument to ensure that all information can be captured as intended. Construct validity was tested when the hierarchical decision model was developed to assure unidirectional hierarchical relationships among decision levels, and independence among decision elements. Criterion-related validity was tested after the completion of the model to see how adequately the results represent the reality.

6.11 Case Study: Determination of TDE on Emerging Electronic Cooling Technologies

The research results were applied to the development of electronic cooling technology, and tested in a leading computer server developer company. The application demonstrated the robustness of the approach and the model. The details are shown below.

Currently, the technological improvement of existing cooling technologies is reaching the volumetric limitation [55, 56]. This challenge will eventually become a roadblock for the electronic industry [57–60]. R&D departments of many institutes in both industry and academia have been working on developing a new cooling technology. Some of the new technologies are completely different from the existing ones as the emerging concepts of nano-engineering and power-free are applied. An official technology roadmap representing the future direction of the industry has not been recently presented because the industry is in the technological transition period and many developments of new technologies are still in an infancy stage.

Two expert panels were formed. EP-1 consisted of 12 members representing industry, academia, and government. Their roles and titles ranged from VP, CTO, engineering manager, senior technical staff, research engineer, and professor. EP-2 consisted of eight members from the company representing R&D, technology enabling, technology implementation, assembling, and manufacturing department.

6.11.1 Steps 1 and 3: Technology Forecasting and Assessment

Thirteen emerging electronic cooling technologies were initially identified from the most up-to-date literature and sent to EP-1 experts to estimate their availability for OEM's implementation. Four new emerging technologies were also added by the experts into the initial list after the first round of Delphi study. Therefore, the total number of emerging electronic cooling technologies included in this study was 17 as listed in Table 6.2.

The group of EP-1 experts agreed that 16 of 17 technologies would be ready for implementation by OEM's implementation by 2010. The group agreement on the time of occurrence of each technology is defined as the specific time by which 50 % of experts agree that this particular technology will be ready for implementation. The specific time of occurrence of each technology is shown in Fig. 6.4.

Experts also provided their estimates on the technological metrics indicating the future development progress of each technology along 22 factors.

Table 6.2 List of emerging electronic cooling technologies

Pre-identified emerging technologies		T10 :	Heat pipes
T1 :	Air cooling	T11 :	Capillary pumped loops
T2 :	Air flow-through and cold-wall cooling	T12 :	Thermoelectric cooling
T3 :	Cold plate cooling	T13 :	Thermo-tunneling
T4 :	Channel flow boiling	*Additional emerging technologies*	
T5 :	Pool boiling/thermosyphons	N1 :	Mechanically pumped single-phase liquid cooling
T6 :	Jet impingement and spray cooling	N2 :	Mechanically pumped single-phase liquid with heat removal by two-phase heat transfer
T7 :	Immersion-liquid cooling	N3 :	Electrohydrodynamics
T8 :	Vapor compression	N4 :	Oscillatory heat pipes
T9 :	Phase change cooling		

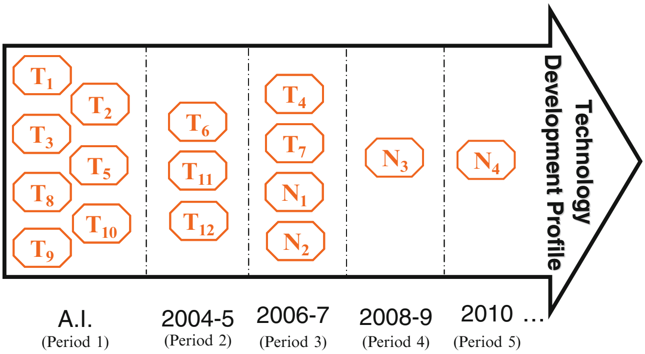


Fig. 6.4 Representing the specific time of occurrence of each technology

6.11.2 Steps 2 and 4: Technological Characterization and Hierarchical Modeling

The group of EP-2 experts agreed on defining the objective of their technology evaluation as “to achieve technological competitiveness from new thermal platform development for computer servers.” Seven criteria and factors associated with each criterion along with their limiting values on the measure of effectiveness were finalized. The hierarchical model for technology evaluation was structured according to the relationship among the seven criteria and all factors as shown in Fig. 6.5.

A series of experts’ comparative judgments on each pair of criteria and factors were analyzed to determine the relative priority of criteria as well as the relative importance of factors associated with each criterion. The desirability curves representing the company’s preference on the technological metrics of each factor were developed.

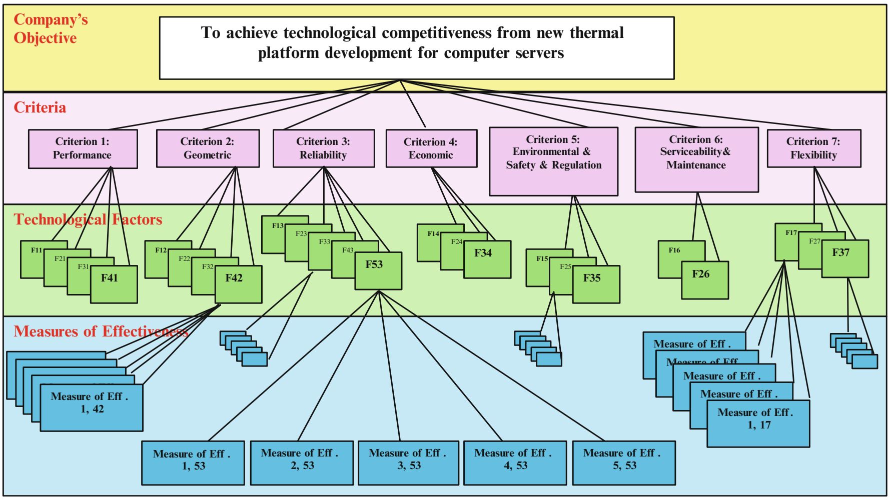


Fig. 6.5 Hierarchical model for the evaluation of electronic cooling technologies

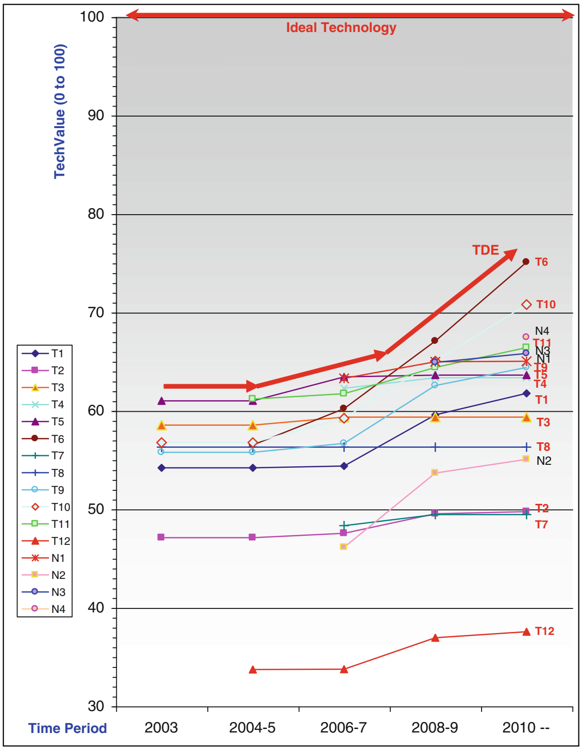
6.11.3 Step 5: Technology Evaluation

Each technology was evaluated in each time period by measuring how well their technological metrics meet the company's desirability level and then factored that by the relative importance of factors and the relative priority of criteria (as described in Mathematical Model section). The results representing technology value of all 16 technologies over time are shown in Fig. 6.6.

The results also indicate that the technology value of jet impingement/spray cooling would be significantly improved over time as the development of this technology goes on. And eventually, this technology would become a dominant technology by the end of the decade. The current technology—air cooling—will not be attractive any more even though the production cost will continue dropping.

6.11.4 Step 6: Formation of Technology Development Envelope

From the results, a TDE was formed as a path connecting pool boiling (T5) in 2003, capillary pumped loop heat pipes (T11) in 2004–2005, mechanically pumped single-phase liquid cooling (N1) in 2006–2007, and jet impingement and spray cooling (T6) from 2008 to 2010. The value of these four technologies is the highest in those periods.



Notation

$T_{n,i}$: Representing technology n which the time of its occurrence is estimeted to be in i period.

i: 1 (2003); 2 (2004-5); 3 (2006-7); 4 (2008-9); 5 (2010-); 6 (Never)

$T_{1,1}$: Air Cooling
$T_{2,1}$: Air flow-Through and Cold-Wall Cooling
$T_{3,1}$: Cold Plate Cooling
$T_{4,3}$: Channel Flow Boiling
$T_{5,1}$: Pool Boiling/Thermosyphons
$T_{6,2}$: Jet-impingement and Spray Cooling
$T_{7,3}$: Immersion-Liquid Cooling
$T_{8,1}$: Vapor Compression
$T_{9,1}$: Phase Change Cooling
$T_{10,1}$: Heat Pipes
$T_{11,2}$: Capillary Pumped Loops
$T_{12,2}$: Thermoelectric Cooling
$T_{13,6}$: Thermo-Tunneling
$N_{1,3}$: Mechanically pumped single-phase liquid cooling
$N_{2,3}$: Mechanically pumped single-phase liquid with heat removal by two-phase heat transfer
$N_{3,4}$: Electrohydrodynamics
$N_{4,5}$: Oscillatory heat pipes

Fig. 6.6 Position of technologies ranked by their impact values on a company's objective

6.12 Flexibility and Generalization of the TDE Model

Flexibility is a prominent feature of the TDE model. The value of technologies can be reevaluated or quantified at almost no time as the changes on the development of any particular emerging technologies or the emergence of new technologies are captured. Then, the TDE diagram would be automatically adjusted to reflect those changes.

Generalization of the TDE model was tested by forming a technology development envelope under the variations in a company's priorities. The parametric approach on changing a company's priorities was applied to represent seven unique emphases of corporate values at the criteria level. For each case, one criterion was determined as the primary criterion with the priority value of 0.4 and the other six were considered as secondary criteria with the priority value of 0.1 each. The TDE was determined for each case as shown in Table 6.3.

The results of TDE analysis on the variation of company priorities represent the strategic direction for each electronic cooling technology. For example, in the year 2010, the heat removal capacity of jet impingement and spray cooling (T6) is

Table 6.3 Formation of a TDE under the variations in a company's priorities

Primary emphases of companies	Technology development envelope
Performance	T5 → T11 → N1 → T6
Geometrics	T2 → T4 → T6 → T6
Reliability	T10 throughout
Economics	T1 → T1 → N4 → N4
Environment	T1 → T4 → N3–N3
Service and maintenance	T1 throughout
Flexibility	T11 → N1 → N3–N4

estimated to be 13 times as high as the capacity of the current cooling technologies. The value of heat pipe (T10) will be very high for reliability-oriented companies especially as the current limitation on its heat removal capacity is expected to be overcome by 2010. Electrodynamic (N3) and oscillatory heat pipe (N4) technologies are expected to be ready for implementation by the end of the decade. N3 will be an attractive technology because of its environment friendliness, and N4 will be attractive because of its power-free operation.

6.13 Conclusion and Contributions

The main contribution of this research is the enhancement of the body of knowledge in strategic planning for development of emerging technologies. The research was a systematic approach for developing a TDE by applying the concepts of technology forecasting, evaluation, and selection in conjunction with multi-criteria decision-making methodologies. The TDE is a strategic input to technology roadmapping. The decision-support model developed in this research fills a challenging gap that technology managers are facing in linking technology development to corporate strategy.

Appendix 1: Determination of the Relative Desirability of Measures of Effectiveness (Metrics) Under Each Factor (j_k) and Criterion (k)

This process is conducted in four steps.

Step a: Identify the best and the worst desirable limiting metrics that each factor can take on.

Step b: Verify the measures of effectiveness whose desirability value is linearly proportional to their numerical value between the two limits.

Step c: Develop a semi-absolute scale by assigning 0 point to the worst and 100 points to the most desirable limiting metrics under each factor:

$$\boxed{\mathbf{0} \leq V\left(m_{i_{jk}}, j_k, k\right) \leq \mathbf{100} \quad \textbf{for each factor } (\mathrm{j_k}) \textbf{ and criterion } (\mathrm{k})}$$

Step d: Calculate the relative desirability of the intermediate values between the two limits by following one of the two approaches described below:

Approach 1: If a characteristic of a factor can be verified as a linearly proportional function, the relative desirability of the measures of effectiveness between the worst and the best metrics is determined as linearly proportional to its numerical values between the limits.

Approach 2: If a characteristic of a factor cannot be verified as a linearly proportional function, the nonlinear functional relationships between the numerical values of the metrics and their desirability values need to be developed. Each expert is asked to assign a value between 0 and 100 representing his/her judgment on the relative desirability of each measure of effectiveness as a ratio of the desirability of the "best" limiting metric. The mean values are calculated among the relative values given by each expert to represent the group decision.

The relative desirability values of metrics under each factor can be graphically presented as a desirability curve by arranging the range of the metrics values on the X-axis and the desirability value on the Y-axis as shown in Fig. 6.7.

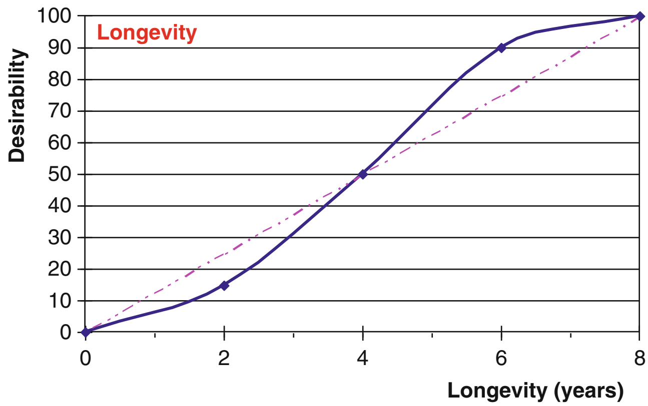


Fig. 6.7 Desirability curves

Appendix 2: Delphi Stopping Rule

Objectives: To test for stability between successive Delphi rounds in order to determine when it is appropriate to stop the Delphi study.
Literature Review:
Dajani et al. [61] suggest that the appropriate criterion for the termination of Delphi studies is stability rather than the agreement criterion. Chaffin and Talley [62] have proved that individual stability is more suitable than group stability for measuring the consistency of responses between successive rounds of a study. Since individual stability implies group stability the converse does not hold.

The chi-square statistic can be applied to determine whether individual response of rounds i and round $i+1$ are independent. To test whether there is a significant difference between individual responses in different rounds, two hypotheses can be presented as

$$H_0 = \text{Individual responses of rounds } i \text{ and } i+1 \text{ are independent.}$$
$$H_1 = \text{Individual responses of rounds } i \text{ and } i+1 \text{ are dependent.}$$

If individual responses in the rounds are dependent, it can be concluded that the same respondents who voted for a given response in the i th round would have also voted for the same response in round $i+1$.

Dajani, Sincoff, and Talley (1979) have proposed a function of chi-square value as

$$\chi^2 = \sum_{k=1}^{n}\sum_{j=1}^{m}\frac{\left(O_{jk} - E_{jk}\right)^2}{E_{jk}}$$

where O_{jk}: Observed frequency of responses in the j th response interval in the i th Delphi round and k th response interval in the $(i+1)$ th Delphi round
E_{jk}: Expected frequency of responses in the j th response interval in the i th Delphi round and k th response interval in the $(i+1)$ th Delphi round
m: Number of nonzero response intervals in the i round
n: Number of nonzero response intervals in the $i+1$ round

If the computed chi-square value is greater than the critical value with (m – 1)(n – 1) degrees of freedom at any desirable level of significance, the null hypothesis, H_0, is rejected. Then, the individual stability can be verified.

Individual Stability Test Between First and Second Rounds of Delphi Study (All Responses on Technology 4: Channel Flow Boiling)

(a) Observed frequencies (second round)

Response interval		A.I.	2004–2005	2006–2007	2008–2009	2010–Later	Never	*Total*
(First round)	A.I.	1					1	2
	2004–2005							0
	2006–2007			5				5
	2008–2009			1	3			4
	2010–Later					1		1
	Never							0
	Total	1	0	6	3	1	1	***12***

(b) Expected frequencies (second round)

Response interval		A.I.	2004–2005	2006–2007	2008–2009	2010–Later	Never
(First round)	A.I.	0.17	0.00	1.00	0.50	0.17	0.17
	2004–2005	0.00	0.00	0.00	0.00	0.00	0.00
	2006–2007	0.42	0.00	2.50	1.25	0.42	0.42
	2008–2009	0.33	0.00	2.00	1.00	0.33	0.33
	2010–Later	0.08	0.00	0.50	0.25	0.08	0.08
	Never	0.00	0.00	0.00	0.00	0.00	0.00

A.I. represents "already implemented"

$$\chi^2 = \sum_{k=1}^{n} \sum_{j=1}^{m} \frac{\left(O_{jk} - E_{jk}\right)^2}{E_{jk}} = 31.50$$

where

Ojk: Observed frequency of responses in the j th response interval in the first Delphi round and k th response interval in the second Delphi round
Ejk: Expected frequency of responses in the j th response interval in the first Delphi round and k th response interval in the second Delphi round
m: Number of nonzero response intervals in the first round
n: Number of nonzero response intervals in the second round

Note: The zero response intervals have been darkened in the table above.
Degrees of freedom $(df) = (m - 1)\ (n - 1) = (4 - 1)\ (5 - 1) = 12$.
Critical chi-square value at a 0.01 level of significance = 26.22.

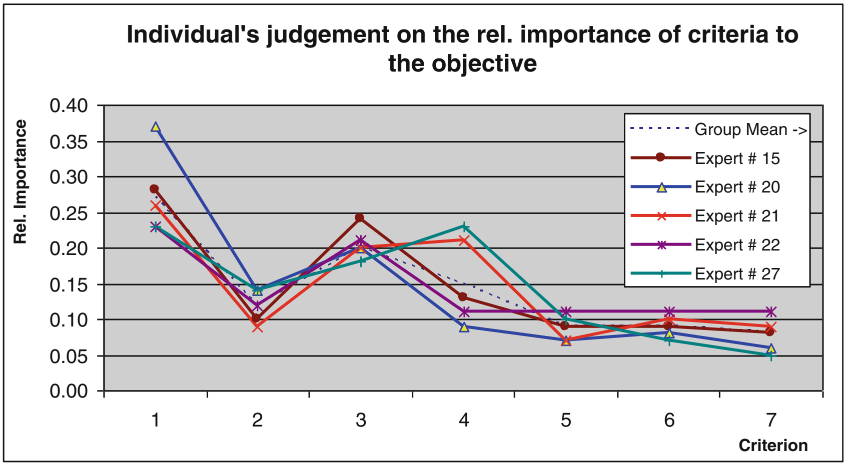
With the chi-square value is being greater than the critical value, the null hypothesis, H_0: individual responses of round i and i + 1 are independent, is rejected and individual stability is verified.

Appendix 3: Analysis of Individual Judgment and Group Agreement

The individual judgments on the criteria are shown below. According to the graph, the responses from five experts can be visually separated into two groups. The first group consists of Expert # 21 and 27, who perceive equal values on the relative priorities between reliability and economic criterion. The other group consists of Expert # 15, 20, and 22, who perceive that reliability is almost twice as important as the economic criterion.

Statistical tests were applied to see whether the visual separation meant disagreement among those experts. The group agreement analyses were conducted using both intraclass correlation coefficient and Kendall's coefficient of concordance, as shown in the following section.

Table 6.4 The relative priority of the seven criteria



Criteria WRT Objective	C1	C2	C3	C4	C5	C6	C7
Group Mean ->	0.27	0.12	0.20	0.15	0.09	0.09	0.08
Expert # 15	0.28	0.10	0.24	0.13	0.09	0.09	0.08
Expert # 20	0.37	0.14	0.20	0.09	0.07	0.08	0.06
Expert # 21	0.26	0.09	0.20	0.21	0.07	0.10	0.09
Expert # 22	0.23	0.12	0.21	0.11	0.11	0.11	0.11
Expert # 27	0.23	0.14	0.18	0.23	0.10	0.07	0.05

Table 6.5 Data representing the relative values of the seven criteria provided by each expert

		Expert # 15		Expert # 20		Expert # 21		Expert # 22		Expert # 27		
		X_1	X_1^2	X_2	X_2^2	X_3	X_3^2	X_4	X_4^2	X_5	X_5^2	ΣS_i
Subjects	Criterion1	0.28	0.08	0.37	0.14	0.25	0.06	0.23	0.05	0.23	0.05	1.36
	Criterion2	0.10	0.01	0.14	0.02	0.09	0.01	0.12	0.01	0.14	0.02	0.59
	Criterion3	0.24	0.06	0.20	0.04	0.20	0.04	0.21	0.04	0.18	0.03	1.03
	Criterion4	0.13	0.02	0.09	0.01	0.21	0.04	0.11	0.01	0.23	0.05	0.77
	Criterion5	0.09	0.01	0.07	0.00	0.07	0.00	0.11	0.01	0.10	0.01	0.44
	Criterion6	0.09	0.01	0.08	0.01	0.10	0.01	0.11	0.01	0.07	0.00	0.45
	Criterion7	0.08	0.01	0.06	0.00	0.09	0.01	0.11	0.01	0.05	0.00	0.39
		$\sum X_1 = 1.0$	$\sum X_1^2 = 0.19$	$\sum X_2 = 1.0$	$\sum X_2^2 = 0.22$	$\sum X_3 = 1.0$	$\sum X_3^2 = 0.18$	$\sum X_4 = 1.0$	$\sum X_4^2 = 0.16$	$\sum X_5 = 1.0$	$\sum X_5^2 = 0.18$	$\sum X_T = 5.03$ $\sum X_T^2 = 0.92$
		$\overline{X}_1 = 0.14$		$\overline{X}_2 = 0.14$		$\overline{X}_3 = 0.14$		$\overline{X}_4 = 0.14$		$\overline{X}_5 = 0.14$		

Approach A: Intraclass Correlation Coefficient

The intraclass correlation coefficient represents the degree to which k respondents agree on the mean rating of n objects. The coefficient is measured in a range between 0 and 1 indicating no agreement and perfect agreement, respectively.

From the data set shown in Table 6.4, the intraclass correlation coefficient was measured as 0.78 and this value was also tested to be statistically significant at 0.01. Therefore, it is concluded that there is a high level of agreement among five experts on justifying their relative values of the seven criteria. The following is the calculation and statistics test process as shown in Table 6.5.

Total subjects (n) = 7

Total experts (k) = 5

(a) Computing intraclass correlation coefficient referring to

$$\mathbf{r}_{\mathrm{IC}} = \frac{MS_{BS} - MS_{res}}{MS_{BS} + (k-1)MS_{res} + \frac{k}{n}(MS_{BJ} - MS_{res})}$$

Total sum of squares (SS_T)	= 0.19
Between-judges sum of squares (SS_{BJ})	= 0.00
Between-subjects sum of squares (SS_{BS})	= 0.16
Residual sum of squares (SS_{res})	= 0.04
Between-judges degrees of freedom (df_{BJ})	= 4
Between-subjects degrees of freedom (df_{BS})	= 6
Residual degrees of freedom (df_{res})	= 24
Total degrees of freedom (df_T)	= 34

Mean square between-conditions (MS_{BJ})	$= SS_{BJ}/df_{BJ}$	= 0.00
Mean square between-subjects (MS_{BS})	$= SS_{BS}/df_{BS}$	= 0.03
Mean square residual (MS_{res})	$= SS_{res}/df_{res}$	= 0.03

Thus, by substituting all values in the equation above:
Intraclass correlation coefficient (r_{IC}) = **0.78**

(b) The F-test for evaluating the null hypothesis (H_o: $\rho_{IC} = 0$, representing no correlation among experts) is obtained by dividing between-subjects variability with residual variability, $F_{BS} = MS_{BS}/MS_{res}$.

Table 6.6 Summary table of analysis of variance

Source of variation	SS	*df*	MS	F
Between-subjects	0.16	6	0.026	16.64
Between-conditions	0.00	4	0.000	
Residual	0.04	24	0.002	
Total	0.19	34		

The critical F-value obtained from the table of F-distribution with $df_{num} = df_{BS} = 7 - 1 = 6$ and $df_{dum} = df_{res} = (7 - 1)(5 - 1) = 24$ at 0.01 level is equal to 3.67. Since $F = 16.64$ is greater than the critical values, the null hypothesis can be rejected at the 0.01 level as shown in Table 6.6.

Approach B: Kendall's Coefficient of Concordance

Kendall's coefficient of concordance represents the degree to which *k* respondents agree on the ranking of *n* objects. The coefficient is measured in the range between 0 and 1 indicating no agreement and perfect agreement, respectively.

From the data set in Table 6.4, Kendall's coefficient of concordance was measured at 0.83, and this value was also tested to be statistically significant at 0.01. Therefore, it is concluded that there is high level of agreement among five experts with respect to how they rank the relative importance of the seven criteria. The following is the calculation and statistics test process.

(a) Convert those relative priority values into ranks. For the criteria that received the same relative importance values, they are considered as tied ranks and their new ranks are assigned to the average of the ranks in which they are involved as shown in Table 6.7.

Table 6.7 Conversion of the relative priority values into ranks

Criteria WRT objective	C1	C2	C3	C4	C5	C6	C7	Total
Expert # 15	1	4	2	3	5.5	5.5	7	
Expert # 20	1	3	2	4	6	5	7	
Expert # 21	1	5.5	3	2	7	4	5.5	
Expert # 22	1	3	2	5.5	5.5	5.5	5.5	
Expert # 27	1.5	4	3	1.5	5	6	7	
$\Sigma(R_m)$	5.5	19.5	12	16	29	26	32	140

The sum of squares of deviations of the column total around their mean, which is $140/7 = 20$, is

$$\begin{aligned} S &= (5.5 - 20)^2 + (19.5 - 20)^2 + (12 - 20)^2 + (16 - 20)^2 + (29 - 20)^2 \\ &\quad + (26 - 20)^2 + (32 - 20)^2 \\ &= 551.5 \end{aligned}$$

The value for tied ranking adjustment is computed as

$$\text{Expert } \# \ 15 = \frac{1}{12}\left(2^3 - 2\right) = 0.5$$

$$\text{Expert } \# \ 21 = \frac{1}{12}\left(2^3 - 2\right) = 0.5$$

$$\text{Expert } \# \ 22 = \frac{1}{12}\left(4^3 - 4\right) = 5.0$$

$$\text{Expert } \# \ 15 = \frac{1}{12}\left(2^3 - 2\right) = 0.5$$

$$\frac{1}{12}\sum_{i=1}^{m}\left(u^3 - u\right) = 6.5$$

With the effect of ties in a ranking, $\widetilde{W} = \frac{S}{S_{\max}}$ is modified to $\widetilde{W} = \frac{S}{\frac{1}{12}m^2(n^3-n)-\frac{1}{12}m\sum_{i=1}^{m}\left(u^3-u\right)}$

Thus, $\widetilde{W} = \frac{551.5}{\frac{1}{12}\left[5^2\left(7^3-7\right)\right]-5(6.5)} = \mathbf{0.826}$

(b) By assuming that the chi-square distribution is a good approximation of the sampling distribution of $\widetilde{W}$, the statistic chi-square test for evaluating the null hypothesis (H_o: $\widetilde{W} = 0$ representing no correlation among ranks assigned by experts) is obtained through $\chi^2 = m(n-1)\widetilde{W}$, and its degree of freedom is calculated as $df = n - 1$. From the data above, $\chi^2 = 5(7-1)0.826 = 24.78$.

Comparing with the tabled critical value at the 0.01 level of significance for $df = 7 - 1 = 6$ ($\chi^2_{0.01,\ 6}$ is equal to 16.81), the obtained χ^2 value is greater than the tabled critical value ($\chi^2 > \chi^2_{0.01,\ 6}$), and the null hypothesis is rejected.

In conclusion, the results from all three approaches indicate a high level of agreement among five experts for justifying the relative priority of the seven criteria as summarized in Table 6.8.

Table 6.8 Comparison of the level of group agreement computed through two different approaches

Intraclass correlation coefficient	Kendall's coefficient of concordance
0.78 (Statistically verified at the 0.01 level of significance)	**0.83** (Statistically verified at the 0.01 level of significance)

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Chapter 7
Strategic Planning: Evaluation of Emerging Technologies in the Taiwan Semiconductor Foundry Industry

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Abstract The semiconductor manufacturing technologies have been evolving continuously since their invention. The semiconductor foundry industry, whose core business is contract semiconductor manufacturing service, is greatly influenced and shaped by the flow of these newly arriving technologies. This research applies the analytic hierarchy process (AHP) model to evaluate the strategic impact of new manufacturing technologies in the semiconductor foundry industry in Taiwan where the industry is in a global leadership position. The model incorporates the levels of overall competitive success, competitive goals, technology strategies, and emerging technologies. Relative impacts of elements in one level on its upper level are obtained by utilizing the inputs from experts of Taiwan semiconductor foundry industry. The results show the relative importance of competitive goals in the semiconductor foundry industry. Each competitive goal is aligned to the technology strategies as well as emerging technologies in the prioritized orders.

7.1 Introduction

Semiconductor devices have become one of the driving forces in the information age. These devices are embedded in a wide variety of products, which enable the functions of creating, storing, processing, and communicating information. Manufacturing of semiconductor devices is very critical to the supply chain of information products. It is the manufacturing process that turns designs of devices into physical products.

In the semiconductor foundry industry, new technologies emerge from both inside and outside the industry. New technology represents either opportunities or

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threats to a firm depending on the characteristics of the technology. It also involves intensive investment in that a typical wafer facility costs more than one billion dollars [1]. In addition, it takes about 2 years between deciding to build a plant and completing it. In general, the semiconductor foundry industry is a technologically intensive and high-stake business.

High capital investment may constrain an organization to certain strategies and make the organization less flexible. On the other hand, technological uncertainty requires an organization to be able to adapt to the changes brought on by emerging technologies. Under this situation, strategic assessment of emerging technologies will help organizations understand the influences of new technologies on their strategies and businesses.

For the recent decades, technology has become an important dimension in the business world. The importance of technology has been illustrated in many ways: displacing products and their embedded technologies [2], shaping the industrial structure [3–5], and creating competitive advantage for profitability [3]. To fully exploit advantages brought by technology, it is necessary to know the attributes of the technology and its feasibility for a firm's business practice.

At the same time, technology can also alter the rules for competition by changing the business environment. These changes bring critical strategic issues to management. These changes in the business environment can be either negative or positive [5, 6]. Negative impacts are deemed as threats to the firm while positive impacts are opportunities for the industry. Regardless of threats or opportunities, management must be able to proactively respond to these changes in order to be successful. It is critical for management to understand the implications of the changes and alter their strategies accordingly [7]. Evaluation of potential technological impacts that change the operational environment of business is an essential task for strategic management.

This research investigates the influences of emerging technologies in the aspects of technology strategies, competitive goals, and overall competitive success in the semiconductor foundry industry. An analytic hierarchy process (AHP) model is developed for this purpose. The model will assess the strategic impacts of emerging technologies on overall competitive success in the semiconductor foundry industry. It will also assess the influence of emerging technologies on technology strategies and competitive goals. The results of the assessment model are expected to align emerging technologies, technology strategies, and competitive goals in order to gain overall competitive success in the industry.

7.2 Technology Evaluation for Strategic Management

Technology plays a critical role in business. The most important role of technology is to create superior capability for the firm to outperform its competitors. Many authors have recognized this key role that technology can play to achieve business success [8–10]. Yet technology should be properly deployed before its economic benefit can be obtained. Firms are striving to adopt technologies and put them in their business processes. The consistency or fit between technology and business operation sets the baseline for a successful technology implementation [11–13].

Probert et al. developed a five-process model for technology management that integrates technology into the business planning process [14]: technology identification, selection, acquisition, exploitation, and protection. When technology is put into this kind of business planning process, it is connected to the strategy of the organization. In other words, the impact of the technology under evaluation greatly depends on the strategic pattern and position of the organization.

A variety of methods have been developed to help technology evaluation and selection. These methods are used to determine the value or impact of a technological project on an organization along certain dimensions. Each method has its framework that reflects the decision process. Taxonomies for technology evaluation methods have been developed in terms of the features of these methods. Meredith and Mantel generally categorized these methods into non-numeric and numeric groups [15].

The non-numerical methods rely on either decision maker [16] or expert judgments [17, 18] or preferences which are not quantified. The decision process based on these judgments or preferences can be either covert such as comparative benefit model [16] or made observable such as cognitive modeling [19, 20].

In the numerical category, there are three classes, economic, priority ranking, and mathematic programming models. Economic models use monetary data and dollar amounts to determine the value of projects [21]. The model applies the concept of time value of money, which is a type of economic equivalence that is used as an index while evaluating technological projects. These indexes include net present value (NPV), internal rate of return (IRR), and return on investment (ROI).

Priority ranking methods select a set of factors that are considered important to evaluate technologies. These factors can be either weighted or non-weighted. Among priority ranking methods, AHP was developed to incorporate the natural decision hierarchy in a model [22]. The hierarchy includes objectives, goals, strategies, and other decision elements of an organization. Pairwise comparison method (PCM) was developed to capture subjective judgments of experts for quantification.

Mathematic programming models optimize the selection result in accordance with a certain objective. In general, there is an objective function that needs to be optimized under certain constraint functions. Various mathematical approaches, such as goal programming [23] and data envelopment analysis (DEA) [24], have been developed to find the optimum solution to the project and/or portfolio selection problem.

Lee et al. and Standke suggested that no technology evaluation method serves as an all-purpose tool [25, 26]. Approaches to technology assessment should be designed in accordance with its problems [27]. Since the 1980s, the uses of economic models for technology evaluation have been considered inadequate for the modern complex business environment [28, 29]. In reviewing the literature on evaluating technological alternatives, the trend tends to employ multiple criteria for the decision process [30–33]. More recently, many authors have suggested incorporating strategic aspects into the evaluation process [34–39].

From the perspective of strategic management, technology can be utilized to differentiate products, lower costs, improve efficiency within a value chain, or create new market opportunity, and as a result sustaining competitive advantages for an organization. Not the technology itself provides all these benefits to a firm but the capability of managing technology in a strategic way. To fully understand the potential of technology, the connection of technology and strategy should be established.

Mintzberg defines strategy as “a pattern in a stream of decisions” which is formed in the business context [40]. He suggests that strategies as patterns of organizational behaviors are the results of complex organizational processes. These patterns of strategies are called “strategy archetypes” or “generic strategies.”

Many authors have developed strategy archetypes to distinguish successful strategies from failure ones [41–47]. However, technology evaluation is rarely linked to these strategy archetypes, which are widely observable in many industries. This research is designed to bridge this gap between technology evaluation and strategic management using Taiwan semiconductor foundry industry as the specific case. It is also to operationalize the concept of strategic patterns or so-called strategy types developed in the literature.

7.3 Research Background

The objective of this research is stated as follows:

> “to develop a technology evaluation model for the assessment of strategic impacts of emerging technologies on overall competitive success in the semiconductor foundry industry.”

The model integrated critical emerging technologies, technology strategies, and competitive goals in order to determine the impact of each emerging technology under consideration on overall competitive success.

7.3.1 Development of Model Hierarchy

The research starts with its objective: to understand the impacts of technologies to competitiveness in the semiconductor foundry industry. Due to the complexity of the stated problem, it is difficult to assess the contributions of technologies to any source of competitiveness directly. Identification of all affecting factors between technologies and competitiveness as well as their connections to each other is the way to construct the analytic model. Since the model represents a system designed to solve the proposed problem, competitiveness should be considered an emergent property of the system [48]. The model consists of a hierarchy of several levels with connections between the elements in any two adjacent levels.

In order to determine the hierarchy, the generic three-level approach is adopted [49, 50]. The three levels are listed below.

1. Impact level contains the objectives and benefits. For this research overall competitive success is the ultimate objective of the model. Overall competitive success is directly supported by competitive goals.
2. Target level contains the goals that are measurable by disaggregating the objectives. In the model, goals are the sources of competitive advantage. Competitive advantages are the result of successful competitive strategies supported by appropriate technology strategies.
3. Operational level contains the strategies and actions that contribute to the target level. In the model, operation level contains technology strategies and emerging technologies. Technology strategies are the decision patterns of management to acquire, deploy, and exploit technologies. In this study, the focus is on the deployment of emerging technologies in the semiconductor foundry industry. The available emerging technologies in that industry are identified and deployed to manufacturing and business processes in accordance with technology strategies.

An AHP model is developed to answer the overall question and to explore strategic implications of the technological changes in the industry. In order to illustrate the question clearly, the hierarchy of the AHP model is depicted in Fig. 7.1.

In the AHP, notations are defined as follows:

T_{ij}: Impact of emerging technology i on technology strategy j
S_{jk}: Impact of technology strategy j on competitive strategy k
G_k: Relative importance of competitive strategy k in the semiconductor foundry industry
i: The number of emerging technologies under evaluation
j: The number of technology strategies
k: The number of competitive goals

Synthesis for overall impacts of emerging technologies on competitiveness can be obtained with the following matrix operation:

$$T_i = \sum_{k=1}^{K} \sum_{j=1}^{J} T_{ij} S_{jk} G_k; \quad \text{for } i = 1, \ldots, \text{I};$$

where

T_i is the impact of emerging technology i on overall competitive success.

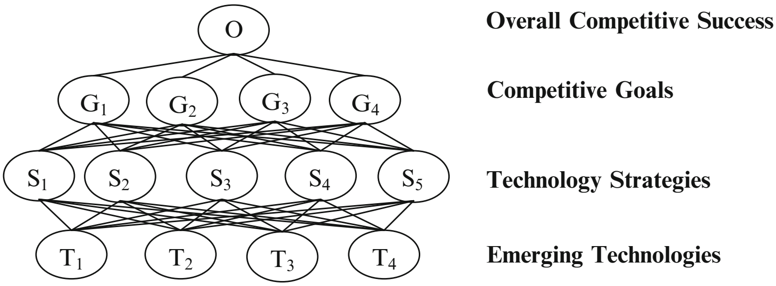

Fig. 7.1 The AHP hierarchy

7.3.2 *Development of Evaluation Criteria in Each Level of the Hierarchy*

The design of the AHP model was based on current literature of strategic management of technology (SMT) and extended it to an integral and operational model. Therefore, the evaluation criteria in each level of the decision hierarchy were extracted from related literature. The definitions of each criterion along with their related literature are summarized in the following sections.

7.3.2.1 Overall Competitiveness

The ultimate impact to be analyzed is the overall competitive success in the semiconductor foundry industry. Overall competitive success is the synthesis of competitive advantages resulted from successful execution of competitive strategies.

7.3.2.2 Competitive Goals

The competitive goals for the model are the combination of competitive advantages and industry key success factors. In the AHP model competitive goals were extracted from literature of competitive strategy. They are listed below.

G1: Cost Leadership: Low overall costs by reducing cycle time, increasing yield, and utilizing economy of scale [51–55].

G2: Product Leadership: Development of cutting-edge and proprietary IC process technologies [51–55]. (For foundry, products are the services of IC manufacturing processes.)

G3: Customer Leadership: Intimate customer relationships to reduce lead time, to improve on-time delivery, and to provide customized processes and services [51–53, 55].

G4: Market Leadership: Development of new markets and strengthening the position in existing market to influence market and to benefit from scale of scope [52, 56, 57].

7.3.2.3 Technology Strategies

Technology strategies are measured in many technology management dimensions. These dimensions are the measurable variables used to distinguish managerial approaches toward technologies. In the literature, the following types of technology strategy along the product and production dimensions have been identified.

S1: Innovation: Use of advanced technology to develop new products for the market. This strategy is to develop the best performance products on the market [41–43, 47, 58].

S2: Imitation: Quick application of technology to product development after the product leader has proved the technology successful [41–43, 47–58].

S3: Diversity: Use of technology to support a spectrum of products that may be during any stage of their life cycles. This strategy increases the variety of products [41–43, 47, 58].

S4: Efficiency: Use of technology to improve production methods. This strategy improves the efficiency of production [41–43, 47, 58].

S5: Flexibility: Use of technology for rapid development of products in quick response to changing market demands. Products under this strategy should have the flexibility to serve different market segments and to adjust in terms of production volume [42, 43, 58].

7.3.2.4 Emerging Technologies

In identifying emerging technologies that have significant strategic impacts on the semiconductor industry, technologies are reviewed along the categories classified by the industrial research institutes. According to the international technology roadmap for semiconductors published by SEMATECH, several technologies are identified as having significant strategic impacts on the industry. These technologies are defined by the function and performance of their overall characteristics, referred to as "technology nodes" in the SEMATECH international roadmap. In the near term of the roadmap, the critical technologies are identified:

1. Increase wafer size to 300 mm and beyond
2. Reduced linewidths to 90 nm and under
3. High k gate dielectrics
4. Low k intermetallic dielectrics
5. Factory integration of manufacturing equipment and inspection tools

7.3.3 Validation of the Model

An expert panel was formed to validate the hierarchical model and its elements in each level. The experts were selected from industry, research institute, as well as government agency of Taiwan.

The research objective, research approach, and process were communicated to the expert panel. Once the experts were familiarized with the research, the validation instruments were sent to them. The expert panel reviewed the structure of the model and the viability of each element in the hierarchy and provided their opinions to the research. Comments from the validation process were taken to finalize the model and the definitions of the evaluation criteria.

7.4 Data Collection

To quantify the AHP model, experts were split into three groups on their expertise. Each group provided one type of measurement. These measurements were the following:

Measurement 1: Relative preferences of competitive goals (G) to overall competitive success (O).

Experts provided the judgment regarding the dimensions of competition in the industry. Competitive advantages are the result of successful execution of generic business strategies. It is assumed that corporations are well aligned to the business strategy and effectively gain the advantage to their competitors.

Measurement 2: Relative impacts of technology strategies (S) to competitive goals (G).

Experts provided the judgments regarding the contributions of technology strategies to competitive goals. Technology strategies are the decision patterns to deploy technologies in order to fulfill management objectives. In this case these objectives are competitive goals in which management decides to excel.

Measurement 3: Contribution of short-term emerging technologies (T) to technology strategies (S).

Experts identify short-term (2003–2007) emerging technologies within and/or outside the industry and determine the relative contributions of these technologies to various technology strategies.

Six experts, based on their expertise in the industry, are assigned to these three measurements. In order to protect the experts' identities, capital letters A, B, C, D, E, and F are assigned to the six experts. Experts were paired to provide judgment quantifications to the model: Experts A and B were assigned to measurement 1, experts C and D worked on measurement 2, and experts E and F took measurement 3.

This allocation of experts is to best utilize their expertise and, in the same time, balance their perspectives [59, 60].

Experts A and B are business executives in the semiconductor foundry industry. They are the decision makers in terms of directing and positioning their organizations. They are the objective setters and strategy practitioners in the industry.

Experts C and D are industrial analysts. They understand the characteristics of the industry and have the intelligence of analyze it. Expert C works for a nonprofitable organization, which collects and analyzes industry intelligence for the public. Expert D is a veteran in the semiconductor foundry industry and is a venture capitalist.

Experts E and F are technologists who have the knowledge of the emerging technologies in terms of their capabilities and developing trends. However, they are from the organizations with different missions.

Multiple experts provided their pairwise comparisons for each measurement. The multiple pairwise comparison results for each measurement can be averaged as the collective and balanced perspective of Taiwan as an organization in the semiconductor foundry industry. On the other hand, these multiple results, when viewed individually, represent the decision preferences at company level and under different business perspectives.

7.5 Results

The research results are based on the three basic measurements and the synthesis of these measurements. The data of pairwise comparisons obtained form experts are calculated with pairwise comparison method (PCM) algorithm that is described in the methodology section. The outputs of the PCM algorithm are the relative impacts of the decision elements under comparison. The calculated results for the three basic measurements are summarized below.

Measurement 1: Experts A and B assess the relative importance of competitive goals to overall competitive success. The data are collected with the instruments and are compiled in the form of matrices as the result of pairwise comparisons. With the algorithm of the pairwise comparison method (PCM), the relative importance of competitive goals to overall competitive success in the semiconductor foundry industry is listed in Table 7.1.

Measurement 2: Experts C and D provided the assessments of the relative impacts of technology strategies on competitive goals. Similarly, the results are complied in the form of a matrix as shown in the following table.

Measurement 3: Experts E and F have assessed contributions of short-term emerging technologies to technology strategies. The results are listed below.

A. Relative importance of the competitive goals in the industry
   From measurement 1, the relative importance of the competitive goals is in the order of cost (0.38), product (0.25), customer (0.21), and market (0.18)

Table 7.1 Relative importance of competitive goals to overall competitive success

Expert	Cost leadership	Product leadership	Customer leadership	Market leadership	Inconsistency
A	0.40	0.21	0.13	0.26	0.020
B	0.35	0.28	0.29	0.09	0.011
Mean	0.38	0.25	0.21	0.18	0.085

leaderships. This rank is the average results obtained from two experts A and B. The rank indicates that the semiconductor foundry industry is competing heavily along the dimensions of cost reduction and product innovation. These two competitive goals are common to Taiwan foundries who, however, can differentiate from each other in either customer leadership or market leadership.

B. Relative impacts of technology strategies on the competitive goals
The relative impacts of technology strategies on the competitive goals represent the alignments of technology strategies to individual competitive goals. They are illustrated in Table 7.2 that are the results obtained from measurement 2. The contributions of the technology strategies to each competitive goal are summarized below.

1. Relative contributions of technology strategies to cost leadership
For the competitive goal of cost leadership, the relative importance of technology strategies is in the order of efficiency (0.43), flexibility (0.29), diversity (0.14), imitation (0.11), and innovation (0.02). The inconsistency for the mean value is low (0.074), which indicates consensus between the two experts.
2. Relative contributions of technology strategies to product leadership
For the competitive goals of product leadership, the relative importance of technology strategies is in the order of innovation (0.54), diversity (0.17), imitation (0.14), flexibility (0.08), and efficiency (0.07). The inconsistency for the mean values is 0.08, which indicates consensus between the two experts.
3. Relative contributions of technology strategies to customer leadership
The mean contributions of the technology strategies to customer leadership are in the order of efficiency (0.27), diversity (0.24), flexibility (0.23), imitation (0.14), and innovation (0.11). The inconsistency for the mean values is 0.104 representing some disagreement between the two experts.
4. Relative contributions of technology strategies to market leadership
The mean contributions of the technology strategies to market leadership are in the order of flexibility (0.24), diversity (0.21), imitation (0.20), efficiency (0.18), and innovation (0.16). The inconsistency for the mean values is 0.134 representing a relatively high disagreement between the two experts.

The major difference is that expert C assigned the highest score to flexibility strategy to market leadership while expert D considered imitation strategy having the highest impact. Expert C believes that flexibility strategy allows an organization shifts among products timely to match the needs of a

Table 7.2 Relative impacts of technology strategies to competitive goals

Competitive Goals	Expert	Innovation	Imitation	Diversity	Efficiency	Flexibility	Inconsistency
	C	0.02	0.13	0.09	0.52	0.24	0.090
Cost leadership	D	0.02	0.10	0.20	0.34	0.34	0.066
	Mean	0.02	0.11	0.14	0.43	0.29	0.074
	C	0.47	0.07	0.21	0.09	0.15	0.023
Product leadership	D	0.60	0.20	0.13	0.05	0.01	0.038
	Mean	0.54	0.14	0.17	0.07	0.08	0.080
	C	0.14	0.07	0.14	0.33	0.33	0.029
Customer leadership	D	0.09	0.22	0.34	0.22	0.14	0.000
	Mean	0.11	0.14	0.24	0.27	0.23	0.104
	C	0.11	0.07	0.21	0.21	0.40	0.049
Market leadership	D	0.22	0.34	0.22	0.14	0.09	0.000
	Mean	0.16	0.20	0.21	0.18	0.24	0.134

dynamic market. By foreseeing the needs of the market, the organization is able to create and sustain the emerging market with flexibility strategy. Expert D, on the other hand, emphasized the requirement of foreseeing the emerging market need in order to sustain market leadership. However, instead of a timely switch among products, expert D believes that imitation of the leading companies, not only in the foundry industry but also in other electronic industries, is the strategy to foresee the market needs. The imitation strategy is not confined to the foundry industry, but extended to related industries and markets.

C. Relative impacts of emerging technologies on technology strategies
The relative impacts of emerging technologies on the technology strategies are the contributions of emerging technologies to each technology strategy. They are illustrated in Table 7.3 and are summarized below.

1. Contribution of Emerging Technologies to Innovation Strategy
From Table 5.3, the relative contributions of short-term emerging technologies to innovation technology strategy are in the order of 300 mm wafer (0.31), factory integration (0.20), 90 nm linewidth (0.19), low k dielectrics (0.17), and hi k dielectrics (0.13). Firms with innovation strategy concentrate on 300 mm wafer technology that accounts for 0.31 of relative contribution. Factory integration and 90 nm linewidth technologies approximately equally contribute to innovation technology strategy with the scores of 0.20 and 0.19, respectively.
2. Contribution of Emerging Technologies to Imitation Strategy
The relative contributions of short-term emerging technologies to imitation technology strategy are in the order of 300 mm wafer (0.29), 90 nm linewidth

Table 7.3 Relative contributions of short-term emerging technologies to technology strategies

Strategy	Expert	300 mm	90 nm	Hi k	Lo k	Factory integration	Inconsistency
	E	0.31	0.21	0.14	0.14	0.21	0.000
Innovation	F	0.30	0.17	0.13	0.21	0.19	0.027
	Mean	0.31	0.19	0.13	0.17	0.20	0.027
	E	0.39	0.19	0.12	0.12	0.17	0.004
Imitation	F	0.19	0.29	0.09	0.22	0.20	0.029
	Mean	0.29	0.24	0.11	0.17	0.18	0.081
	E	0.20	0.31	0.20	0.20	0.08	0.000
Diversity	F	0.24	0.24	0.10	0.23	0.21	0.008
	Mean	0.22	0.27	0.15	0.21	0.14	0.058
	E	0.21	0.21	0.14	0.14	0.31	0.000
Efficiency	F	0.24	0.22	0.10	0.22	0.22	0.003
	Mean	0.22	0.21	0.12	0.18	0.27	0.043
	E	0.09	0.21	0.19	0.23	0.28	0.015
Flexibility	F	0.09	0.37	0.07	0.21	0.26	0.059
	Mean	0.09	0.29	0.13	0.22	0.27	0.065

(0.24), factory integration (0.18), low k dielectrics (0.17), and hi k dielectrics (0.11). Similar to innovation strategy, firms with imitation strategy concentrate on 300 mm wafer technology that accounts for 29 % of relative contribution. Ninety nanometer linewidth technology (0.24) is the second large contributor to imitation technology. Due to the costly 300 mm wafer equipment and 90 nm lithograph tools, imitation strategy benefits most from two technologies by following the success paths of the pioneers.

3. Contribution of Emerging Technologies to Diversity Strategy
   The relative contributions of short-term emerging technologies to diversity technology strategy are in the order of 90 nm linewidth (0.27), 300 mm wafer (0.22), low k dielectrics (0.21), hi k dielectrics (0.15), and factory integration (0.14). Ninety nanometer linewidth technology allows smaller IC feature products while material technologies such as hi k and lo k dielectrics diversify into various IC functionalities. In the meantime, 300 mm wafer technology, although it does not diversify products, is the second important technology to diversity strategy due to its overwhelming benefit in productivity.
4. Contribution of Emerging Technologies to Efficiency Strategy
   The relative contributions of short-term emerging technologies to efficiency technology strategy are in the order of factory integration (0.27), 300 mm wafer (0.22), 90 nm linewidth (0.21), low k dielectrics (0.18), and hi k dielectrics (0.12). Factory integration enhances the efficiency between complicate IC manufacturing processes and contributes most to efficiency technology strategy. Similarly, 300 mm wafer and 90 nm linewidth technologies allow more IC chips being manufactured for the same amount of cycle time.
5. Contribution of Emerging Technologies to Flexibility Strategy
   The relative contributions of short-term emerging technologies to flexibility technology strategy are in the order of 90 nm linewidth (0.29), factory integration (0.27), low k dielectrics (0.22), hi k dielectrics (0.13), and 300 mm wafer (0.09). Ninety nanometer linewidth technology extends the flexibility to manufacture products in more advanced processes and factory integration technology enables smaller batches and customized processes. The 300 mm wafer technology (0.09) on the other hand constrains the size of least production and does not contribute much to flexibility strategy.

D. Relative impacts of technology strategies on overall competitive success
   The relative impacts of technology strategies on overall competitive success in the semiconductor foundry industry are obtained by synthesizing measurement 1 and measurement 2. It is a vector [S/O] which is the multiplication of measurement 2 matrix [S/G] by measurement 1 vector [G/O] (Table 7.4):

$$[S/O] = [S/G]x[G/O]$$

Table 7.4 The vector of impact of technology strategies on overall competitive success

Innovation	Imitation	Diversity	Efficiency	Flexibility
0.19	0.14	0.18	0.27	0.22

Table 7.5 The matrix for short-term emerging technologies to competitive goals

Goal	300 mm	90 nm	Hi k	Lo k	Factory integration
Cost leadership	0.19	0.24	0.13	0.19	0.24
Product leadership	0.27	0.22	0.13	0.18	0.20
Customer leadership	0.21	0.24	0.13	0.19	0.22
Market leadership	0.22	0.24	0.13	0.19	0.21

The most important technology strategy to overall competitive success in the semiconductor foundry industry is efficiency (27 %) followed by flexibility (22 %), innovation (19 %), diversity (18 %), and imitation (14 %). Because of the relatively short product life cycle of IC products, time to market is critical. Efficiency strategy enables cost-effective production which is critical to market share. Flexibility strategy, as a complement to efficiency strategy, facilitates the production to cope with changing market demands while not losing much efficiency.

E. Relative impacts of emerging technologies on competitive goals.
For short-term technologies, the [T/G] matrix is the result of multiplication of measurement 3, the [T/S] matrix, by measurement 2, the [S/G] matrix:

$$[T/G] = [T/S]x[S/G]$$

Table 7.5 is the matrix for the relative contributions of short-term emerging technologies to competitive goals. In general, 300 mm wafer, 90 nm linewidth, and factory integration technologies are relatively important than high k and low k dielectrics technologies. Hi k dielectrics technology is the least important technology and low k dielectrics technology has the second least priority. Among the top three technologies, the ranks of these technologies vary with the competitive goals.

For the competitive goal of cost leadership, the rank is in the order of 90 nm linewidth, factory integration, and 300 mm wafer. In fact, factory integration ties with 90 nm linewidth that altogether contribute 48 % to the competitive goal of cost leadership.

For the competitive goal of product leadership, the order is in 300 mm wafer, 90 nm linewidth, and factory integration. 300 mm wafer technology is the most important technology to competitive goal of product leadership and is 5 % more than the second important 90 nm linewidth technology.

For the competitive goal of customer leadership, the order is in 90 nm linewidth, factory integration, and 300 mm wafer. Again, 90 nm linewidth is the most important technology for the competitive goal of customer leadership.

Table 7.6 The vector for impact of short-term emerging technologies on overall competitive success

300 mm	90 nm	Hi k	Lo k	Factory integration
0.22	0.24	0.13	0.19	0.22

For the competitive goal of market leadership, the scores of the short-term emerging technologies are similar to those of customer leadership, except the slight 1 % differences in 300 mm wafer and factory integration technologies.

In summary, among the top three short-term emerging technologies, 90 nm linewidth is commonly important to all competitive goals and accounts for 22–24 % contributions. Factory integration also stably contributes 20–24 % to all competitive goals. The 300 mm wafer technology is important to the competitive goal of product leadership (27 %), but is relatively of less contribution to cost leadership (19 %) and almost evenly contributes to customer leadership (21 %) and market leadership (22 %).

F. Relative impacts of emerging technologies on overall competitive success

These vectors, [T/O] and [T′/O], represent the importance of both short-term and long-term emerging technologies to overall competitive success in the semiconductor foundry industry. They are obtained by synthesizing all the matrices of measurement 3 [T/S] and measurement [T′/S] with measurement 2, the matrix [S/G] and measurement 1, the vector [G/O]:

$$[T/O] = [T/S]x[S/G]x[G/O];$$

Table 7.6 contains the vector of the relative impacts of short-term emerging technologies on overall competitive success. The results show that 90 nm linewidth is the most important short-term emerging technology and 300 mm wafer and factory integration technologies are equivalently the second important technologies to the overall competitive success in Taiwan semiconductor foundry industry.

7.6 Conclusion

This research explored the strategic impact of emerging technologies in the semiconductor foundry industry in Taiwan. The strategic insight of the emerging technologies in terms of their priorities to technology strategies, competitive goals, and overall competitive success was obtained. In addition to the priorities of emerging technologies, the alignments between technology strategies and competitive goals and the relative importance of each competitive goal were also presented.

The research results can be applied to both the industry and individual companies in the industry. The synthetic or commonly shared research results are for Taiwan semiconductor foundry industry as an organization. On the other hand, companies in the industry can look at the alignments of technologies, strategies, and goals to differentiate themselves.

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Chapter 8
Strategic Planning: Model Development for Strategic Decision for Technology Selection in the Petrochemical Industry

Toryos Pandejpong

Abstract An interactive decision-support model for technology selection in the petrochemical industry is presented. With the assistance of an expert panel, Analytical Hierarchy Process (AHP) is utilized to define the decision problem and to provide the justification for selecting the alternative that best matches organization's requirements. A specific case study has been developed for the purpose of demonstrating and validating the model.

8.1 Introduction

Many companies spend considerable time and resources to improve their technology management practice. However, one of the critical elements of technology management, namely the process of selecting and planning technology, is typically incomplete, vague, and difficult to convert to action. In most companies, key players in strategy implementation do not or cannot understand and buy into the results, even if they have been part of the process [1, 2].

Selecting the *right* technology requires an understanding of organizational goals, customer needs and the ability to identify and select technologies that are vital to the success of an organization. This, in turn, requires an effective methodology. Very little research has been done on how the decision-makers in the petrochemical industry make their decisions, how the risks associated with each technology are quantified, how the relative importance values are assigned to those factors, and how the decision-makers in the petrochemical industry cope with all the different criteria to make consistent decisions.

The petrochemical industry covers 305 international and local companies. In terms of output, it is the second largest in the manufacturing sector, after the

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electronics industry [3]. A petrochemical is defined as a chemical compound or element, which can be derived entirely, or in part, from petroleum or natural gas hydrocarbons, and is intended for chemical markets. Most of the petrochemical products are true commodities, specified by their chemical composition and physical characteristics [4]. Innovations take place more often in refining processes (process innovation) than in the introduction of new products (product innovation) [5].

Petrochemical products are sold in the world market where efficient operation and quality control are the most critical elements for success. Since petrochemical products are almost entirely produced to serve as intermediate products to other industries, the demand for the products is closely related to the prospects of growth of the major purchasing industries and general economic conditions.

The petrochemical industry is characterized by the wide variety of its products and their end uses, the complexity of production, the alternative routes of production processes to final products and the flexibility in the choice of feedstock. The industry is highly capital-intensive with sophisticated production facilities incorporating the process and product modifications of recent decades [6, 7].

8.2 Research Methodology

This research objective is to develop an interactive decision-supporting model that will improve the existing project evaluation and selection practice in the petrochemical industry. Through the assistance of an expert panel, the AHP (Analytical Hierarchy Process) approach [8] will be used to determine the relative impacts of various technology alternatives toward organization strategies and needs. Those impacts will then be used to generate the best possible allocation of resources to each individual technology.

Four research questions have been formulated:

1. What factors should be used to evaluate technologies?
2. How should technologies be assessed in terms of their contributions to the corporate mission, goals, and strategies?
3. How should technologies be selected within financial and other constraints?
4. How should the three questions raised above be applied to the petrochemical industry?

The present paper propose to develop a decision supporting model that will guide managers in selecting the technologies that best match the organization's objectives. The model deals explicitly with technology's role in corporate strategy—the way that technology supports the corporate mission and goals. It provides a methodology to help plan technology strategy that expressly supports the critical technology decisions for success in a highly uncertain future.

With the help of expert panel, AHP approach is used to determine the relative impacts of various technology alternatives on organizational mission, goals, and factors. Those impacts will then be used to allocate resources to an optimum set of technologies. The prospective technologies will be evaluated by the degree to which they will meet the organization's objectives.

The expert panel is a group of people who have expertise in the petrochemical industry and/or technology (portfolios) selection. Members of the panel provide balanced representation of ideas and have little or no biases about the outcome of the study. The experts that participate in this study are all in a position to understand and influence decisions in the petrochemical industry. The expert panel is composed of experts from industry, educational institutes, and government agencies. In order to have a manageable size while assuring multiple perspectives and representation, there are six people in the panel. Communication with the experts is conducted mainly via e-mail, telephone, fax, and face-to-face interaction.

8.3 Case Study

In order not to reveal the identity of the company, it will be referred to as "Company". *Company* is a Thailand subsidiary of a major international corporation providing energy and petrochemical products. It has more than 3,000 employees in Thailand. The case year is 1993. The *Company* emphasizes its production on Olefins and Aromatics, which represent 60 % of its total assets. It is considering expanding its operations to a full range of the petrochemical products in order to comply with the national policy and the increasing domestic and East Asia demand.

The decision hierarchy for this case study represents the breakdown of needs and alternatives of the *Company*. By incorporating information acquired from the *Company* and expert panel that plays the decision-makers role for the *Company*, the multi-level decision hierarchy for evaluating and selecting technologies is generated. The potential alternatives are then evaluated by the degree to which they contribute to the organization's objectives.

For this specific case study, the hierarchy is divided into three sections each with a different source of inputs:

1. The first section of the hierarchy is made up of two levels: (1) Mission statement, (2) Corporate goals. This section is company specific. The executives of the company provide the list of the elements.
2. The second section also has two levels: (1) Systems, (2) Decision factors within each system. The list of initial decision factors is obtained from the literature and from the suggestions of the expert panel. Afterwards, the factors are filtered and clustered under the systems in accordance with the recommendations of the expert panel (See Appendix 1 and 2 for details about the hierarchy).
3. The third section is the list of the alternatives under consideration. It is important to point out that all the alternatives in this hierarchy already pass the prescreened test where all the rigid constraints such as financial constraint are used. This section is also company specific. Information about the technologies being

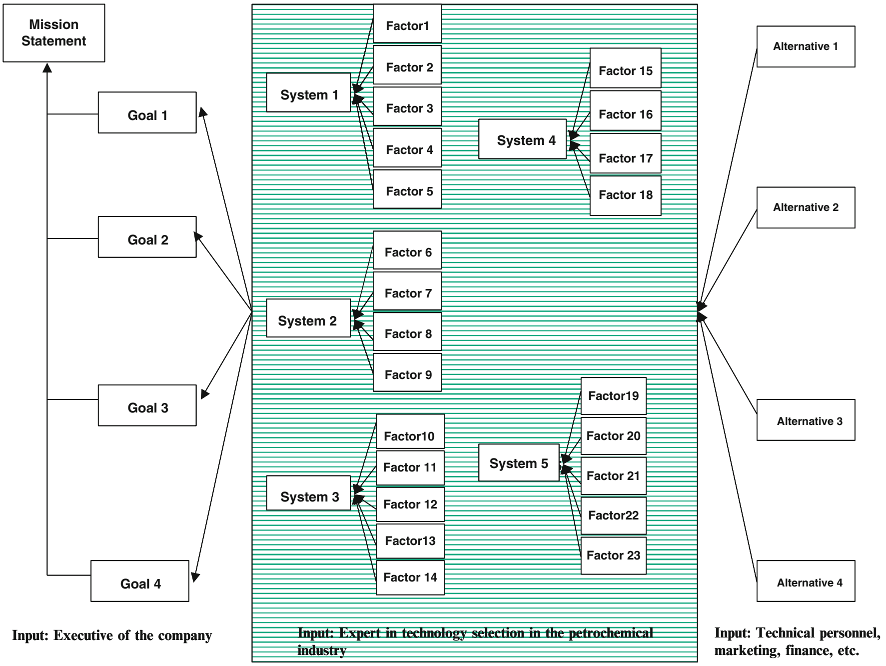

Fig. 8.1 Decision hierarchy

considered, the product and process features, cost of implementation, and project schedules are provided to assist the expert panel during the evaluation process. In this paper, the term "alternatives" and "projects" will be used interchangeably.

8.4 Results

Because of multiple and often conflicting objectives, the difficulty to explicitly express the associated trade-off preferences, the high number of feasible alternatives, and continuous change of the environment, technology selection is a highly complex process. This research establishes a descriptive decision-making process model in the petrochemical industry in order to effectively identify, evaluate and select the appropriate technologies for the company. The research identifies important decision-making factors and establishes their relative measures. The information was gathered through a combination of literature survey and input from an expert panel who are directly involved in the petrochemical industry. The result from the application to the petrochemical company was verified by the expert panel and confirmed the practicality of the proposed decision support model. The model was applied to experts who are away from one another. E-mail, fax, and telephone were the main channels for communication. The results were proven to be consistent with the expert judgment and the actual decisions that were made.

The application discussed in this paper is for the petrochemical company in Thailand. However, this method can be used in any other environment or country by inputting the importance weights of criteria for that environment or country. The validity of the data should be tested for that local condition.

The information used in the application is from 1993. Therefore, the results also hold true for that period. Results from the application of the decision support model show that the full-scale expansion (both horizontal and vertical integration expansions) is the best alternative for the decision environment that existed during the time period considered in this research (1993). Please see Appendix 3 for the model results. Since Thailand's domestic demand was large enough to help foster the growth and to service the company to a size large enough to compete in overseas markets, the expansion should provide the opportunity for the company to supply more value-added products for its customers in the future [9].

Goal-4 (improve cost competitiveness and operational excellence) is the most significant contribution to the mission statement. The driving force behind investment decisions of the petrochemical companies is to maximize their value by producing products at the lowest cost to get the highest profit margin. Moreover, as a result of the increasing competition from foreign suppliers and the effects of the AFTA agreement (Asean Free Trade Area), which will limit the import tariff within the members' countries from the current level of 20–60 % to 0–5 %, cost competitiveness and operational excellence have become major contributors to the short- and long-term growth of the company [9].

System-4 (competitive system) is the most important issue that needs to be addressed. In the 1990s, the fast growing domestic and Southeast Asia demands for the petrochemical industry's products attracted many new companies. Many companies had gone through several cycles of expansion. In 1993, the industry consisted of numerous companies, and even the largest companies accounted for merely a small portion of the industry. Without restraint, overexpansion could eventually lead to overcapacity and intense competition [6, 9].

Lastly, the significant factors in achieving the Company's mission statement are Factor 10 (resource compatibility), Factor 15 (the competitiveness of the company), and Factor 18 (potential benefits from market expansion), while the rest of the factors are secondary. The factors reflect the three most fundamental issues for the success of companies. Resource compatibility is concerned with the availability of resources and ability to match them with the project requirements [10]. The competitiveness of the company represents how well the company can compete in the industry and the likelihood that the company's product will be able to succeed in the market place [11]. Finally, potential benefit from market expansion is the future benefit that could be acquired from the prospect of the market and expansion of the customer base [12].

8.5 Conclusions

The conclusions drawn from this research are summarized below:

1. A participative decision process using expert opinions and quantified judgments can be used effectively in addressing the complex strategic decision-making problems in petrochemical industry.
2. Systems view can be applied to the petrochemical industry decisions by appropriately clustering the decision factors under the key systems representing the internal, competitive, and external environments.
3. According to the industry experts who participated in this study, market competitiveness and effective use of organizational resources are more significant issues than the technical, strategic, and external issues in technology selection decisions in petrochemical industry.
4. Relative emphasis placed on the issues by industry experts is different from the existing research literature:

   (a) Relative frequency of research an micro level decision elements in the technical and internal systems is higher than the relative priority placed on those elements by the experts
   (b) Relative priority placed on the macro level decision elements in the strategic, competitive, and an external system is higher than the relative frequency of research on those elements. Consequently, it is concluded that there is a need for shifting research emphasis to the issues affecting the petrochemical companies' strategic decisions, market competitiveness, and response to changes in the economic, political, and global conditions.

8.6 Recommendations for Implementation

The proposed model is based on AHP for dealing with complex problems. The strength of this approach is the capability it provides in addressing the complex problem with a relatively simple process. Even though the mathematical foundations of AHP are complex, the application through the solicitation of expert opinions is straightforward [13]. Following are some of the general recommendations for implementing this model in a real setting.

1. *Decision-makers' selection*: The inherent complexity and uncertainty surrounding the problem requires many individuals in the decision process. It is necessary to select a mix of "actors" to form the decision-making panel. The selection process requires specifying the number of experts, non-experts, staff personnel, and upper-level management to participate, as well as choosing the appropriate individuals. The expert should come from both operation level to be able to respond to questions related to technical details and strategic level to be able to identify company strategic decision. Experts from multiple disciplines are

recommended to provide balanced representation of ideas. Expert should have little or no biases about the outcome of the study. They should also be in a position to understand and influence the decision problem. The appropriate size of the panel is between five and eight people in order to have a manageable size while assuring multiple perspectives and representation [14–16].

2. *Running the Decision-Making Session*: After the group has been chosen, the members should begin preparing for decision-making session by formalizing their agenda, structuring the allowable interactions between participants, and clearly defining the purpose of the session in advance. Decision elements should be discussed and provided with concise definitions that can be understandable by everyone in panel.

   (a) Develop a hierarchical model by breaking the problem into decision elements (levels). The complexity of the problem requires a multiple perspectives approach. Implementing the model, the technical, organizational, and personal aspects of the organization should be emphasized [17].

   Identify the overall objective: What is the company's main objective, which is usually referred to as the Mission Statement of the company.

   Identify goals to achieve the overall objective. If relevant, identify time horizons that affect the decisions.

   Review the list of 23 factors proposed in this dissertation, and make adjustments as necessary.

   Identify and gather information related to technologies under consideration.

   Include "not taking any action" as an alternative, if appropriate.

   Identify and eliminate the preferentially dependent attributes from the hierarchy after the expert panel members have reviewed and revised' hierarchy.

   (b) Make pairwise comparisons to calculate the relative impacts of decision elements at each level on the element on the next higher level. (Please refer to 6.1.2 for details regarding pairwise comparisons). Once the experts agree on the hierarchy, entries must be evaluated for the pairwise comparison matrices. At each level, the experts assign values to the elements of each pair to express their judgments of the relative impact of each element in comparison with the other one. This process should be continued until all elements in all levels are evaluated.

   The decision hierarchy was divided into non-overlapping sections and each section was evaluated by one expert in this dissertation. The results were then combined. This approach is used when unique expertise in each section is identified and the evaluations for that section are limited to that specific expert. However, if multiple experts evaluate the same set of elements, their quantified judgments should be aggregated by using the geometric means or arithmetic mean. Geometric mean is recommended by Saaty [18], but arithmetic mean is easier to calculate. Either method can be used. After the aggregated means are obtained, group consistency is calculated (Please refer to 3.3.2 Validation of the hierarchy for details regarding the consistency index). If the consistency Index (CI) is low, the quality if aggregated judgments should be improved by discussion and a new set of evaluations by the experts. This cycle should be repeated until a group consensus is reached or the experts agree with the overall outcomes despite their individual disagreements.

3. Discuss results and implications: Expert panel members should be given an opportunity to evaluate the results at the end of each session and make modifications as needed. Final results should be communicated to the experts to assure that their judgments have been captured. If not process should be repeated. It is important not to view the results of the model as a one-time application, but rather as a process that has on-going validity and usefulness to an organization.

   Since the experts will frequently have expertise, influence, and perspective in different areas their cooperation may take some coaxing by the leader. Patience of the leader and the group is desirable. An unhurried, structured group discussion can yield more satisfactory outcomes than the ones achieved quickly and with little debate.

8.7 Future Work

This research is not the final word on the topic of technology selection in the petrochemical industry. Following list is a list of key related topics that can be studied.

1. Dynamic features can be added to the model to customize it for future needs such as the need for a quick computational model based on minimum input when there is a necessity to revise the allocation of an R&D budget due to the change in the inputs [31].

   The proposed model incorporates features that allow future users to be able to adjust to the changes of the organization's objectives and environment. The author recommends that a future study could include indicators (such as changes in input decision variables, or the emergence of new technology) or routine model execution for validating the technology portfolio. In addition, some forms of built-in inertia such as trade-off cost function or penalty function for dropping old technology from the portfolio should be developed in order to maintain continuity and stability of technology development and at the same time not hinder new innovation. The recommended factors that should be included in the function are the contribution of the technology to the organization mission (benefits), investment and knowledge acquired, future investment (costs), and risk (uncertainty).
2. The petrochemical industry is only a fraction of the entire chemical industry, the extension of the model to cover the entire chemical industry is recommended.

Many lessons learned during this study can be utilized in such an extension. Moreover, the proposed framework that includes organizational needs and multiple perspectives (strategic system, technical system, internal, competitive, and external system) could also be extended to other industries as well.

3. Descriptive research study could be conducted to study how petrochemical companies currently select technology. An in-depth survey and/or case study analysis of petrochemical companies can be performed to obtain an insight of how companies currently perform their selection activities and use the acquired information to provide recommendations on how to improve the model.
4. The proposed model can be applied to a specific company, and the results can be measured to determine the predictive validity of the model. For implementation purposes, impact relationships among the systems and decision factors are recommended to be kept constant. Information about organization needs can be obtained from company executives while impact relationships between the systems' level and the organization needs can be obtained from the related functional managers. Finally, the relationships among the alternatives and the decision factors can be obtained from the technical personnel in the company.
5. The evidence of how the model can help improve company performance is very critical for the success of model implementation. Further studies can be conducted to determine the correlation, if any, between the use of the proposed model and company performance.

Appendix 1: Definition of Systems

The project selection process is defined by the systems. Multiple perspective approach is used [1, 19–21]. There are 5 systems in which the company is operating. Each system represents several critical issues that affect the project selection process. The systems and the critical issues are listed below:

1. *Strategic System* represents the issues related to the company's strategic direction, its culture, and long-term company's commitments.
2. *Technical System* represents the issues related to the technical aspects of the technology in the company and those under consideration.
3. *Internal System* represents the issues related to *the readiness of the company to implement the project*. They are internal operational characteristic of the company including the company's resources, feasibility of the project (excluding technical aspects), allocation plan, people, and scheduling.
4. *Competitive System* represents all the external factors that have impacts on the competition in the market including market conditions, competition, competitor (s), and the benefits and costs of entering the market.
5. *External System* represents the issues related to general economic trends, the government and its policy including regulations, trade agreements, and political conditions (Fig. 8.2).

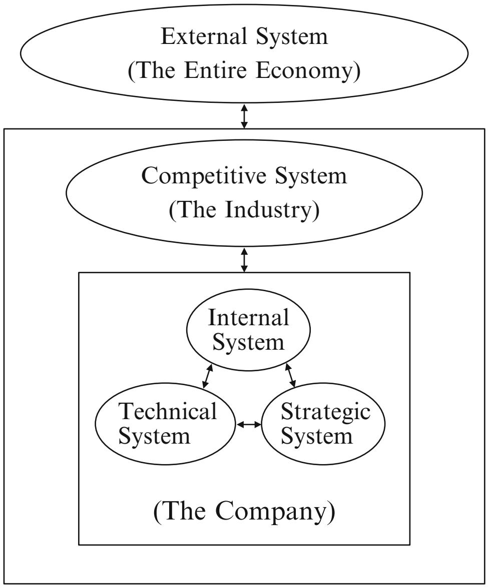

Fig. 8.2 Technology selection system

Appendix 2: Definition of Factors

Definition of Factors

The system is desegregated into the next lower hierarchy, factors. It is done to facilitate the decision-makers, to provide subjective judgment in the alternatives evaluation process. The decision space between system and alternative are divided by factors. Pairwise comparisons will be used to obtain the impacts between system and factor and also between alternative and factor. When the measurements are combined the impact relationship between alternative level and the system level are determined. The factors are produced by identifying all the important performance criteria affecting the company from the literature and in consultation with the Expert Panel. The following factors are the preliminary list that is obtained from the literature; they are used as the evaluation criteria for the alternatives.

Strategic System [22–24]

Factor-1:. *Company's technology competence* includes the issues related to technological strength of the company to do what is needed.

Factor-2:. *Current strategic issues of the Company* includes the strategic issues that are important to the company and can be linked to the project selection process. It also includes the issues related to organizations and business enterprise with whom the company work, and with whom it has to compete (including alliance, competitor, and supplier).

Factor-3:. *Potential for expansion* is the issue related to the opportunity to expand the products' capacity, and the opportunity to vertically integrate the supply or product chain.

Factor-4:. *Company's reputation* is the opinion or image of the company as viewed by local community and public as a whole.

Factor-5:. *Synergy with the current operations* is the issue related to the additional strategic benefit that can be obtained from implementing the project along with the company current operations.

Technical System [25–27]

Factor-6:. *The current life-cycle stage of the technologies and successor technology* represents the current stage of technology and the opportunity to enhance the current technology both for products and process.

Factor-7:. *Probability of technical success* is the likelihood that the technology will be able to meet the company's expectations. The issue covers every step from evaluating, acquiring, and implementing technology.

Factor-8:. *Technology merits* represents the issues related to the technical merits or production synergy that can be obtained from implementing the project along with the current process/technology

Factor-9:. *Work place environment and safety* represent the environmental and safety issues in the work place.

Internal System [28, 29]

Factor-10:. *Resource compatibility* concerns two main issues, which are the availability of the resources and ability to match them with the project requirements. It includes resource procurement and risk (ex. currency fluctuation), preparation, and allocation of both financial and human resources (skilled labor, research personnel, technical, legal, and commercial expert) in order to implement and operate the project (Adsorption and Internalization capability).

Factor-11:. *Site Infrastructure* includes the issues related to transportation of products and raw materials, location, and infrastructure of the production site and facilities.

Factor-12:. *Alternative uses of scientific personnel and facilities when the project is terminated.*

Factor-13:. *Impacts of the project delay and ability to make correction* are the likelihood that project will be delayed and the impact to the company from the delay of the project and the ability to resolve the problem.

Factor-14:. *Financial risk* is the issue related to financial risk from deciding to implement projects.

Competitive System [23, 24, 27]

Factor-15:. *The competitiveness of the company* represents how well the company can compete in the industry and the likelihood that the company's product will be able to succeed in the market place.

Factor-16:. *Cost and benefit of implementing each alternative include* the issue related to the worthiness of the project, which include the cost of the alternative and the direct and indirect benefits that company will receive after selecting and implementing that project. Cost/Benefit ratio can be used to reflect the efficiency of the resource allocation process.

Factor-17:. *Ease of market entry* is the degree of difficulty for the company's product to establish itself in the market.

Factor-18:. *Potential benefit from the market expansion* is the future benefits that could be acquired from the prospective of the market and expansion of the customer base.

External System [30]

Factor-19:. *Ability to meet the current and potential future regulations* represents the concerns and the capability to meet current and future regulation. The issue includes the ability to meet disposability/recyclability standard.

Factor-20:. *The impact on environment* includes the impacts of the project and the overall community for example noise, pollutants issues etc.

Factor-21:. *Government policies and legal framework* are all policies related to the project in particular, company, and the whole petrochemical industry in general. It also includes the incentive plans that are proposed or likely to be proposed by the government to encourage investment. Moreover, it includes the issues related to the adequacy of the legal framework for protection of intellectual property.

Factor-22:. *Political and economical situation of the country* includes the issues related to political and economical conditions of the local market.

Factor-23:. *Global Trends* include the issues related to the general trend of the industry worldwide.

Appendix 3: Model Results

The figure below represents the decision structure. The shadow boxes with thick borders represent perceived critical elements for the technology evaluation process by the expert panel.

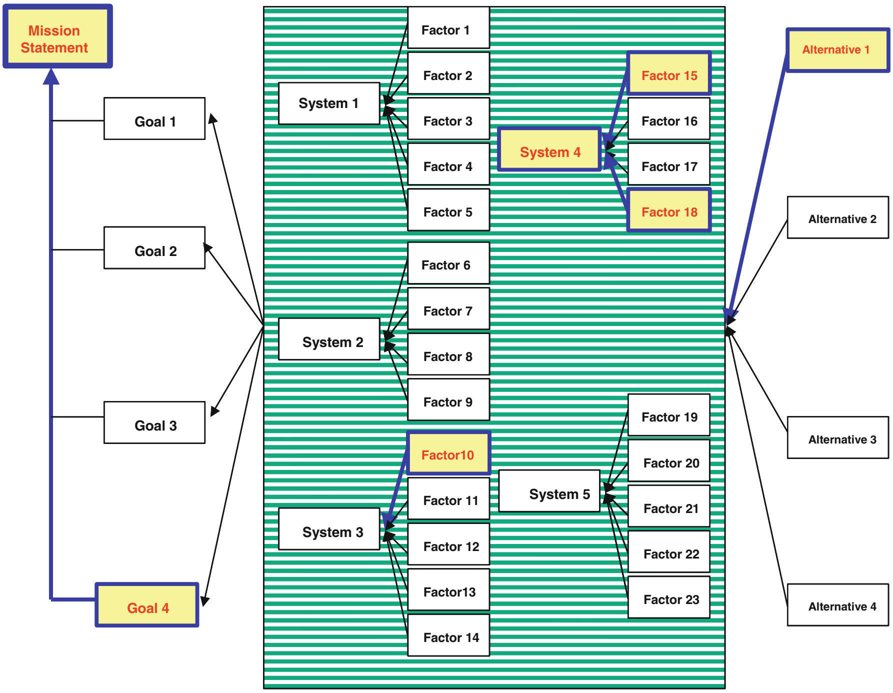

Table 8.1 Relative contribution of the "Goals" to the "Mission Statement"

G1 contribution to Mission Statement:	**34.0**
G2 contribution to Mission Statement:	**12 .0**
G3 contribution to Mission Statement:	**12.0**
G4 contribution to Mission Statement:	**42.0**
Total:	**100.0**

Table 8.2 Results: relative contributions of the "Systems" to the "Mission Statement"

S1 contribution to Mission Statement:	**15.3**
S2 contribution to Mission Statement:	**14.3**
S3 contribution to Mission Statement:	**23.5**
S4 contribution to Mission Statement:	**32.4**
S5 contribution to Mission Statement:	**14.5**
Total:	100.0

Table 8.3 Results: relative contributions of the "Factors" to the "Mission Statement"

F1 contribution to Mission Statement: **2.4**
F2 contribution to Mission Statement: **3.4**
F3 contribution to Mission Statement: **3.1**
F4 contribution to Mission Statement: **2.4**
F5 contribution to Mission Statement: **4.0**
F6 contribution to Mission Statement: **2.9**
F7 contribution to Mission Statement: **5.0**
F8 contribution to Mission Statement: **5.0**
F9 contribution to Mission Statement: **1.4**
F10 contribution to Mission Statement: **10.8**
F11 contribution to Mission Statement: **5.9**
F12 contribution to Mission Statement: **0.7**
F13 contribution to Mission Statement: **3.1**
F14 contribution to Mission Statement: **3.1**
F15 contribution to Mission Statement: **11.3**
F16 contribution to Mission Statement: **3.2**
F17 contribution to Mission Statement: **7.8**
F18 contribution to Mission Statement: **10.0**
F19 contribution to Mission Statement: **1.3**
F20 contribution to Mission Statement: **1.6**
F21 contribution to Mission Statement: **5.5**
F22 contribution to Mission Statement: **4.5**
F23 contribution to Mission Statement: **1.6**
Total**: 100.0**

Table 8.4 Results: relative contributions of the "Alternatives" to the "Mission Statement"

A1 contribution to Mission Statement: **33.5**
A2 contribution to Mission Statement: **20.3**
A3 contribution to Mission Statement: **25.4**
A4 contribution to Mission Statement: **20.7**
Total: 99.9 (99.9 instead of 100.0 because of round-offs)

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Part III
National Technology Planning

Chapter 9
National Technology Planning: A Case Study on the Biopharmaceutical Industry in China

Leong Chan, Tugrul U. Daim, and Dundar F. Kocaoglu

Abstract In this research, a technology policy choice framework is developed to link prospective high-tech areas, technology development strategies, and various innovative resources. The research approach is to develop a Hierarchical Decision Model. Experts are invited from diverse sources to provide a balanced perspective representing different stakeholders. This research focuses on the fast developing Chinese biopharmaceutical industry as a case study. The results of this research have identified thirteen biotech areas, four strategies, and eight types of innovation resources to achieve industrial competitiveness in the biopharmaceutical industry. The research outcomes serve as guidelines in resource allocation and policy making for technology development.

9.1 Introduction

Innovations in science and technology (S&T) constitute the core of national competitiveness [1]. Nations across the world invest heavily on high technology innovations, but they are facing different challenges due to diversiform developmental contexts. For Western developed countries, they need to maintain their technological competitiveness and sustain their innovative leadership [2, 3]. For emerging countries, they aim to improve technological competitiveness through catching up and leapfrogging [4, 5]. Strategic innovation policy for effective technology development becomes key issue for all countries. The fundamental and common problem is how nations achieve and sustain S&T competitiveness.

With the growing trend of globalization and rapid development of high technologies, emerging countries face more challenges because they are chasing a fast-moving technological frontier. They need to identify global technology trends and adapt them according to local needs and capabilities. Even though technology

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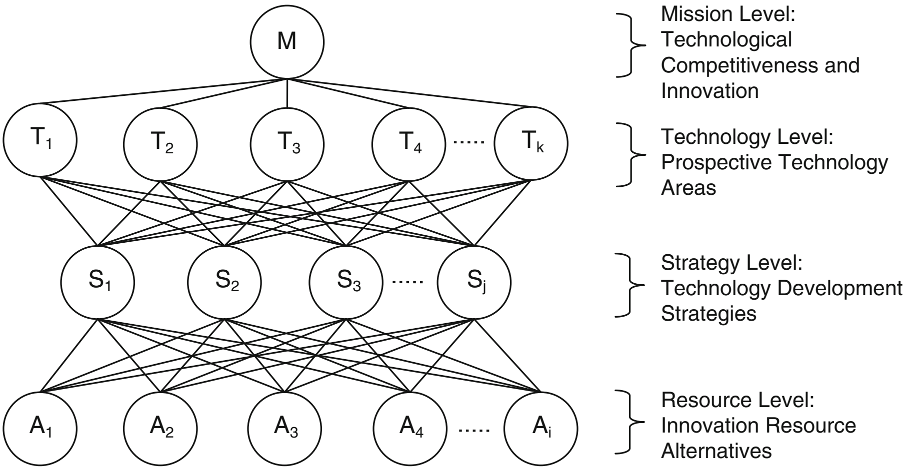
programs such as foresight studies generally provide broad pictures about the future, implementation of various high technologies remains a common challenge. The development of high-tech industries suggests that it is necessary but difficult to find balance between local and global, internal and external innovation. How much an industry can benefit from external alliances largely depends on the effectiveness and efficiency of the national innovation system [6]. Emerging countries may rely more on learning advanced technologies from advanced countries, but they face the "make or buy" dilemma in technology development. International technology transfer can be a major channel to obtain state-of-the-art technologies from advanced countries. However, it is also a high-risk process since there is no guarantee that technology transfer would result in future innovation for the host country. A more comprehensive technology development framework at strategic level becomes necessary in the present environment of global competition.

9.2 Research Methodology

With research questions on mind, this research utilizes an analytical approach to create a model for exploring effective technology implementation mechanisms to align with national innovation objectives. Experts are invited to provide judgmental data in determining the relative relationships among the decision elements at various levels of the model. The methodology to be utilized is an Analytic Delphi study where experts assess the criteria related to technology, strategy, and innovation resources. The initial research includes face-to-face consultation of experts to identify critical issues and define the criteria. Subsequent pair-wise comparison instruments are developed based on the results provided by the experts in the interviews. The Analytic Hierarchy Process (AHP) is followed to quantify experts' judgmental data on the issues.

The analytic hierarchical process (AHP) provides a systematic approach to develop priorities for alternatives based on the experts' judgments. A hierarchy or network structure will be constructed to represent a decision problem. AHP utilizes pairwise comparisons to give priorities for the alternatives or criteria based on the experts' opinions. The appropriate alternatives are selected based on the quantitative solution to these rankings. AHP has been proved an effective quantitative decision-support method to deal with complex multi-attribute decisions. For instance, Gerdsri (2009) used AHP and expert judgment quantifications to develop national R&D strategies for agricultural nanotechnology in Thailand [7]. The method has been widely applied in areas of management, policy-making, and conflict resolution. It can be utilized for structuring, measurement, and synthesis of factors or elements that affect decision-making [8].

A hierarchical research framework is developed based on pair-wise comparisons to quantify expert decisions. It takes into consideration of several factors in the research process, including appropriate technologies, implementation strategies, and allocation of innovation resources according to desirability for long-term benefit. Through a series of judgmental quantification from the experts, the prioritized value for each innovation resources can be calculated, which represents its



M: Mission – Technological Competitiveness and Innovation
Tk: Prospective Technology Areas (k) k = 1, 2, 3 … K
Sj: Technology Development Strategies (j) j = 1, 2, 3 … J
Ai: Innovation Resource Alternatives (i) i = 1, 2, 3 … I

Fig. 9.1 Generalized framework for technological competitiveness and innovation

desirability corresponding to the improvement of innovation capacity. The results can thus indicate better investment targets to be made in the industry for selected high technology fields (Fig. 9.1).

The structure of the model can be used to develop implementation strategies for appropriate technologies for a host country. The HDM has four levels including Mission level, Technology level, Strategy level, and Resource level.

9.3 Case Background

China has been developing fast in terms of economic and social achievements, with a lot of visible improvements but also many underlying weaknesses in technology management. The Chinese innovation system is still at an early stage and its development is always determined by the macro environment. In order to achieve national competitiveness in S&T, the country needs to improve its innovative capacity. One of the most determinative factors is its strength of sustained innovation in a globalized environment. Core objective of the country is to locate its right position in the global innovation networks, and to construct an innovation infrastructure that can serve as the driving force for future development. Appropriate technology policy measures can integrate domestic innovation efforts along with foreign innovation resources. Such measures may help the country to catch up with the developed world or even leap ahead into the global innovation frontier. The article develops a research model to help achieving this objective. The research results may also be helpful to other emerging countries to achieve innovation objectives and promote national competitiveness.

The Chinese pharmaceutical market is highly fragmented and very different from the market in developed countries. In 2010, generic drugs have about 76 % of the entire pharmaceutical market in China, while only 4 % of the market comprises innovative drugs still under patent protection. The remaining 20 % of the market consists of off-patent drugs [9]. The generic drugs market has the largest segment and mostly been controlled by domestic products. However, the profit margin is low due to intense competition. The innovative drug market has the smallest segment and is dominated by imported products, particularly those produced by MNCs. For the off-patent drug segment, both imported and domestically produced branded drugs compete to survive.

The Chinese biopharmaceutical sector has been developing fast in recent years. Although the overall innovation capability of domestic players is not very strong, research in some specialty areas has already caught up with the level of leading countries. Since this is still a new area with good prospect, many conventional pharmaceutical companies are trying to get into the industry. There has been a paradigm shift in industrial R&D from high-risk synthetic pharmaceuticals towards R&D in biopharmaceuticals. In summary, it is generally accepted that the Chinese pharmaceutical industry needs to catch up with global standard, especially in high tech areas.

9.4 Model Development

This section will focus on crafting the model and applying it to the emerging Chinese biopharmaceutical sector. Decision criteria in each level of the hierarchical model are analyzed and customized according to the conditions in China's biopharmaceutical sector. This provides a foundation for further validation by experts. The model will be finalized based on the feedback from expert panel.

9.4.1 Mission Level

The top level mission has been defined as "Technological Competitiveness and Innovation"[5]. This mission is applicable to the fast developing biopharmaceutical industry in China [10, 11]. Due to historical reasons, technology level of the Chinese biopharmaceutical sector remains less competitive globally, and it still faces challenges including weak innovative capacity and lack of R&D investment. Due to high investment risk and long development cycle, the biopharmaceutical sector relies heavily on regulations and supports from governments. Strengthening technological competitiveness and building up innovative capabilities are primary concerns of industry as well as policy makers.

9.4.2 Technology Level: Prospective Technology Areas

The rationale of technology level of the model is to identify global technology trends and adapt to local capabilities and needs. Choosing the right technology areas and guiding investment are major topics in technology policy. While it is unrealistic for the Chinese biopharmaceutical industry to excel in all high technology areas, it is more realistic to focus on key areas that the country has potential capabilities to achieve competitive advantages. From the perspective of industrializing countries, appropriate technology can offer windows of opportunity to catch up with leading countries. In other words, China should look into the global technology frontiers and seize the opportunities for catching up.

To represent the global technology trends and emerging areas in the model, this research will incorporate the findings from technology forecasting reports published by international organizations such as the United Nations (UN) and Organization for Economic Co-operation and Development (OECD). UN has published the research results of Top Ten Biotechnologies for Improving Health in Developing Countries [12]. More recently in 2009, OECD published the forecasting report "Human Health Biotechnologies to 2015", which is based on the conditions of its member countries [13, 14].

The available research indicated that different countries have different needs for technologies due to various developmental conditions [15]. As an emerging nation, which walks in between the developed and developing cohort, China needs to identify prospective technology areas based on its needs and capabilities. The following model criteria and definitions were developed based on the reports from OECD and UN [12–14], and have been consulted with experts.

Recombinant therapeutic proteins—therapeutic proteins are used to treat many non-communicable diseases. These technologies provide affordable and sustainable sources for treatment of chronic disease [12–14].

Recombinant vaccines against infectious diseases—vaccines produced using recombinant DNA technology. The products can be used to effectively treat infectious diseases [12–14].

Monoclonal antibody technology—Monoclonal antibodies (mAb) can be used for therapeutic treatment and diagnostic tests. Many therapies are undergoing clinical trials. Most are concerned with immunological and oncology targets [13, 14].

Tissue engineering technologies—These technologies involve techniques that replace or act directly on cells and tissues in the body. The treatment repairs damaged tissues from injuries and diseases [13, 14].

Stem cell therapy—This type of treatment leads to the production of entire organs. These technologies include the use of stem cells as a therapeutic or to repair specific tissues or to grow organs [13, 14].

Gene therapy—This technology involves the treatment of a disease by introducing a new gene into a cell. It either uses or acts directly on nucleic acids, which are the molecules that serve as the building blocks for DNA and RNA [13, 14].

Antisense therapy—Antisense drugs are being researched to treat a wide range of diseases such as cardiovascular diseases, asthma, and arthritis. There are currently more than 30 antisense therapies in clinical trials [13, 14].

RNAi (ribonucleic acid interference)—This includes all entries for products which act therapeutically via an RNA interference mechanism. There has been a great deal of research activities in this new area. Most proposed clinical uses are aimed at treating infections [13, 14].

Nanobiotechnology for efficient drug and vaccine delivery—This type of technology aims for improved drug delivery systems from the convergence between biotechnology and nanotechnology [13, 14].

Bioinformatics to identify drug targets and to examine pathogen–host interactions—These technologies cover the manipulation and analysis of large datasets of genetic and health information [12–14].

Pharmacogenetics—This technology identifies inherited differences (variation) between individuals in drug metabolism and response. It can be applied in clinical trials and in prescribing practice [13, 14].

Gene sequencing—Sequencing of pathogen genomes provides ways to identify new antimicrobials. These technologies can accelerate the process of drug discovery and the fight against infectious diseases [12–14].

Biotechnology diagnostics—This technology includes both in vitro diagnostics and in vivo diagnostics. Modified molecular technologies provide affordable and simple diagnosis of infectious diseases [12–14].

9.4.3 Strategy Level: Technology Development Strategies

The Strategy Level defines how technologies should be developed and implemented. As an industrializing country, China faces the decisions of “Make” or “Buy”, or somewhere in between [16]. According to the findings from the literature review section, the following strategies are defined to describe the situation:

Indigenous Innovation—This strategy relies on the host country’s local technology base and available innovation resources to build up indigenous competence [17–19].

Imitative Innovation—It is also known as re-innovation in literature, both of which are based on imitation, adaptation, and improvement of the original innovators’ technology [17, 20, 21].

Collaborative Innovation—This strategy means the participants cooperates and develops new ideas altogether. Competitors may share resources and work together toward innovation [17, 22].

International Technology Transfer—This includes technology import and acquisitions. This is a fast track to save valuable time and resources during the catching-up process [23–26].

9.4.4 Resource Level: Innovation Resource Alternatives

Under the condition of a transitional economy, China's National Innovation system carries some characteristics from both market economy and centrally planned system. Here we need to identify the key contributors toward technology development and innovation in the Chinese biopharmaceutical sector. Subsidies and favorable policy measures should be designed and prioritized to strengthen the performance of effective innovators. The following innovation resources have been identified by literature review.

State-Owned Enterprises (SOEs)—SOEs are medium- to large-sized companies left by the centrally planned system. These companies constitute the main production capacity of the Chinese pharmaceutical industry, but most of them are specialized in low-tech generics drugs. Compared with foreign counterparts, domestic pharmaceutical companies are weaker in terms of technology level and research capabilities [16, 27–29].

High-tech Small-to-Medium Enterprises (SMEs)—These smaller companies have emerged since the 1980s, when government started to allow private ownership of companies. Many small dedicated biotechnology firms (DBFs) belong to this category. They probe into potential technology areas with the purpose to obtain leadership status in some niche sub-sectors [27, 30, 28].

Multinational Company and subsidiaries (MNCs)—Currently, many top MNCs have established subsidiaries in China. These large American and European pharmaceutical companies have dominant innovative capability in most technological areas. They act as technology leaders in both production and R&D activities in the Chinese pharmaceutical sector [11, 30, 31].

Contract Research Organizations (CROs) and Contract Manufacture Organizations (CMOs)—These organizations provide services for both foreign and domestic companies. Through learning-by-doing from leading innovators, CROs and CMOs have shown increasing capabilities in developing advanced technologies and manufacturing practice aligning to international standards [32, 30, 33].

University Research Programs (URPs)—Some top research universities are emerging forces in pharmaceutical innovation, and they have been producing more publications and patents in recent years. Not only these research universities innovate through laboratories, but also they cultivate young talents for the domestic pharmaceutical industry [28, 30].

Equity Joint Ventures (EJVs)—This is a common way for foreign companies to enter the Chinese biopharmaceutical sector, especially during the 1990s. Two or more investors share the ownership and control over the equity, property (including IP), and operation [30, 34, 29].

Public Research Institutes (PRIs)—PRIs and national R&D laboratories are owned and managed by government departments. These organizations carry out research projects according to government instructions [28, 30].

Foreign R&D Centers (FR&D)—In recent years, some foreign invested R&D centers have been established in China. The biopharmaceutical sector is one of the target areas. This also happens in India in the recent years. Foreign R&D Centers are capable to carry out comprehensive researches to develop new medicines at the innovation frontiers [32, 35].

9.4.5 *The Finalized Research Model*

After the decision criteria for each level of the hierarchy were prepared by the researcher, the model was sent to related experts for validation. The researcher also provided background information about the research along with the model. During the validation process, each level was tested for criteria's preferential independence. The experts were asked to comment about the model construct and they were allowed to add and/or remove criteria as appropriate. After several iterations, the results were finalized when a consensus had been reached. It should be acknowledged that the experts' feedbacks were very encouraging and informative. the finalized research model is illustrated in Fig. 9.2. Modifications of criteria were incorporated according to feedback. In summary, there are four levels as described above, and the complete sets of criteria associated with each level are listed below:

9.5 Discussion

Chan et al. [36] present the results of the study which quantified the model presented in Fig. 9.2.

The findings from data analysis were summarized in Table 9.1.

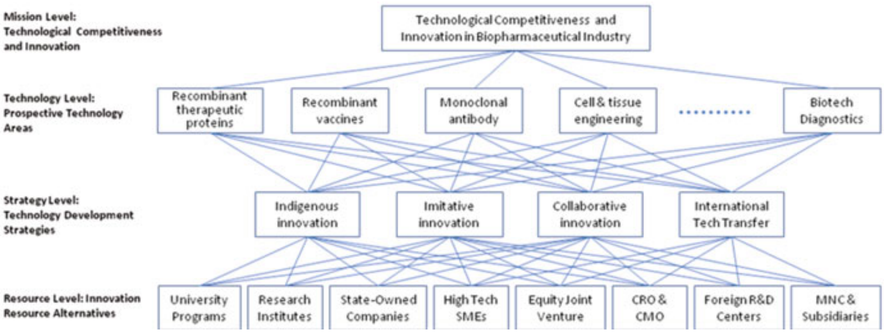


Fig. 9.2 The finalized research model

Table 9.1 Summary of findings

Category	Prospective technology areas	Preferred technology development strategies	Preferred innovation resource alternatives (top 3)
High >10 %	T1: Recombinant therapeutic proteins	S2: Imitative Innovation	1. High-tech Small-to-Medium Enterprises
			2. University Research Programs
			3. Public Research Institutes
	T2: Recombinant vaccines	S1: Indigenous Innovation	1. MNCs and Subsidiaries
			2. High-tech Small-to-Medium Enterprises
			3. Foreign R&D Centers
	T3: Monoclonal antibody technology	S2: Imitative Innovation	1. High-tech Small-to-Medium Enterprises
			2. University Research Programs
			3. Public Research Institutes
Medium (6–10 %)	T4: Cell and tissue engineering	S2: Imitative Innovation	1. High-tech Small-to-Medium Enterprises
			2. University Research Programs
			3. Public Research Institutes
	T5: Gene therapy	S2: Imitative Innovation	1. High-tech Small-to-Medium Enterprises
			2. University Research Programs
			3. Public Research Institutes
	T8: Nanobiotechnology	S2: Imitative Innovation	1. High-tech Small-to-Medium Enterprises
			2. University Research Programs
			3. Public Research Institutes
	T10: Bioinformatics	S1: Indigenous Innovation	1. MNCs and Subsidiaries
			2. High-tech Small-to-Medium Enterprises
			3. Foreign R&D Centers
	T11: Pharmacogenetics	S2: Imitative Innovation	1. High-tech Small-to-Medium Enterprises
			2. University Research Programs
			3. Public Research Institutes
	T12: Gene sequencing	S2: Imitative Innovation	1. High-tech Small-to-Medium Enterprises
			2. University Research Programs
			3. Public Research Institutes
	T_{13}: Biotechnology Diagnostics	S2: Imitative Innovation	1. High-tech Small-to-Medium Enterprises
			2. University Research Programs
			3. Public Research Institutes

(continued)

Table 9.1 (continued)

Category	Prospective technology areas	Preferred technology development strategies	Preferred innovation resource alternatives (top 3)
Low (1–5 %)	T6: Antisense therapy	S2: Imitative Innovation	1. High-tech Small-to-Medium Enterprises
			2. University Research Programs
			3. Public Research Institutes
	T7: RNAi	S2: Imitative Innovation	1. High-tech Small-to-Medium Enterprises
			2. University Research Programs
			3. Public Research Institutes
	T9: Synthetic biology	S2: Imitative Innovation	1. High-tech Small-to-Medium Enterprises
			2. University Research Programs
			3. Public Research Institutes

9.5.1 *Prospective Technology Areas*

With a mission of achieving technological competitiveness and sustained innovation, the model examined a number of prospective technology areas in the biopharmaceutical industry. Although the experts come from different backgrounds, they have reached a high level of agreement in their judgment. The results can be classified under the three categories.

Category "High" is defined where the contribution is larger than 10 %. These are the technology areas that China should give the highest priorities for research and development. The recommended areas include T1 Recombinant Therapeutic Proteins, T2 Recombinant Vaccines, and T3 Monoclonal Antibody Technology. Category "Medium" is defined where the contribution ranges from 6 % to 10 %. These technology areas are recommended as medium priorities for China to carry out research and development. This list consists of seven technology areas including T4 Cell and tissue engineering, T5 Gene therapy, T8 Nanobiotechnology, T10 Bioinformatics, T11 Pharmacogenetics, T12 Gene sequencing, and T13 Biotechnology Diagnostics. Category "Low" is defined where the contribution equals to or less than 5 %. These technology areas are regarded as having lower priorities for China. This list consists of three technology areas including T6 Antisense therapy, T7 RNAi, and T9 Synthetic biology.

The research results of technology level highlighted the directions for investment and improvement. For most of the above discussed high-tech areas, the USA is the dominant leader worldwide. China and some major European countries belong to the second tier in these areas. As a latecomer country in the biopharmaceutical industry, China's innovation capabilities have been steadily growing since the mid 1990s. However, China's technology level is still lagging behind the world's leading standard, and the country needs to take a learning position as discussed in the above analyses. In order to accelerate the catching-up process, the government's role of long-term investment in these identified areas cannot be overemphasized.

9.5.2 Imitative Innovation

Accumulation of technological capacities to compete in the global market has become a major concern for China. The research brings to light that imitative innovation is still the best option to achieve such a purpose under the current conditions. The experts' judgments gave high priority to imitative innovation (33 %) in the development of biopharmaceutical technologies. This conforms to the fact that technology leaders in high-tech areas are mostly foreign enterprises, which mainly belong to the USA and Western Europe. If the latecomers want to catch up with the technological frontiers, their strategies are likely to start from imitation. This has been the case for many of East Asian economies—for Japan first, then for Taiwan, Korea, and Singapore—and now for China [37]. The results of this research indicate that China's biopharmaceutical industry is at the stage of learning from advanced countries.

When discussing about imitative innovation in the biopharmaceutical industry, biosimilars are topics that cannot be circumvented. Novel biologics are noted for high cost to produce and expansive prices to purchase. Biosimilars bring clear potential for payers in the emerging pharmaceutical or "pharmerging" markets, such as Brazil, India, and China [38]. Developing biosimilar products is also a relatively low-risk strategy for newcomers entering the health biotech space and generating short-term revenues [39]. Of the approximate 150 approved originator biologic drugs on the market today, almost half of them have lost or are close to losing their patent protection. This provides an external condition for cheaper biosimilar products to enter the market and be available for consumers. However, under the current registration regime, biosimilar drugs and new biologic drugs are not treated with any differences in China. Both applications require the same process for clinical trials. Although the USA does not currently have related regulations, India and the European Union have developed abbreviated approval process for biosimilar products [38]. China should consider adopting similar approaches to remove or lower the legislative hurdles for the development of biosimilars.

9.5.3 Supportive Innovation Resources

This case application provides the Chinese biopharmaceutical industry a performance report of various innovators with regard to their contribution toward global strategies and technology objectives. This will assist policy makers to determine which infrastructure items require improvement or investment. Based on the feedback from result validation, the research suggests improving the conditions and environment for innovation. The result analyses indicated that High-tech SMEs are the most important contributors for China's biopharmaceutical industry in the current development stage. The second group of important contributors is considered to be the MNCs and subsidiaries. The Foreign R&D Centers and University Research Programs tie for the third place toward mission. These important innovation resources are discussed in this section.

9.5.3.1 High-tech SMEs

Owing to the narrowed gaps of competitive advantages in recent years, many emerging biotech SMEs have entered the race for technology development. These companies have certain advantages over large established enterprises, including greater flexibility, better efficiency, less bureaucracy, and profit-seeking behaviors which allow them to succeed in the fast-changing markets. Many biotech SMEs in the Chinese biopharmaceutical sector shared similar advantages and traits. For example, they are more successful in some specialized high-tech areas, and most of them are very eager or active in collaborative innovations with other players. This is mainly due to the reality that SMEs are usually not strong as standalone innovators. They need to search for complementary resources to cover their deficiencies in certain aspects.

9.5.3.2 Multinational Companies and Subsidiaries

MNCs' technological strength, institutional heritage, and their global coverage generated specific advantages for their operations in the Chinese biopharmaceutical sector. MNCs are in a better competing position because they are better endowed with both R&D capacities and funding capital. Chiesa and Chiaroni (2005) found that the presence of foreign pharmaceutical firms can make a number of important contributions to the success of the industrial networks of the host country. For example, these firms have better expertise in developing and protecting intellectual property with high commercial potential, they have well-established marketing and distribution channels, and they are experienced in both shaping and working within strict regulatory guidelines [40]. Domestic players in the host country may benefit from technology spillover through MNCs' demonstration effects, labor turnover, and overall industrial structure upgrading (both upstream and downstream) [41, 42]. These are essential factors to build up a better innovation ecosystem for the biopharmaceutical industry in China.

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Chapter 10
National Technology Planning: A Case Study of Nanotechnology for Thailand's Agriculture Industry

Pisek Gerdsri

Abstract This research develops a systematic approach for policy makers to strategically define the national technology policy for emerging technologies. In this approach, a hierarchical decision model is built and qualified expert opinions are used as measurements. There are four levels in the hierarchy: mission, objectives, technological goals, and research strategies. Three panels are formed based on their background and expertise in order to minimize and balance any possible biases among the members. The objectives, technological goals, and research strategies are evaluated and prioritized, according to their contribution to the country's mission, by quantifying the experts' judgments. This research also demonstrates several approaches for the validation of results. Inconsistency measure, intraclass correlation coefficient, and statistical test for the reliability of the experts and group agreement are used for that purpose. Finally, HDM sensitivity analysis is brought in to study the robustness of the rankings, especially at the technology level that may be caused by potential changes in the national strategic direction.

10.1 Introduction

Effective national technology planning is becoming a success factor for increasing national competitiveness not only in developed but also in developing economies [1, 2]. As global competition increases, governments worldwide are playing an increasing role in supporting technology research and development in their countries [1, 3]. When an emerging technology is being considered, the government's role is even more interventional—from supporting to nurturing and guiding [1]. But the technologies that the government should support and the technology policies and strategies that it should plan are still unclear.

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National technology policy and strategy has to be defined in a way that maximizes the contributions of technologies to national objectives. This requires a systematic approach for assessing and evaluating technologies to help national policy makers set the appropriate direction for technology policy and strategy.

10.2 Literature Review

The literature review was conducted in four stages. The purpose of each stage is described below.

- To understand the management of emerging technologies at the national level, forecasting and assessment of an emerging technology are emphasized.
- To study the importance of managing a technology nationally and how a country develops its technology policy and strategy, various approaches and methodologies are reviewed, i.e., technology capabilities, technology foresight, technology development envelope (TDE), analytic hierarchy process (AHP), and technology roadmapping.
- To review the process and approach applied for national technology planning, a case study of Thailand is presented.
- To summarize the literature and identify the gaps.

Table 10.1 shows the summary of existing literature and gap.

Technological capability research, by itself, does not satisfy the need because it has not established the link between developing technological capability and technology strategy and policy, especially for emerging technologies. It can be considered as a way to self-assess the capability in adopting, using, learning, and adapting to new technologies at the corporate or national level.

Even though foresight exercises have been practiced broadly, there are several concerns from practitioners in their implementation. Technology foresight still has difficulties in linking technology foresight and technology planning. Technology foresight becomes a less effective approach unless a better method to close the gap is developed.

Technology roadmapping is a planning process which helps decision makers align technology with organizational goals. Specific methodologies and steps in building a strategic roadmap such as TDE have been developed [27, 28]. Even though technology roadmapping has been applied at different levels of decision making, very little attempt has been made to establish guidelines for national science and technology roadmapping [32–34].

The commitment of technology development agency in Thailand in supporting the national economic development plan is described in references [29–31]. However, Thailand is still struggling with finding a way to efficiently manage resources and to develop a plan for national technology policy.

It is concluded in the literature review that the matter of nationally managing emerging technologies is a critical issue, but a systematic way to evaluate them is

Table 10.1 Summary of existing literature and gap

Topic	Emphasis in existing literature	Gaps
National science and technology policy [1, 4–9]	The significance of effective technology management to support competitiveness and innovation	Lack of a systematic approach for helping to manage and prepare for the future development of emerging technologies by linking the broad mission of the country to technology policy and strategy planning [10–12].
Methodologies for technology policy and strategy planning	*Technological capability* [13–16] Assessment of the capability in adopting, using, learning, and adapting new technologies in the organization	
	Technology foresight [17–21] Difficulty in transferring foresight results into implementation plans	
	Technology roadmapping [22–26] Aligning technology with organization goals from top mission to resource planning	
	Technology development envelope (TDE) [27, 28] • Systematic approach for building a corporate roadmap of emerging technologies • Being able to assess and evaluate emerging technology based on the company's objective	
Technology policy and strategy planning in Thailand [29–31]	Establishment of broad missions and national clusters	
	Raising awareness of the needs for technology development agencies to support the national plan	
	Technology policy development process is still at learning stage	

not yet in place. Techniques for forecasting emerging technologies have been widely practiced in various organizations but methods to strategically evaluate the impacts of an emerging technology and its research strategy from the national viewpoint need to be developed.

10.3 Research Objective, Goals, and Questions

The objective of this research is to develop a systematic approach for evaluating emerging technologies and planning for R&D strategies in support of them.

Table 10.2 Research goals and research questions

Research goals	Research questions
RG1: Assess and evaluate the high-level policy in developing an industry	RQ1: What is a country's mission in developing an industry? RQ2: What are the objectives to fulfill the mission? RQ3: What is the relative priority of each objective with respect to the mission?
RG2: Assess and evaluate the impact of emerging technologies benefitting to the industry	RQ4: What are the goals for developing emerging technologies in supporting the objectives? RQ5: What are the contributions of the technological goals with respect to the objective?
RG3: Assess and evaluate R&D strategies to fulfill the technological goals	RQ6: What are the R&D strategies in fulfilling each technological goal? RQ7: What are the contributions of each R&D strategy in fulfilling the goal?

To fulfill the research objective, three research goals have to be satisfied. For each goal, one or more research questions need to be answered. The research goals and questions are summarized in Table 10.2.

10.4 Research Methodology

10.4.1 AHP

AHP is a decision support tool for complex decision problems. The underlying principle of AHP is decomposing problems into hierarchies. Then, decision makers quantify their judgments through pairwise comparisons. A decision maker can incorporate quantitative and qualitative judgments into pairwise comparison and provide numerical values for the priorities [35]. AHP has been developed in such a way that decision makers can organize feelings, intuition, and logical thinking in the decision-making process [36].

AHP is the selected methodology in this research since decision makers can cope with multi-objective, multi-criterion, and multifactor decisions [37] in selecting which national strategies of which technologies the country should pursue. Furthermore, AHP can improve collective thinking, reasoning, and efficiency of group decision making [38].

In AHP process, a hierarchical decision model is built. The hierarchical decision model is used for quantifying expert judgments such as the relative priority of objectives, the relative impact of technological goals, and the relative importance of the research strategies. The generic model representing relationships among mission, objectives, technological goals, and research strategies is shown in Fig. 10.1.

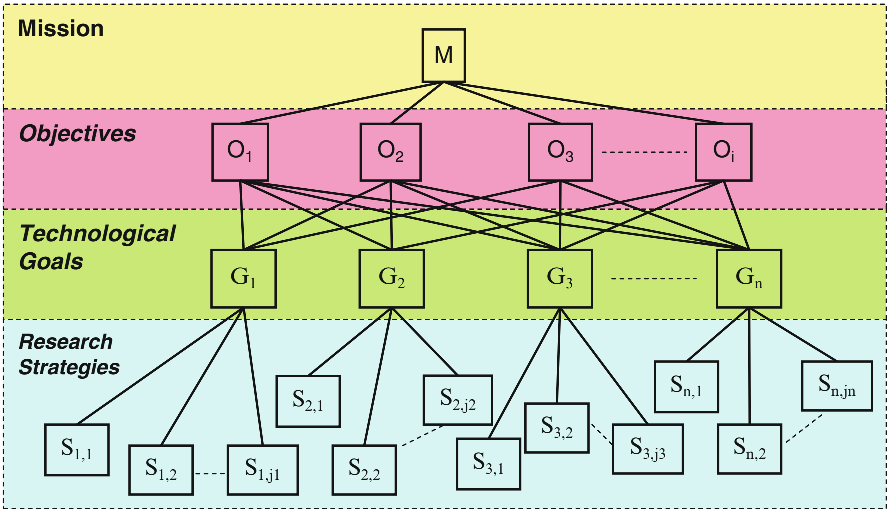


Fig. 10.1 Generic form of the hierarchical decision model with four decision levels

10.4.2 Emerging Technology

Emerging technologies such as nanotechnology, biotechnology, information technology, and energy-related technologies are becoming dominant technologies in which many countries are trying to invest in order to strengthen their national capabilities [39]. An emerging technology is described as a new technology derived from entirely new methods and processes [40]. Oftentimes, the term "emerging technology" is used for promising technologies that have been demonstrated in a research and development activity but are not yet ready for production [40, 41]. The distinction between any new advancing technology and an emerging technology is that an advancing technology will bring incremental changes to the user while an emerging technology will lead to radical innovation [42]. Complexity is a unique characteristic which differentiates an emerging technology from other existing technologies.

An emerging technology tends to have a high degree of uncertainty and a limited amount of data available [43]. Therefore, the conventional forecasting techniques of the benefit or contribution for the emerging technology such as regression, trend analysis, and growth curve are not suitable [39, 44, 45]. According to several research groups, the most appropriate forecasting methods when an emerging technology is considered are Delphi and AHP [43, 45–47].

10.5 Research Approach

The systematic research approach for national technology policy and strategy development is shown in Fig. 10.2.

10.5.1 *Strategic Planning, Technology Assessment, and Technology Forecasting*

In general, to assess and evaluate the high policy level, a country must go through a process called self-assessment. At this step, the country should be knowledgeable about global issues. From that, the country should identify the strategic direction and needs of the country in order to stay competitive. The next step is to search for potential technologies and research activities to support and fulfill the needs. This step is also called technology forecasting and technology assessment.

It is noted that for the purpose of demonstrating the systematic approach in this research, the application area of nanotechnology for supporting the development of the agriculture industry in Thailand is introduced as an example.

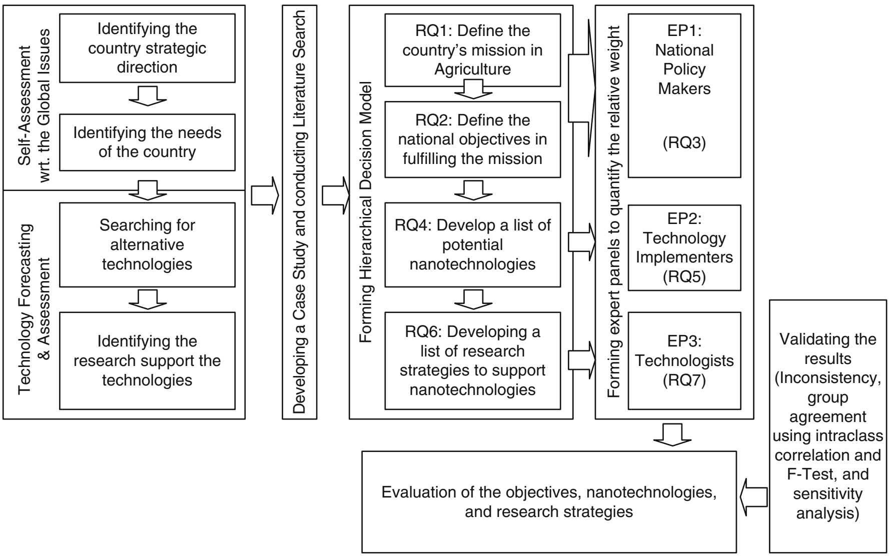


Fig. 10.2 Research approach

10.5.2 HDM Development

The next step is forming a hierarchical decision model which is composed of four levels. Four different research questions are addressed in each level. The first level is defining the country mission in agriculture (RQ1). The second level is defining the national objective to fulfill the mission (RQ2). The third level is providing a list of potential nanotechnologies supporting agriculture (RQ4). The last level is providing a list of research strategies and activities to support the development of the identified nanotechnologies (RQ6).

10.5.3 Expert Panels

After developing the model, three groups of experts are formed. The first group is called National Policy Makers (EP1). This group provides the relative priority of each objective with respect to the mission (RQ3). The next group of experts called Technology Implementers (EP2) is formed to provide the judgment quantification on the contribution of the technological goals to the objectives (RQ5). The last group of experts called Technologists (EP3) provides judgment quantification on the contribution of the research strategies for each goal (RQ7).

10.5.4 Validating the Results

Before arriving at the evaluation of the objectives, technological goals, and research strategies, a series of data validation methods is conducted.

10.5.4.1 Comparative Judgments and Quantification

In judgment quantification, each expert is asked to complete the series of comparative judgments by allocating a total of 100 points between two elements at a time. This method is called "constant-sum method." The series of judgments is converted to a normalized measure of relative values in ratio scale of the elements. A pairwise comparison software called "pairwise comparison method (PCM)[1]" is used for the calculations. In addition to the relative values of the elements and the group means, the level of inconsistency of each expert is also determined. The inconsistency value represents the quality of weights. The recommended value of inconsistency is between 0.0 and 0.10. The level of inconsistency measure is computed as follows [48]:

[1] The PCM software was developed by Dundar F. Kocaoglu and Bruce J. Bailey.

For n elements, the constant-sum calculations result in a vector of relative values $r_1, r_2, \ldots, r_n$ for each of the n! orientations of the elements. For example, if four elements are evaluated, n is 4; and n! is 24; thus there are 24 orientations such as ABCD, ABDC, ACBD, ACDB, . . ., DBAC, DCBA, etc. If there is no inconsistency in the judgments expressed by an expert in providing pairwise comparisons for these elements, the relative values are the same for each orientation. However, inconsistency in the expressed judgments results in differences in the relative values in different orientations. Inconsistency measure in the constant-sum method is a measure of the variance among the relative values of the elements calculated in the n! orientations.

Let r_{ij} = relative value of the i[th] element in the j[th] orientation for an expert.

r_{subi} = mean relative value of the i[th] element for that expert:

$$= \left(\frac{1}{n!}\right)\sum_{j=1}^{n!} r_{ij}$$

Inconsistency in the relative value of the i[th] element is

$$\frac{1}{n!}\sum_{j=1}^{n!}\left(r_{subi} - r_{ij}\right)^2 \quad \text{for } i = 1, 2, \ldots, n$$

Inconsistency of the expert in providing relative values for the n elements is

$$\text{Inconsistency} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\frac{1}{n!}\sum_{j=1}^{n!}\left(r_{subi} - r_{ij}\right)^2} \tag{10.1}$$

10.5.4.2 Agreement Among a Group of Experts

The level of group agreement on the relative priority of the objective, the relative contribution of the technological goals, and the relative contribution of the research strategies can be determined from the coefficient of intraclass correlation. This coefficient is represented by the degree to which k judges are in agreement with one another on the relative priority values of n subjects.

The intraclass correlation coefficient may theoretically fall within the range of $-1/(k-1) < r_{ic} < +1$ [49]. Its value is equal to +1 when the relative priorities of the subjects from all judges are exactly the same (absolute agreement). On the other hand, the value of r_{ic} is equal to 0 when there is substantial difference among the subjects' values from all judges. Any value of the intraclass correlation coefficient that falls in between 0 and 1 indicates the degree to which all judges agree upon the subjects' values; the higher the value is the higher the level of agreement. When the r_{ic} has a negative value, the negative correlation is generally treated as 0 [50].

Because, r_{ic} gives only a guideline to interpret the degree to which all judges agree upon in the ratio between 0 and 1, Shrout and Fleiss enhanced the evaluation of the intraclass correlation coefficient by using an F-test. They applied F-test to determine whether or not there is absolute disagreement among the judges, in other words, whether or not the population intraclass correlation (r_{ic}) is equal to zero [51]. To perform the F-test, the null hypothesis is defined as H_0: $r_{ic} = 0$ (no correlation among the judges on the subjects, which indicates absolute disagreement among experts).

In this research, the group judgment quantifications are accepted when the null hypothesis is rejected at 0.01 level.

10.6 Evaluation of Technologies, and Research Strategies

The evaluation of technologies and R&D strategies can be done through a series of computations. Judgment quantifications obtained from each expert panel are used as an input in the calculation. The mathematical expression for calculating the value of each technological goal is given below.

Referring to Fig. 10.1:

$$S^M_{n,\,jn} = 100 \times \sum_{i=1}^{I} \left(O^M_i\right)\left(G^O_n\right)\left(S^G_{n,\,jn}\right) \tag{10.2}$$

$$\text{For} \quad \begin{aligned} n &= 1,\ 2,\ \ldots,\ N \\ jn &= 1,\ 2,\ \ldots,\ Jn \end{aligned}$$

where

$S^M_{n,jn}$	Relative value of the jnth R&D strategy under the nth technological goal with respect to the country's mission (M)
O^M_i	Relative priority of the ith objective with respect to the country's mission (M), i = 1, 2, 3, …, I
G^O_n	Relative contribution of the nth technological goal with respect to the objective (O), n = 1, 2, 3, …, N
$S^G_{n,jn}$	Relative contribution of the jth R&D strategy under the nth technological goal, jn = 1, 2, 3, …, Jn, and n = 1, 2, 3, …, N

10.7 Research Results

Expert Panel 1: *National Policy Makers* (*EP1*): EP1 is composed of ten people. They represent a group of policy makers responsible for planning and setting the national strategic direction of related industries. The members of this panel are selected from senior government officials, industry leaders, and scholars in the country (Table 10.3).

Table 10.3 Distribution and background of the expert in EP1

	Admin.	Gov.	Academic	Private	Institution/sector
1. EX1	●				MOAC
2. EX2	●				MOST
3. EX3	●			●	MOC
4. EX4		●			MOAC
5. EX5		●			MOAC
6. EX6		●			MOAC-Commerce
7. EX7			●		Food Science
8. EX8			●	●	Agro-Econ, NGOs
9. EX9				●	Food Exporter
10. EX10				●	Plantation/Food Processing

Table 10.4 Intraclass correlation coefficient and F-value of the relative priority of objectives

	r_{ic} ($0 < r_{ic} < 1$)	F-value	F-critical at 0.01 level	F-test result
10 experts	0.18	2.76	3.91	Cannot reject H_0
First subgroup (6 experts)	0.71	12.61	4.43	Reject H_0
Second subgroup (3 experts)	0.84	13.89	7.01	Reject H_0
Third subgroup (1 expert)	N/A	N/A	N/A	N/A

From PCM, the values indicating the level of inconsistency of all experts are largely below 0.10. It represents the high quality of the relative weight (priority) of the objectives with respect to the mission. The group agreement is determined using the intraclass correlation coefficient and F-test. The result shows that there is a disagreement among the ten experts on the relative priorities of the objectives to the mission. Among the ten experts in EP1, their responses can be divided into three subgroups based on the intraclass coefficients and F-test results (Table 10.4).

(a) The first subgroup focuses on the farming aspect. They believe that improving efficiency is the most important (33 %) followed by improving safety (22 %). The rest of the objectives, namely improving quality, adding values, and reducing environmental effects, have roughly equal priority weights. They are ministry administrators, senior government officers, and academicians.
(b) The second subgroup believes that the top two objectives are improving safety and reducing environment effects (24 %). Next is adding value (20 %) followed by improving efficiency and quality which have roughly equal weight. This subgroup is made up of NGOs and private sector.
(c) The third subgroup believes that adding value (31 %) and improving quality (29 %) are the top two objectives. Improving safety and efficiency are at the third and fourth ranks, 19 % and 17 %, respectively. Lastly, reducing environmental effects has the least relative weight (5 %). This "group" is made up of agricultural economists.

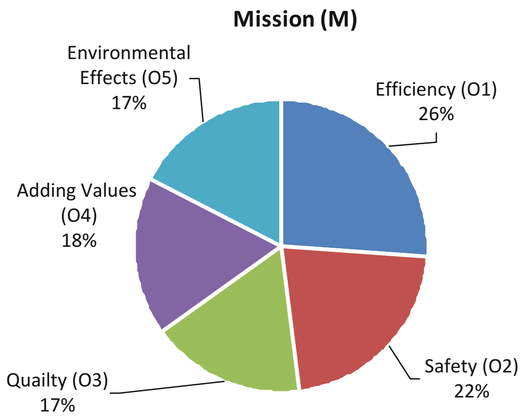


Fig. 10.3 Relative priority of the objective

However, there is some disagreement in the weights and ranking of objective priority. As a group decision, two objectives with the highest relative priority are improving efficiency (26 %) and improving safety (22 %). The rest of the objectives, namely improving quality, adding value, and reducing environmental effects, have roughly equal priority weights (Fig. 10.3).

Expert Panel 2: *Technology Implementers* (*EP2*): EP2 is composed of eight people. They represent a group of scientists, engineers, and officers who are typically studying, promoting, implementing, or applying emerging technologies to help develop the industry in a country. The members of this group are selected from the national technology development bodies, which are usually under the Ministry of Science and Technology (MOST) or similar agencies, ministerial personnel, and scholars (Table 10.5).

The values indicating the level of inconsistency of individual experts in EP2 which are obtained from PCM are varying between 0 and 0.056 which falls in the acceptable range. The intraclass correlation coefficients and the F-values for all five objectives are calculated and shown in Table 10.6.

It can be concluded that all experts in EP2 agree among each other on the relative contribution of the technological goals to the relevant objectives. The summary of the relative contributions of the technological goal with respect to specific objective is shown in Fig. 10.4.

Expert Panel 3: *Technologists* (*EP3*): EP3 is composed of 16 people. They represent a group of researchers, engineers, and scientists who are actively involved in or have access to information about the progress of the development of relevant technologies. This group of experts is selected from the technology experts in the country. The panel is consisted of representatives from government bodies, corporate research institutes, and universities (Table 10.7).

Table 10.5 Distribution and background of the expert in EP2

	Gov.	Academia	Private	Institution/sector
1. EX5	●			MOAC
2. EX6	●			MOAC-Commerce
3. EX7		●		Food Science
4. EX10			●	Plantation/Food Processing
5. EX11	●	●		Science Agency/Nanotechnology
6. EX12	●			MOAC-Food Standard
7. EX13	●	●		Science Agency/Nanotechnology
8. EX14		●	●	Agriculture Research Agency

Table 10.6 Intraclass correlation coefficient and F-value of all goals

Technological goals under	r_{ic} $(0 < r_{ic} < 1)$	F-value	F-critical at 0.01 level	F-test result
O1	0.86	32.43	6.51	Reject H_0
O2	0.74	18.06	4.87	Reject H_0
O3	0.74	16.12	6.51	Reject H_0
O4	0.70	15.22	4.87	Reject H_0
O5	0.82	29.09	4.87	Reject H_0

After obtaining the individual judgment on the relative contributions of the research strategies to the goal, the level of individual inconsistency is calculated. The results show that they vary between 0 and 0.05, which is relatively low compared to the acceptable range between 0 and 0.10. The intraclass correlation coefficient and F-test are calculated to test the level of agreement among EP3. The intraclass correlation coefficient and F-test indicates that there is an agreement among the members in EP3 as shown in Table 10.8.

The summary of the relative contributions of the research strategies under each technological goal is shown in Fig. 10.5a–g. Please note that SGn,jn is used for $S^{G}{}_{n,jn}$ notation in Fig. 10.5a–g because of the limitation of the graph function of Microsoft Excel. For example, SG7,3 is the notation for $S^{G}{}_{7,3}$.

10.7.1 Evaluation of the Technological Goals, and Research Strategies

At the intermediate step before evaluating the research strategies, the evaluation of the technological goals can be performed. The relative contribution of the goals to the mission is calculated by multiplying the arithmetic mean of the relative priority and the mean values of the relative contribution of the goals to the objectives.

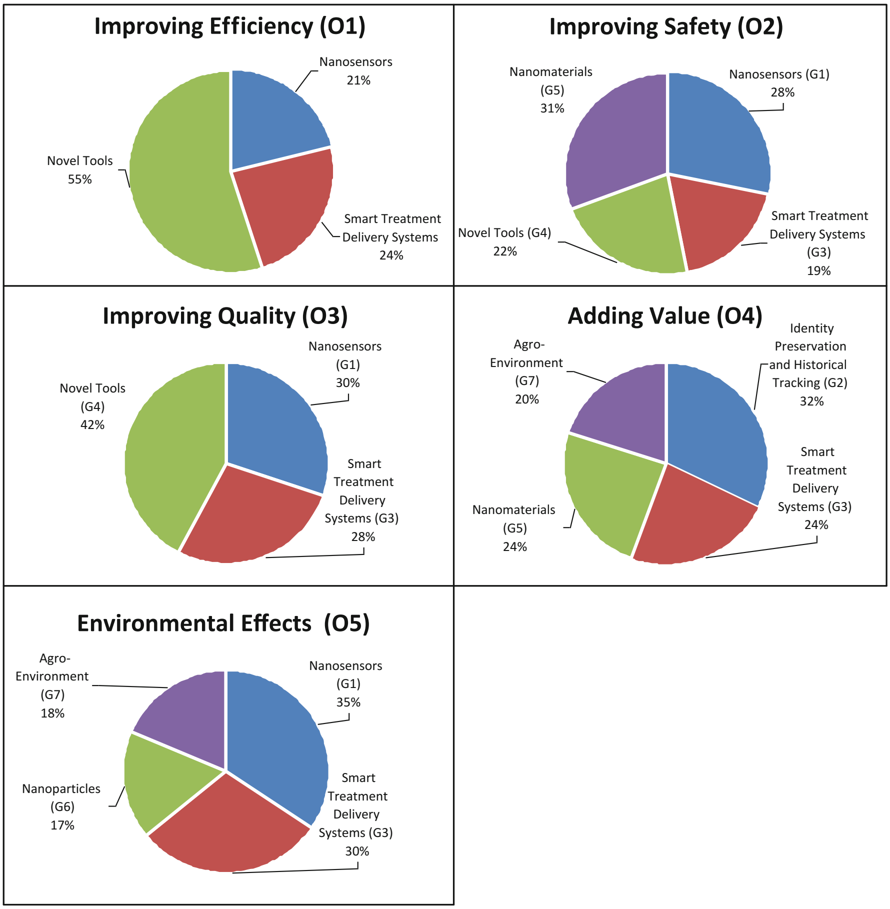


Fig. 10.4 Relative contribution of the technological goals

The calculations of the relative contribution of the goals to the objectives are shown in Table 10.9.

As a group decision, the relative weight and rankings are developing novel tools (26 %), smart treatment delivery system (24 %), nanosensors (23 %), nanomaterials (11 %), agro-environment (7 %), identity preservation and historical tracking (6 %), and nanoparticles (3 %).

The additional analysis is conducted to investigate whether the relative contributions of the goals are significant difference when the three subgroups of the EP1 make personal decision. The relative priority from the three subgroups in EP1 is multiplied by the mean value of the relative contribution of the goals to the objectives as shown in Table 10.10.

The results show that there are slight differences in the relative contributions and rankings of the technological goals when using the relative priorities of the

Table 10.7 Distribution and background of the expert in EP3

	G_1	G_2	G_3	G_4	G_5	G_6	G_7	Background/affiliation
1. EX13	●	●	●	●	●	●	●	Nanotechnology, Sci. and Tech. Agency
2. EX15	●	●	●	●	●	●	●	Physics, Univ.
3. EX16	●			●				Medical Technology, Univ.
4. EX17	●	●	●	●			●	Allied Health Science, Univ.
5. EX18			●			●		Pharmaceutical Technology, Univ.
6. EX19			●					Pharmaceutical Technology, Univ.
7. EX20		●			●	●	●	Chemistry, Science, Univ.
8. EX21	●							Chemistry, Science, Univ.
9. EX22						●		Chemical Engineering, Univ.
10. EX23		●						Botany, Univ.
11. EX24	●							Electronics, Sci. and Tech. Agency
12. EX25			●	●				Nanotechnology, Sci. and Tech. Agency
13. EX26	●			●				Nanotechnology, Sci. and Tech. Agency
14. EX27			●		●	●		Nanotechnology, Sci. and Tech. Agency
15. EX28					●		●	Nanotechnology, Sci. and Tech. Agency
16. EX29	●							Electronics, Sci. and Tech. Agency
Total	8	5	7	6	5	6	5	

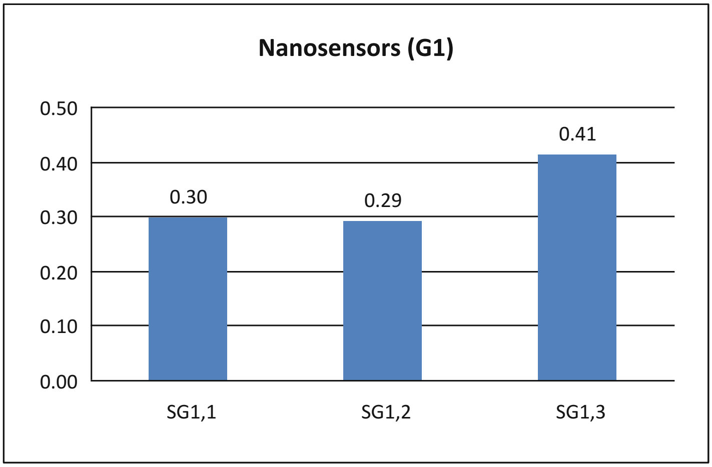
Table 10.8 Interclass correlation coefficient and F-value of research strategies

Research strategies under	r_{ic} $(0 < r_{ic} < 1)$	F-value	F-critical at 0.01 level	F-test result
G1	0.59	8.71	6.51	Reject H_0
G2	0.94	56.86	8.65	Reject H_0
G3	0.65	10.56	5.09	Reject H_0
G4	0.75	13.09	7.56	Reject H_0
G5	0.68	9.15	5.95	Reject H_0
G6	0.64	10.00	3.85	Reject H_0
G7	0.65	8.71	4.10	Reject H_0

objectives based on the three subgroups instead of the mean values. From the rankings, G4, G3, and G1 rank first, second, and third, respectively, for the first and third subgroups. The ranking reverses in the case of the second subgroup where G3 comes up to be the first rank followed by G1 and G4. However, in all cases, the top three ranks are still within these three technological goals. In other words, G_2, G_5, G_6, and G_7 are unable to make it to the top three in any case. G5 and G6 always remain in the fourth and seventh places. There is also a slight rank switching between G2 and G7 under the second subgroup.

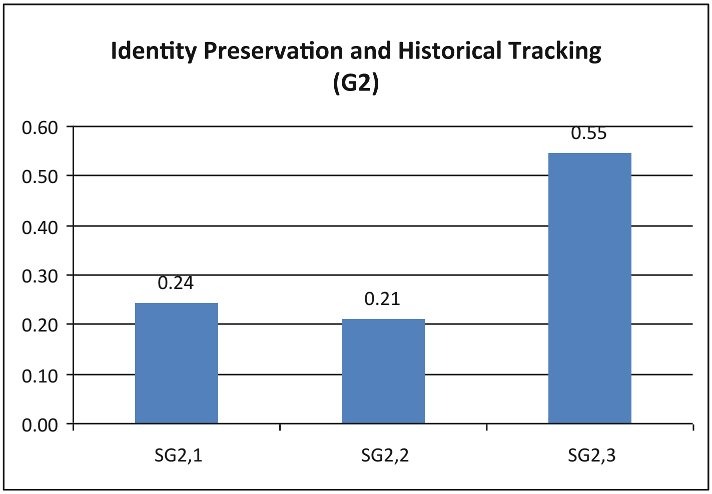
It can be concluded that no matter which subgroups, administrators, government officers, and academicians who emphasize on improving efficiency and safety, NGOs and private sector representatives who focus on improving safety and reducing environmental effects, or economists who focus in adding value and improve quality, the top three leading technological goals are novel tools, smart treatment delivery system, and nanosensors.

a



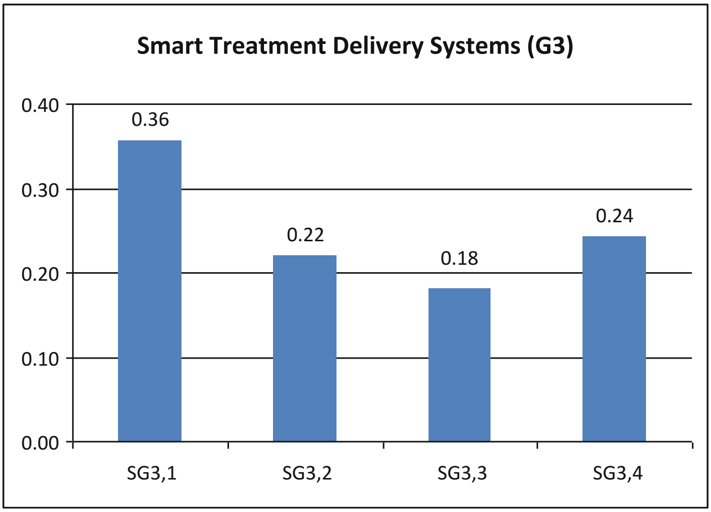
SG1,1 Developing methods to capture and hold the pathogen or chemical
SG1,2 Developing methods to recognize the pathogens or chemical
SG1,3 Developing methods for near real-time transduction of signal and location reporting

b



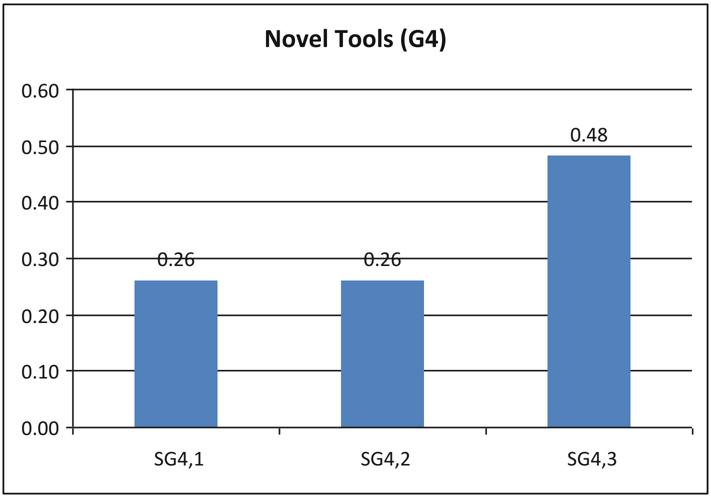
SG2,1 Quantifying metabolic process which is energetics at a macromolecular scale using biodegradable sensor devices
SG2,2 Developing a nanothermal device/data logger to monitor temperature changes over the life history of commodities
SG2,3 Developing device/data loggers for detection of pesticides and fertilizers over the life history of commodities.

Fig. 10.5 (**a**) Relative contribution of the research strategies under nanosensors. (**b**) Relative contribution of the research strategies under identity preservation and historical tracking. (**c**) Relative contribution of the research strategies under smart treatment delivery systems. (**d**) Relative contribution of the research strategies under novel tools. (**e**) Relative contribution of the research strategies under nanomaterials. (**f**) Relative contribution of the research strategies under nanoparticles. (**g**) Relative contribution of the research strategies under agro-environment c



SG3,1 Developing delivery systems for biological and bioactive systems including drugs, pesticides, nutrients, probiotics, nutraceuticals and implantable cell bioreactions;
SG3,2 Developing integrated sensing, monitoring, and controlling capabilities with on-board intelligence for self-regulation or remote activation for food production, storage, and packaging;
SG3,3 Developing targeted site delivery capability from implants in animals and plants that can be activated only as needed; and
SG3,4 Designing food nanostructure, oral delivery matrices, particulates, emulsions and nanodevices for enhanced food flavor and digestibility.

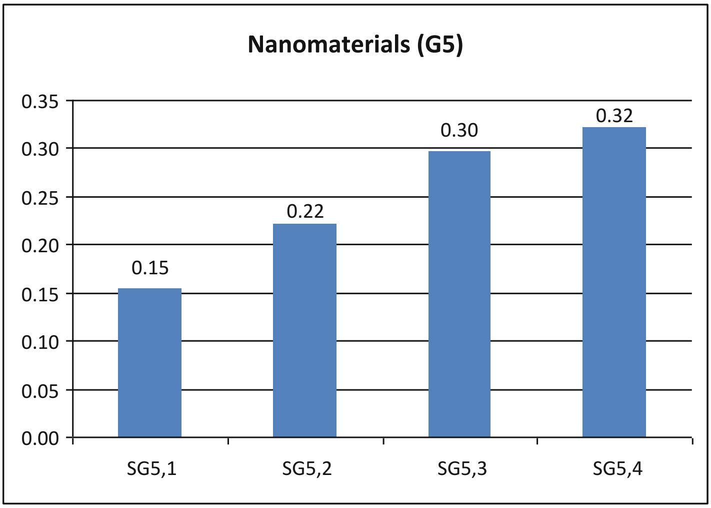
d



SG4,1 Developing of nanoseparation for biomolecules in the range of <100 nm and tools for quantification using fluorescent dyes attached to enzymes, nanoparticles, tags, markers, quantum dots and fiber optics or mass spectrometry
SG4,2 Developing nanobioreactors for the study of enzymatic processes, microbial kinetics, molecular ecology, mixed enzyme systems and rapid assessment of response to environmental factors
SG4,3 Developing nanodevices and materials for enhanced gene insertion processes, DNA delivery techniques for gene therapy, DNA vaccinations, disease diagnosis, and prevention for veterinary medicine

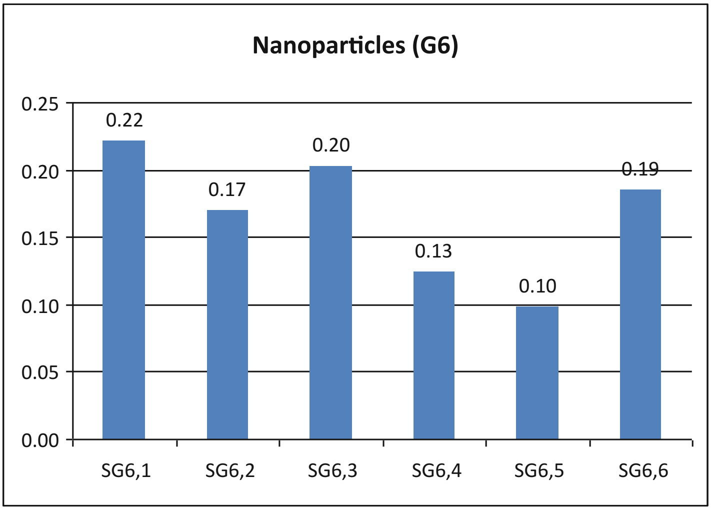
Fig. 10.5 (continued)

e



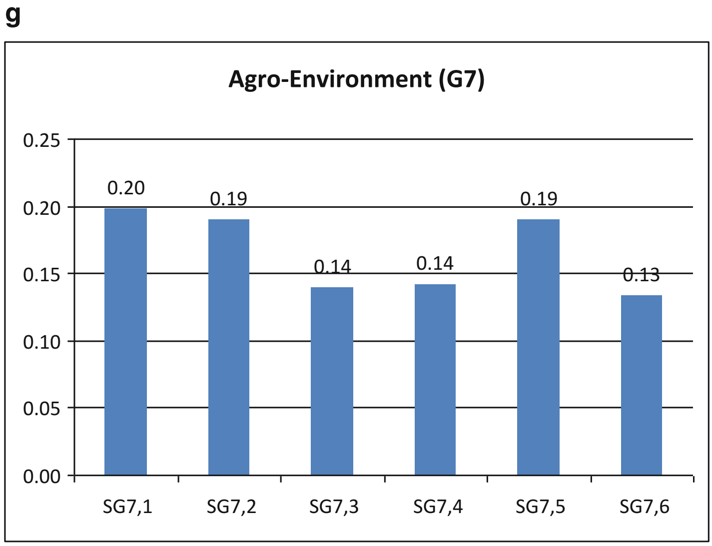
SG5,1 Applying the DNA building block technique to develop new materials and bioselective surfaces;
SG5,2 Developing self-healing materials;
SG5,3 Developing surfaces with enhanced selectivity for cells and biomolecules; and
SG5,4 Developing smart surfaces to control active spatial, temporal binding, and release properties.

f



SG6,1 Developing better nanophase soil additives such as fertilizers, pesticides, and soil conditioners
SG6,2 Developing research on nanoparticles in the transport and bioavailability of nutrients and pollutants
SG6,3 Developing research on the transportation and toxicity of nanoparticles in pollution
SG6,4 Developing research to increase the understanding of soil properties as a complex nanocomposite
SG6,5 Developing research to increase the understanding of nanoparticles' role in the global carbon cycle and CO_2 levels
SG6,6 Developing research on nanoparticles in water retention and conditioning of soils

Fig. 10.5 (continued)



SG7,1 Identifying new agriculturally derived biopolymers for industrial and biomedical applications;
SG7,2 Exploring more efficient methods for biopolymer modification;
SG7,3 Developing research on structural and functional aspects of biopolymers;
SG7,4 Developing nanocatalysts for waste bioprocessing;
SG7,5 Developing nanoscale processes for the reduction and/or conversion of animal or plant waste into value-added products; and
SG7,6 Developing nanoscale processes to manage local and environmental emissions.

Fig. 10.5 (continued)

Table 10.9 The relative contribution of the technological goals to the mission

O_i	O_i^M	G_n^O		G_1^M	G_2^M	G_3^M	G_4^M	G_5^M	G_6^M	G_7^M
O_1	0.26	G_1	0.21	0.05						
		G_3	0.24			0.06				
		G_4	0.55				0.14			
O_2	0.22	G_1	0.28	0.06						
		G_3	0.19			0.04				
		G_4	0.22				0.05			
		G_5	0.31					0.07		
O_3	0.17	G_1	0.30	0.05						
		G_3	0.27			0.05				
		G_4	0.42				0.07			
O_4	0.18	G_2	0.32		0.06					
		G_3	0.23			0.04				
		G_5	0.24					0.04		
		G_7	0.20							0.04
O_5	0.17	G_1	0.36	0.06						
		G_3	0.30			0.05				
		G_6	0.17						0.03	
		G_7	0.19							0.03
Sum				0.23	0.06	0.24	0.26	0.11	0.03	0.07

Table 10.10 The relative contribution to the mission from the three subgroups

	G_1	G_2	G_3	G_4	G_5	G_6	G_7
Arithmetic mean	0.23(3)	0.06(6)	0.24(2)	0.26(1)	0.11(4)	0.03(7)	0.07(5)
First subgroup	0.23(3)	0.05(6)	0.24(2)	0.29(1)	0.10(4)	0.03(7)	0.06(5)
Second subgroup	0.24(2)	0.06(6)	0.25(1)	0.21(3)	0.12(4)	0.04(7)	0.09(5)
Third subgroup	0.19(3)	0.10(5)	0.24(2)	0.26(1)	0.13(4)	0.01(7)	0.07(6)

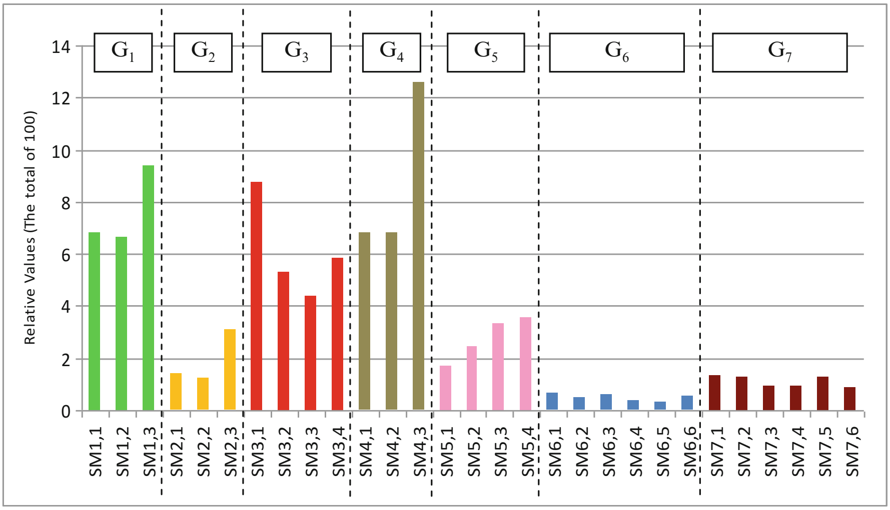


Fig. 10.6 Relative contribution values of the research strategies contributed to the mission

The final step is to evaluate the research strategies by determining the relative value of the research strategies under each technological goal with respect to the mission. It can be calculated by multiplying the relative contribution of the research strategies by the technological goals and the relative contribution of the technological goals with respect to the mission. The graphical representation of the relative contribution value of research strategies is shown in Fig. 10.6. Please note that SMn,jn is used for $S^M{}_{n,jn}$ notation in Fig. 10.6. For example, SM4,3 is the notation for $S^M{}_{4,3}$.

Based on the relative value of each research strategy, the top three strategies out of 29 research strategies that have the highest contribution to the mission are the following:

1. $S_{4,3}$ (Third Strategy under Goal-4): Developing nanodevices and materials for enhanced gene insertion processes, DNA delivery techniques for gene therapy, DNA vaccination, disease diagnosis, and prevention for veterinary medicine (12.61)
2. $S_{1,3}$ (Third Strategy under Goal-1): Developing methods for near-real-time transduction of signal and location reporting (9.36)
3. $S_{3,1}$ (First Strategy under Goal-3): Developing delivery systems for biological and bioactive systems including drugs, pesticides, nutrients, probiotics, nutraceuticals, and implantable cell bioreactions (8.73)

10.8 Sensitivity Analysis

There are two major sensitivity analysis methods applied in this research. The first method is applying the sensitivity analysis of HDM developed by Chen and Kocaoglu [52] to determine the impact of changing the priority of the objectives on the mission. The second part is investigating the sensitivity of the individual ranking of the goals by EP1 as well as the sensitivity of the ranking of goals by the three subgroups in EP1.

10.8.1 HDM Sensitivity Analysis

The sensitivity analysis of HDM [53] is applied to determine the allowance of perturbation induced on each objective without any impact on the original ranking of technological goals. In other words, the original ranking of goals will not change as long as the values of the perturbations fall into the allowable region.

According to Chen, the original ranking of G_r and G_{r+n} will not reverse if

$$\lambda \geq P_{l^*}^{O} * \lambda^{O} \tag{10.3}$$

For the perturbation $P_{l^*}^{O}$

where $-C_{l^*}^{O} \leq P_{l^*}^{O} \leq 1 - C_{l^*}^{O}$

where $\lambda = C_r^A - C_{r+n}^A$

$$\lambda^O = C_{r+n,l^*}^{A-O} - C_{r,l^*}^{A-O} - \sum_{\substack{l=1 \\ l \neq l^*}}^{L} C_{r+n,l}^{A-O} * \frac{C_l^O}{\sum_{\substack{l=1 \\ l \neq l^*}}^{L} C_l^O} + \sum_{\substack{l=1 \\ l \neq l^*}}^{L} C_{r,l}^{A-O} * \frac{C_l^O}{\sum_{\substack{l=1 \\ l \neq l^*}}^{L} C_l^O} \tag{10.4}$$

$$sens(O_l) = \frac{1}{|\delta_{1l} - \delta_{2l}|} \tag{10.5}$$

The allowable range of perturbations, tolerance, and sensitivity coefficient of all five objectives are shown in Table 10.11.

The criterion that has the biggest sensitivity coefficient is the most critical criterion for keeping the current top rank as it is. As a result, it can be concluded that O5 (4.405) is the most critical criterion in keeping G4 as the top rank. The second most critical criterion is O4 (4.049).

G4 is less sensitive to O1, O2, and O3 because the sensitivity coefficients of O1, O2, and O3 are relatively low, 1.263, 1.984, and 1.042, respectively. By considering

Table 10.11 Allowable range of perturbations, tolerance, and sensitivity coefficient of the five objectives

	O_1	O_2	O_3	O_4	O_5
Base relative priority	0.26	0.22	0.17	0.18	0.17
Allowable ranges of perturbations	[−0.052,0.74]	[−0.22,0.284]	[−0.13,0.83]	[−0.18,0.067]	[−0.17,0.053]
Tolerance	[0.208,1]	[0,0.504]	[0.04,1]	[0,0.247]	[0,0.223]
Sensitivity coefficient	1.263	1.984	1.042	4.049	4.405

Table 10.12 Individual relative contribution and ranking of the goals to the mission

	G_1	G_2	G_3	G_4	G_5	G_6	G_7
EX1	0.22 (3)	0.05 (5.5)	0.24 (2)	0.31 (1)	0.10 (4)	0.02(7)	0.05 (5.5)
EX2	0.25 (1)	0.04 (6.5)	0.24 (2.5)	0.24 (2.5)	0.12 (4)	0.04 (6.5)	0.07 (5)
EX3	0.23 (3)	0.05 (6)	0.24 (2)	0.29 (1)	0.10 (4)	0.02 (7)	0.06 (5)
EX4	0.25 (2.5)	0.03 (7)	0.25 (2.5)	0.29 (1)	0.08 (4)	0.04 (6)	0.07 (5)
EX5	0.22 (3)	0.06 (5.5)	0.24 (2)	0.29 (1)	0.10 (4)	0.02 (7)	0.06 (5.5)
EX6	0.19 (3)	0.10 (5)	0.24 (2)	0.26 (1)	0.13 (4)	0.01 (7)	0.07 (6)
EX7	0.22 (3)	0.05 (5.5)	0.24 (2)	0.30 (1)	0.12 (4)	0.02 (7)	0.05 (6)
EX8	0.24 (2)	0.06 (6)	0.25 (1)	0.21 (3)	0.12 (4)	0.04 (7)	0.08 (5)
EX9	0.23 (2)	0.07 (6)	0.24 (1)	0.20 (3)	0.13 (4)	0.04 (7)	0.09 (5)
EX10	0.24 (2)	0.06 (6)	0.25 (1)	0.22 (3)	0.11 (4)	0.04 (7)	0.08 (5)

Note that the number in the parentheses indicates the ranking of the goal. In the case of a tie, the value is assigned by the mid-rank method

the tolerance, the relative priority of O1 can increase up to 1 and decrease to 0.208 without affecting G4 as the top rank. The relative priority of O2 can increase more than twice, from 0.22 to 0.504, while the top ranking still remains the same. For its low limit, the relative priority of O2 can reduce to 0 without changing the top rank. O3 is the least sensitive because its relative priority can decrease to 0.04 and increase up to 1 without affecting the top rank.

10.8.2 F-Test for Sensitivity of the Ranking

In this section, the sensitivity of the individual and subgroup of goals by EP1 is determined. The rank correlation F-test for agreement in multiple judgments is applied in order to investigate the statistical significance of the correlation between each expert and the ranking (Table 10.12).

10.8.2.1 The Correlation of EP1's Individual Ranking

Each individual relative priority from the members in EP1 is multiplied by the mean value of the relative contribution of the goals to the objectives. The results are indicated in the following table. The first, second, and third rankings shift among G4, G3, and G1. G5 always ranks fourth; and the fifth, sixth, and seventh switch among G7, G2, and G6. The rank correlation F-test for agreement in multiple judgments can be applied to investigate the statistical significance of the correlation between each expert and the rankings.

The null hypothesis, "H_0: the ranking is independent," is developed. The interpretation of H_0 is that there is a statistically significant difference in the rankings of the technological goals among the individual experts. The following is the mathematical equation to calculate the F-value:

$$S = \frac{nk\left(k^2 - 1\right)}{12} \tag{10.6}$$

S_D = the sum of the squares of the differences between subjects' mean ranks and the overall mean rank:

$$D_1 = \frac{S_D}{n}, D_2 = S - D_1, S_1^2 = \frac{D_1}{K - 1}, S_2^2 = \frac{D_2}{K(n - 1)} \tag{10.7}$$

where n = number of judges (ten subgroups), and k = number of subjects (seven technological goals).

The computed F-value of the individual is 112 where the F-critical at 0.01 level is 3.09. Because the computed F-value is larger than the F-critical, the null hypothesis can be rejected. As a result, it can be concluded that there is no statistically significant difference in the ranking of technological goals among the three different subgroups in EP1. In other words, there is an agreement among the individuals on the rankings of the seven technological goals.

10.8.2.2 The Correlation of EP1's Subgroup Ranking

The rank correlation F-test for agreement in multiple judgments can be applied to investigate the statistical significance of the correlation between the subgroups and the rankings [54]. The null hypothesis, "H_0: The ranking is independent," is developed. The interpretation of H_0 is that there is a statistically significant difference in the rankings of the technological goals among the three subgroups. The rankings of all seven technological goals according to the three subgroups are shown in Table 10.13.

The F-test of the different rankings of the technological goals based on these three subgroups is studied and compared. The first subgroup is composed of six experts: EX1–5 and EX7. The second subgroup is composed of three experts (EX8–10). And the third subgroup is EX6. The computed F-value of the three subgroups is 34.42, where the F-critical at the 0.01 level is 4.46. Because the computed F-value is larger than the F-critical, the null hypothesis can be rejected. Therefore, it can be concluded that there is no statistically significant difference in the ranking of technological goals among the individuals in EP1. In other words, there is a general agreement among the three subgroups on the rankings of the seven technological goals.

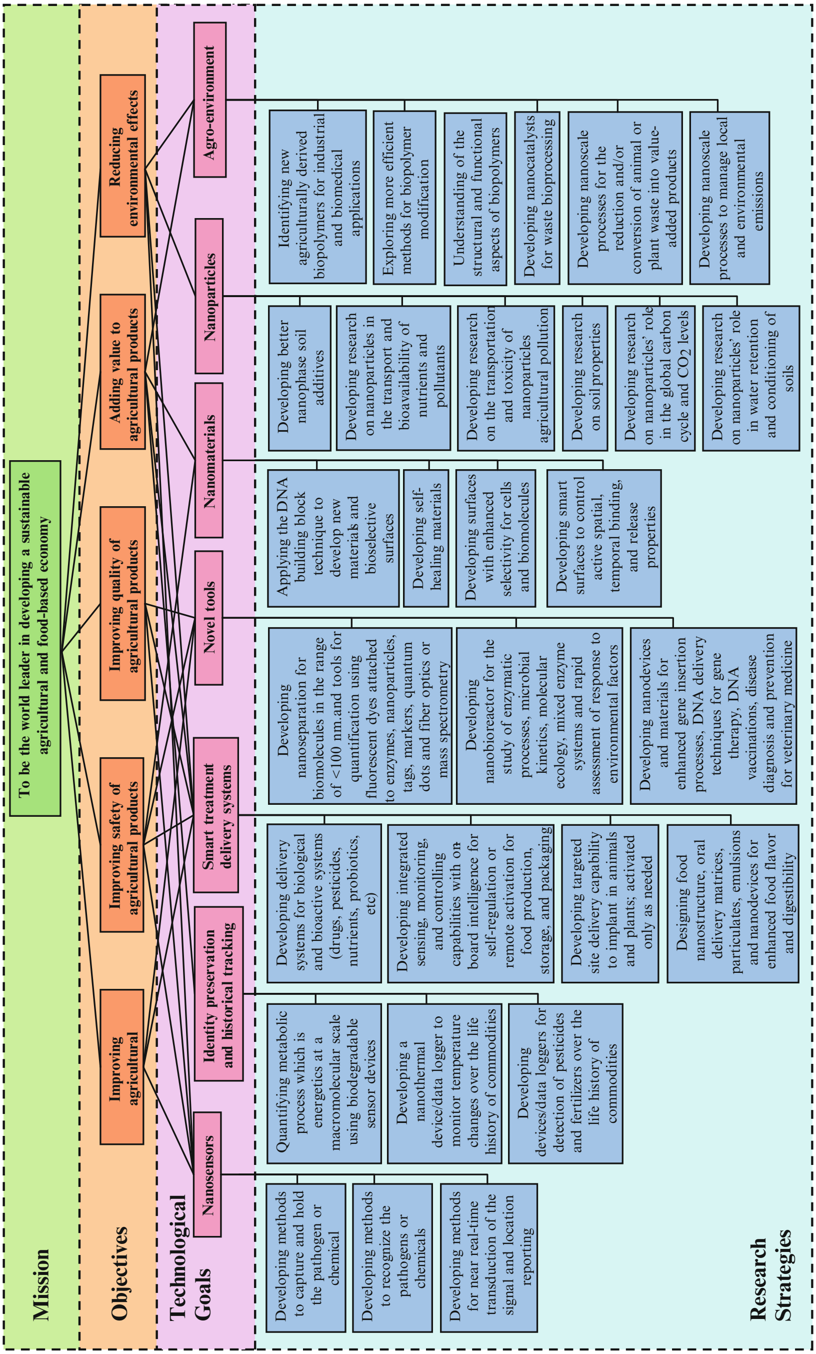
Table 10.13 Rank number of the seven technological goals

	Relative contribution (rank number)						
	G_1(3)	G_2 (6)	G_3 (2)	G_4 (1)	G_5 (4)	G_6 (7)	G_7 (5)
First subgroup	3	6	2	1	4	7	5
Second subgroup	2	6	1	3	4	7	5
Third subgroup	3	5	2	1	4	7	6

10.9 Conclusions

Several methodologies and techniques are integrated to build a systematic and comprehensive approach for national emerging technology policy and strategy development. This approach is developed based on multiple scientific methods such as AHP, Delphi expert panels, statistical test for expert group agreement, sensitivity analysis using HDM algorithm, and F-test with multiple stakeholders in the policy maker process, for example politicians and technocrats who design national technology policy and strategy, technology implementers who seek for adopting technology in order to improve agricultural and food industry (in this specific case study), and scientists and researchers who are currently developing R&D in the area of nanotechnologies (in this specific case study). The researcher believes that by following step by step this rigorous approach, technology policy and strategy can be effectively developed.

Appendix: HDM for Developing Nanotechnology Research Policy and Strategy


Mission
To be the world leader in developing a sustainable agricultural and food-based economy
Objectives
Improving agricultural
Improving safety of agricultural products
Improving quality of agricultural products
Adding value to agricultural products
Reducing environmental effects
Technological Goals
Nanosensors
Identity preservation and historical tracking
Smart treatment delivery systems
Novel tools
Nanomaterials
Nanoparticles
Agro-environment
Research Strategies
Developing methods to capture and hold the pathogen or chemical
Developing methods to recognize the pathogens or chemicals
Developing methods for near real-time transduction of the signal and location reporting
Quantifying metabolic process which is energetics at a macromolecular scale using biodegradable sensor devices
Developing a nanothermal device/data logger to monitor temperature changes over the life history of commodities
Developing devices/data loggers for detection of pesticides and fertilizers over the life history of commodities
Developing delivery systems for biological and bioactive systems (drugs, pesticides, nutrients, probiotics, etc)
Developing integrated sensing, monitoring, and controlling capabilities with on board intelligence for self-regulation or remote activation for food production, storage, and packaging
Developing targeted site delivery capability to implant in animals and plants; activated only as needed
Designing food nanostructure, oral delivery matrices, particulates, emulsions and nanodevices for enhanced food flavor and digestibility
Developing nanoseparation for biomolecules in the range of <100 nm.and tools for quantification using fluorescent dyes attached to enzymes, nanoparticles, tags, markers, quantum dots and fiber optics or mass spectrometry
Developing nanobioreactor for the study of enzymatic processes, microbial kinetics, molecular ecology, mixed enzyme systems and rapid assessment of response to environmental factors
Developing nanodevices and materials for enhanced gene insertion processes, DNA delivery techniques for gene therapy, DNA vaccinations, disease diagnosis and prevention for veterinary medicine
Applying the DNA building block technique to develop new materials and bioselective surfaces
Developing self-healing materials
Developing surfaces with enhanced selectivity for cells and biomolecules
Developing smart surfaces to control active spatial, temporal binding, and release properties
Developing better nanophase soil additives
Developing research on nanoparticles in the transport and bioavailability of nutrients and pollutants
Developing research on the transportation and toxicity of nanoparticles agricultural pollution
Developing research on soil properties
Developing research on nanoparticles' role in the global carbon cycle and CO2 levels
Developing research on nanoparticles' role in water retention and conditioning of soils
Identifying new agriculturally derived biopolymers for industrial and biomedical applications
Exploring more efficient methods for biopolymer modification
Understanding of the structural and functional aspects of biopolymers
Developing nanocatalysts for waste bioprocessing
Developing nanoscale processes for the reduction and/or conversion of animal or plant waste into value-added products
Developing nanoscale processes to manage local and environmental emissions

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Chapter 11
National Technology Planning: Digital Divide in Emerging Economies (Case: Costa Rica)

Audrey Maria Alvear Báez

Abstract The methodology selected for conducting this study is the analytic hierarchy process, and the model is based on the United Nations Development Program report titled "Creating a Development Dynamic: Final Report of the Digital Opportunity," concepts from the literature and expert judgments. A four-level hierarchical decision model has been developed using weights provided by an expert panel. The model computes the contribution to the reduction of the internal DD, due to the reduction of the DD in different key sectors, ICT applications, and ICTs. The model was developed for short and longer terms. The judgmental values were tested for consistency and sensitivity, and verified by the expert panel. The study found that a reduction of the DD in the education sector would have the largest impact followed by the reduction of the DD in the economic, government, and health sectors. Education and government applications have the largest impact on reducing the internal digital divide, due to their focus on innovation and creativity, enhancing the education process through ICT use as well as improving the efficiency of public administration.

11.1 Research Methodology

11.1.1 Research Objective

The digital divide and the use of ICTs have been widely studied. The majority of the research analyzes the current infrastructure development or the device penetration. It also covers case studies and gives recommendations at a policy level; one of these studies is the Digital Opportunity Initiative report from United Nations Development Program (UNDP). Although quite comprehensive, this report has not been operationalized with a systematic approach.

This chapter is a part of the dissertation of Audrey Alvear Báez done while the author was a student at Portland State University.

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The model presented in this chapter considers the five specific development goals defined by UNDP as key sectors. These sectors will have ICT applications that will have an impact on the reduction of the digital divide in each sector. In turn the reduction of the digital divide of each sector may impact the reduction of the internal digital divide in a developing country such as Costa Rica. The research objective is the identification of ICTs, technology applications, and sectors and their impact on the reduction of the internal digital divide in a developing country.

11.1.2 Research Questions

There are five research questions in this study:

1. What is the relative impact of the reduction of the digital divide of each one of the five key sectors on the overall reduction of the internal digital divide in a developing economy?
2. What critical ICT applications contribute to the reduction of the digital divide in a developing economy?
3. What are the relative impacts of the ICT applications on the reduction of the digital divide of each of the five key sectors?
4. What are the relative contributions of the available ICTs on each of the ICT applications?
5. To what degree does each ICTs impact the reduction of the digital divide in a developing economy?

11.1.3 Research Approach

The study utilizes the analytical hierarchy process (AHP) for creating a developing technology selection model to reduce the digital divide in a developing economy. An expert panel provided subjective values to determine the relative impact relationships among the decision elements at all levels of the hierarchy.

11.1.3.1 The Expert Panel

An expert panel was formed to help develop the hierarchy, to provide the data for the relative impacts, and to interpret the results. The experts were selected from academia, industry, and government agencies in Costa Rica. Many of them were members of the Advisory Council of the Ministry of Science and Technology of Costa Rica.

The selection of the members of the expert panel was based on their in-depth knowledge and experience at a high level of decision making in health, education, economic, environmental, and political sectors impacting strategic development and policy making in Costa Rica. This panel included at least three experts for each sector. The experts had to fulfill the following criteria:

1. Decision-maker role or expertise in advising decision makers in Costa Rica.
2. Representation of industry, government, or academic institutions in a balanced mix.
3. Expertise in at least one of the sectors considered in the study.
4. Expertise in developing, acquiring, or implementing technology at a strategic level for improving one or more of the sectors under consideration.

A total of 15 experts agreed to participate with at least four experts for each key sector defined as ICTs for specific development goals by the UNDP [1].

The experts identified the strategies for each dimension of the study and provided quantified values for their subjective judgments about the impact of each decision element on the next level of the decision hierarchy. Finally, they provided assistance in evaluating, validating, and interpreting the results.

11.1.3.2 Model Definition

The use of ICTs for specific development goals has been studied by the UNDP. The UNDP has identified five key areas: health, education, economic opportunity, empowerment and participation, and environment [1].

The model presented in this chapter considers these five areas as key sectors which by reducing the digital divide in each sector may impact the reduction of the digital divide in a developing country such as Costa Rica. This part presents the definitions of the reduction of the digital divide in each sector and the respective ICT applications. In this research the ICT applications are mechanisms to help the sectors to reduce the digital divide using ICTs. The initial set of ICT applications were taken from the final report of the Digital Opportunity Initiative elaborated by the United Nations, Markle Foundation, and Accenture Foundation in July 2001. However, the final ICT list of applications used in this model had some modifications coming from and approved by the expert panel.

A four-level hierarchical model has been developed as shown in Fig. 11.1:

The following sections present each level of the hierarchy and its definitions. The definitions presented here are the compiled and finalized version of what was identified first by gathering information from the literature and then modified by the expert panel members.

First Level

This level represents the objective of this study: the reduction of the internal digital divide.

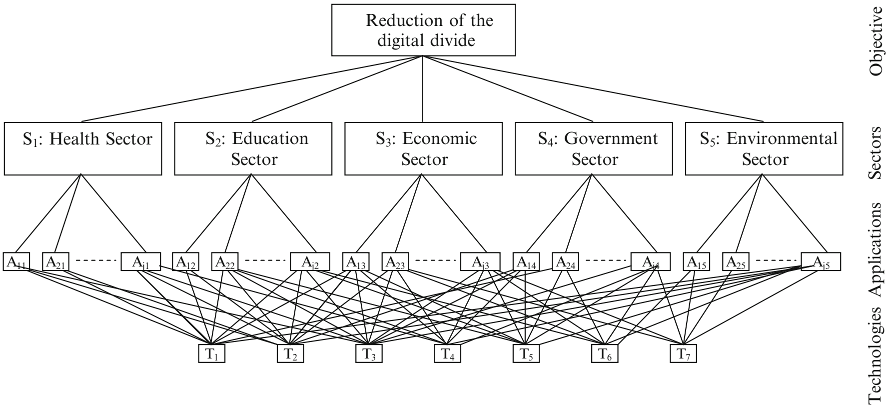


Fig. 11.1 The decision hierarchy

Second Level

The second level consists of five key sectors: health, education, economic, and government and environmental sectors. The reduction of the digital divide in each of these sectors will have an impact on the overall goal of reducing of the digital divide in the country, but what is the reduction of the digital divide in each sector?

The reduction of the digital divide on the health sector in terms of this research is bringing hospitals, clinics, health centers, and health professionals in rural and urban areas to a level where they can utilize ICT capabilities, and providing the community with the tools that are required for access to good medical service.

The reduction of the digital divide on the education sector is bringing all the educational institutions and professionals in the country to a level where they can benefit from the use of ICTs, and providing the community with the tools that are required for access to good education no matter where the individuals are or what education degree they pursue.

The reduction of the digital divide on the economic sector is improving business efficiency and productivity throughout the country to become competitive in a global economy through the use of ICTs, and providing businesses, professionals, farmers, and the general population with ideas and solutions to create and/or capture markets and economic opportunities.

The reduction of the digital divide on the government sector is fostering empowerment and participation of the people through the use of ICTs, and making government processes more efficient and transparent by sharing information among individuals, business, and government.

The reduction of the digital divide on the environmental sector is managing information about biodiversity and creating sustainable development through the use of ICTs with a focus not only on the research community but also on the public in general.

Third Level

The third level consists of a diverse range of information technology applications. Each technology application has an impact on the reduction of the digital divide in the sector with which it is associated. Following is a comprehensive list of the applications used in this model described sector by sector.

Applications in the Health Sector

A.1.1. Expanding the availability of health services and identification of the appropriate level of medical response for the needs of the population: Telemedicine, remote consultation, diagnosis, and treatment that take place without having the patient in the same physical location as the physician; the information is gathered and then sent through digital means to the respective physicians [2, 3].

A.1.2. Preventing diseases and improving epidemic response: Capturing information about cases of contagious diseases, monitoring them, and disseminating information by broadcast media or other ICT means, creating diagnosis-related groups (DRGs).

A.1.3. Providing online medical libraries: Making medical libraries accessible to health professionals, especially in remote areas, to keep up to date on medical knowledge and related literature, and providing the general population with the means to learn more about certain illnesses or health issues.

A.1.4. Facilitating diagnosis in distant medical labs: Using ICT technologies to get data for clinical trials locally to be evaluated in distant labs. Standardizing the processes used in the labs for consistency and effectiveness of illness identification.

A.1.5. Improving the efficiency of the health system in every geographic area: Using e-applications which provide low-cost healthcare information and facilitate consultation, referrals, scheduling, and unique medical record e-procurement; developing a data base of medical records with Internet access for use by public and private healthcare providers; and improving the efficiency in procurement and resource management in health systems according to the geographic areas' needs.

A.1.6. Creating awareness of health issues in the population through the use of ICTs: Disseminating information about infant to old age health problems to the population through the use of ICTs.

Applications in the Education Sector

A.2.1. Enhancing the learning process through the use of ICTs: Providing access to knowledge and facilitating collaborative and interactive learning, thus enhancing the traditional education system [4, 5]. It includes online communities for students, teachers, and/or professors; instructor support through multimedia learning materials, bulletin boards, and e-mails; collaborative projects among instructors and students; student tracking systems to evaluate the student's progress; chat rooms, e-mail, bulletin boards, conceptual maps, and home pages; special programs for educating teachers about how to utilize computer technologies as a teaching tool, promoting education with IT use in K-12; and creating new instruments for evaluation and appraisal.

A.2.2. Improving the education system administration: Using technology applications, with the objective of making them available to the entire population, and providing a transparent and efficient management of resources at schools and in the Ministry of Education.

A.2.3. Expanding distance learning: Delivering education by ICTs where professors and students do not have to be in the same physical location, but can access the same virtual space where they interact or find the necessary information to acquire knowledge and the necessary tools to test the online acquired knowledge.

A.2.4. Providing technical and vocational training to the entire population: Developing specific skills for technology use including hardware/software systems, as well as skills needed in various fields including health-related professions, agriculture, and mechanical repair through the use of technological applications, Internet, and Web-based classes.

A.2.5. Making programs that foster innovation, creativity, and research available throughout the country: Creating programs where academics and students can freely interact with the computer in an open environment according to their interests; encouraging shared research efforts among researchers.

Applications in the Economic Sector

A.3.1. Improving market intelligence available to every business in the country: Providing timely access to market information such as the status of a crop, fluctuations in the tourism industry, changes in the software industry, pricing structures, and supply/demand relationships; facilitating data mining to identify predictive patterns in the market behavior (this is also a tool for information dissemination).

A.3.2. Enhancing rural economic opportunities: Enabling people to work anywhere, so local communities are integrated into the global economy. For example, the use of telecenters, which are community resource centers equipped with the latest technology such as computers, faxes, and Internet connections.

A.3.3. Improving business efficiency and productivity of small-to-medium-sized enterprises (SMEs) through information and communication technologies: Using ICTs to reduce operational cost by decreasing material, procurement, and transaction costs, and enabling SMEs throughout the country to use more and better information to improve the value of their output.

A.3.4. Sharing ICT resources among enterprises: Enabling small- to-medium-sized enterprises to share resources for reducing the cost of access to technology; developing data centers and centralized computer systems for computing on demand: for example, two SMEs can share a computer to work on business accounting.

A.3.5. Creating new business models based on information networks: Using ICTs to create and deliver products and services on a global scale, and to give developing countries access to new markets for competitive advantage; improving direct marketing and data acquisition for import/export of specific products; identifying the vendors, buyers, and suppliers. These new business models include applications such as e-trading, marketplaces, business to business, and portals.

A.3.6. Creating a database to match the available human resources and job offerings: Matching the skills of the available man power with the needs that exist in the economic sector.

Applications in the Government Sector

A.4.1. Facilitating participation of the public in democratic processes: Encouraging the public's participation in the democratic process via elections, forums, discussions, establishment of criteria about specific topics, enforcement of accountability of public officials, and voting in elections through the use of ICTs.

A.4.2. Providing universal access to information and online services to empower people: Developing hardware and software infrastructure that interconnects computers and provides free Internet access, free e-mail accounts, and information to citizens nationwide; making information accessible through citizen service centers; providing the citizens with technological access to government agencies; promoting the use of applications that permits the citizens to have an equitable/fair access to the services of the government, so they can make educated choices and political decisions at local, regional, and national levels.

A.4.3. Improving public administration throughout the country: Developing applications to improve the quality of service and the level of responsiveness of government institutions everywhere in the country; increasing the efficiency and transparency of government processes for the entire population; bringing hardware/software and technological platforms of the governmental agencies up to date in all provinces; improving the capabilities of the personnel by providing education in the IT field and access to the information networks; improving the capability for equitable public spending and tax collection.

Applications in the Environmental Sector

A.5.1. Monitoring and disseminating information on ecological conditions: Using technology applications to improve efficient use of resources to fight contamination and to set prevention and mitigation measures. Technology applications can collect data and forecast pest problems and pesticide use. Weather information and soil monitoring are also parts of ecological monitoring.

A.5.2. Promoting public awareness of environmental issues throughout the country: Using ICTs to disseminate information about environmental and biodiversity-related issues, impacts on environmental quality, farming sustainability, marine management, and energy sources. It includes a national computer database to contribute to biodiversity and environmental knowledge and awareness.

A.5.3. Monitoring environmental conditions to facilitate decision making: Using ICTs to send information, including images of environmental disasters, on a timely basis, so the decision makers can have the information they need when they need it; incorporating satellite information in environmental decision making (examples include fire emergencies, oil spills, as well as developing strategies to protect the environment).

A.5.4. Promoting biodiversity and sustainable development: Using ICTs to disseminate information about biodiversity and the impact on society; encouraging the society to put a higher value on natural resources and to conserve them.

A.5.5. Dissemination of information about best practices: Making information available about successful approaches to environmental management; describing best practices to establish benchmarks for comparison.

Fourth Level

The fourth level is a set of information and communication technologies. A large list of ICTs was presented to a panel of experts, and through various iterations the technologies were grouped into seven categories:

T1: General-purpose software: Software for general applications including back-office and front-office programs, databases, CRM, OLAP, ERP, data analysis tools, data modeling tools, simulation tools, multimedia tools, geographic information systems, and other similar software.

T2: Mobile devices and infrastructure: Laptop computers, PDAs, imaging devices such as video cameras or digital cameras, cell phones, and the required infrastructure to make them work such as low earth orbit satellite systems and wireless for LAN.

T3: Internet content and infrastructure: Basic uses of the Internet, such as Web searching, Web services, security systems on the Internet, e-mail, Internet content, and other related Internet tools as well as the required infrastructure to make them work. (Collaborative Internet tools such as web forums and chats are not included in this group of technologies.)

T4: Collaborative tools: Web forums, chats, videoconferencing, teleconferencing, and other related collaborative tools and the required infrastructure to make them work.

T5: Land-based devices and infrastructure: Low-cost computers, personal computers, servers, as well as the improvement of land-based telephone systems and the required infrastructure to make them work such as fiber-optic systems, DSL, and cable.

T6: Country-specific software: Applications software customized for the specific requirements of the country, including multilingual tools, reading tools for the vision impaired, interpreting/translating tools for content, voice recognition tools, and other similar software.

T7: Mass communication systems: Television, radio, and other related hardware and broadcast devices as well as the required infrastructure to make any of these devices work.

11.1.3.3 The Outputs and Information Sources

The model provides six main outputs:

1. Identification of:
   (a) Sk: Sector (k) for k =1, . . ., 5
   (b) Aj: ICT application (j) for j = 1, . . ., J
   (c) Ti: Information and communication technologies (i) for i = 1, . . ., I
2. t_{ij}: Relative impact of ICTs (i) on application (j)
3. a_{jk}: Relative impact of ICT application (j) on sector (k)
4. s_k: Relative impact of reducing the digital divide on sector (k) on objective (reducing the digital divide):
5. $a_j = \sum_{k=1}^{k} a_{jk} * s_k$: Relative impact of ICT application (j) on reducing the digital divide
6. $t_i = \sum_{k=1}^{k} \sum_{j=1}^{j} t_{ij} * a_{jk} * s_k$: Relative impact of ICTs (i) on reducing the digital divide

The following figure depicts the information sources and outputs of the model (Fig. 11.2).

The sectors, ICT applications, and ICTs were identified by gathering information from the literature, and having it modified and validated by the expert panel. For outputs 2–4, the source of information was the expert panel. Outputs 5–6 were obtained based on the analysis of the experts' quantified judgments.

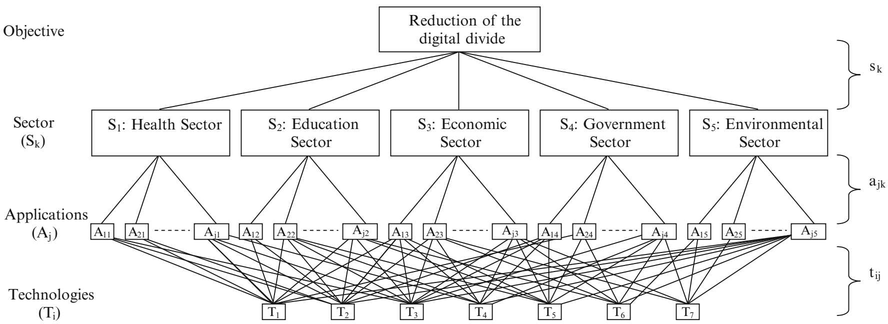


Fig. 11.2 Output and information sources of the model

11.2 Data Collection

11.2.1 Process

This research has four main steps for the data collection process:

1. Obtain the consent of expert panel members for participation in the study.
2. Develop the model and the applications through interviews and the Web instrument.
3. Create, distribute, and collect the judgment quantification instruments for pairwise comparison by the experts.
4. Present the results to the expert panel members for validation.

11.2.2 First Step: Human Subjects

The human subjects form for obtaining consent of expert panel members for participation in the study was translated into Spanish and sent to each participant via e-mail. The forms were received with a digital signature before the data collection started. The original signatures were also collected when the pairwise comparison instrument was subsequently personally presented to each expert panel member.

11.2.3 Second Step: Model Definition

A framework model was constructed based on the UNDP concepts presented in "Creating a Development Dynamic: Final Report of the Digital Opportunity" [1] in addition to the concepts of the literature search. Detailed information about the process and the methodology used for this study was provided to the expert panel in person. A preliminary list of suggested sectors and ICT applications was also presented to the expert panel members. Each expert panel member was asked to analyze this information and determine if he/she believed it necessary adding, deleting, or modifying the list of applications and the sectors.

In order to prevent any bias that the experts might have had toward their own additions to the model, additions from multiple experts were combined and reworded such that no addition was solely based on the exact words of one expert.

The expert panel members with technological backgrounds were asked to identify all the ICTs that will impact the reduction of the digital divide and/or ICTs needed for the ICT applications and to group these technologies under a more generic classification. The compiled list of 42 technologies was reviewed, modified, finalized, and consolidated into a list of seven ICTs described in Sect. "Fourth Level."

11.2.3.1 Web Instruments

After these first interactions with the expert panel members, the complete hierarchical model was presented to the expert panel via a Web instrument for a final review and approval. The complete expert panel was asked to review the model and the definitions of each item in the hierarchy to identify and propose any suitable modification for the proposed model.

The Web instrument has eight parts as follows:

- Part I: Registration, introduction, and presentation of the model.
- Part II: The instructions, the definition of the objective "the reduction of the digital divide in Costa Rica," and the definitions of reduction of the digital divide of each sector.
- Parts III to VII: The instructions, the objective of each instrument, the definition of the reduction of the digital divide in each sector, the definition of the ICT applications of the sector, and an open part to make changes and/or comments if needed.
- Part VIII: The instructions for the ICTs, the definition of each ICTs, and an open section for changes and comments, as needed.

11.2.4 Third Step: Judgment Quantification Instrument

Once the model was finalized, the expert panel members were asked to fill out a series of pairwise comparison instruments with two time frames of reference: short and longer terms. The judgment quantification instrument is a set of 31 pairwise comparison instruments. Instrument 1 includes the pairwise comparison of the relative impact of the reduction of the digital divide on each key sector on the overall reduction of the digital divide in the country. Instruments 2–6 include comparisons of the relative impact of the ICT applications on the reduction of the digital divide of the appropriate sector. Instruments 7–31 are the instruments to evaluate the relative impacts of the ICTs in each ICT application.

11.3 Results

11.3.1 Impact of Key Sectors on the Reduction of the Digital Divide in Short Term

Figure 11.3 represents the impacts of the key sectors in the reduction of the digital divide in Costa Rica for short term according to the judgment of the experts.

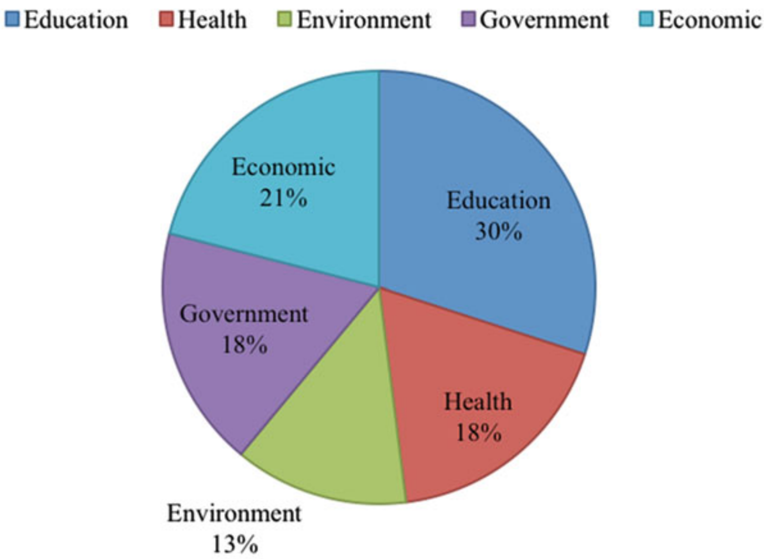


Fig. 11.3 Impacts of the reduction of the digital divide on key sectors in the overall reduction of the internal digital divide in short term

In short term the sector with the highest impact on the reduction of the digital divide is the education sector. If we group the sectors by high, medium, and low impact on the reduction of the digital divide, the groups will be as follows:

• High impact:	Education
• Medium impact:	Economic, government, and health sectors
• Low impact:	Environmental sector

11.3.2 *Impact of Key Sectors on the Reduction of the Digital Divide in Long Term*

Figure 11.4 represents the impacts of key sectors in the overall reduction of the digital divide in Costa Rica for long term according to the judgment of the experts.

For the year long term, the sector with the highest impact on the reduction of the digital divide is again the education sector. By grouping the sectors by their impact on the reduction of digital divide we will obtain:

• High impact:	Education
• Medium impact:	Economic, government, and health sectors
• Low impact:	Environmental sector

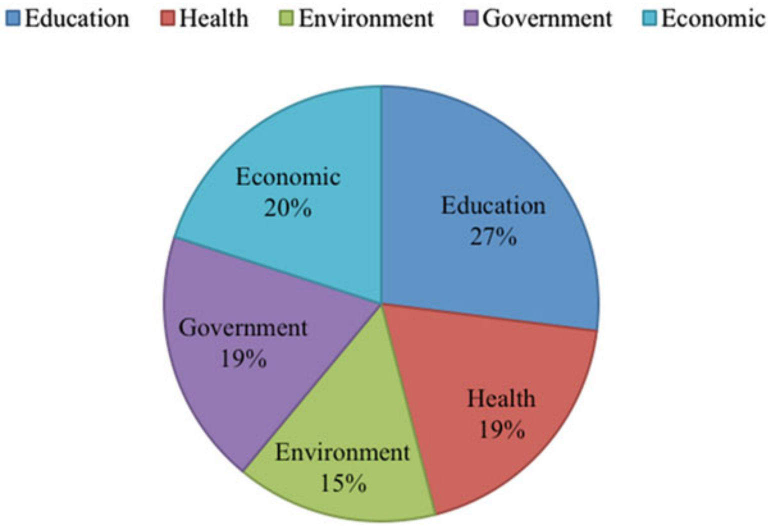


Fig. 11.4 Impacts of the reduction of the digital divide on key sectors in the overall reduction of the internal digital divide in long term

The relative impact rankings on the reduction of the digital divide for the sectors remain the same. However, the values have a slight change. The education sector is lower than in short term and the other sectors are higher. There was a heavy emphasis on the reduction of the digital divide on the education sector in short term. For the year long term, the emphasis on the education sector will continue, but the impact of the other sectors will gain a higher relative importance than in short term.

11.3.3 Impact of Applications on the Reduction of the Digital Divide in the Health Sector

Figure 11.5 represents the impacts of the ICT applications on the reduction of the digital divide in the health sector for the short term and long term.

Grouping the applications by the level of impact, we will have:

• High impact:	A13: Providing online medical libraries
• Medium impact:	A11: Making health services widely available and identifying appropriate level or medical response according to the population's needs A15: Improving the efficiency of the public health system in every geographic area A12: Preventing diseases and improving epidemic responses
• Low impact:	A16: Creating awareness of health issues in the population through the use of ICTs A14: Facilitating medical research in distant research facilities

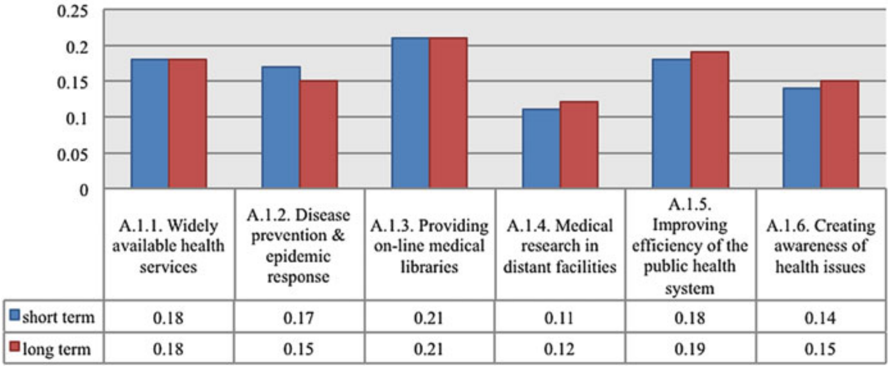


Fig. 11.5 Impacts of ICT applications on the health sector for short term and long term

Providing online medical libraries, making medical libraries accessible to health professionals, especially in remote areas to keep up to date on medical knowledge, and providing the general population with the means to learn more about certain illnesses or health issues are the applications with the highest relative impact in both short term and long term. The second group relates to improving the current health system. Finally, the third group relates to general awareness and medical research.

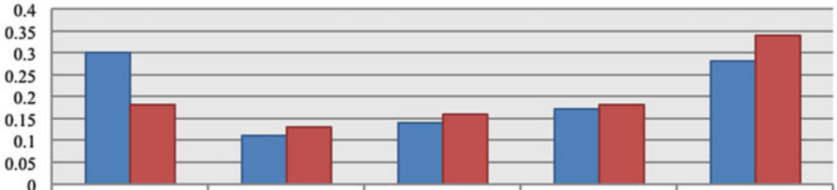
11.3.4 Impact of Applications on the Reduction of the Digital Divide in the Education Sector

Figure 11.6 represents the impacts of the ICT applications on the reduction of the digital divide in the education sector for the short term and long term.

Grouping the applications by the level of impact on the reduction of the digital divide in the education sector in short term, we have:

• High impact:	A21: Enhancing the learning process through the use of ICTs A25: Making programs that foster innovation, creativity, and research throughout the country
• Medium impact:	A24: Providing technical and vocational training to the entire population
• Low impact:	A23: Expanding distance learning A22: Improving the education system administration

On the other hand, we see the following groupings of applications by the level of their impact in the year long term.



	A.2.1. Enhancing the learning process	A.2.2. Improving education system administration	A.2.3. Expanding distance learning	A.2.4. Technical & vocational training	A.2.5. Programs that foster innovation, creativity & research
short term	0.3	0.11	0.14	0.17	0.28
long term	0.18	0.13	0.16	0.18	0.34

Fig. 11.6 Impacts of technology applications on the education sector for short term and long term

•	High impact:	A25: Making programs that foster innovation, creativity, and research throughout the country
•	Medium impact:	A24: Providing technical and vocational training to the entire population A21: Enhancing the learning process through the use of ICTs A23: Expanding distance learning
•	Low impact:	A22: Improving the education system administration

There is an emphasis on enhancing education through the use of ICTs, enhancing the traditional education system, facilitating collaborative and interactive learning, as well as fostering innovation and research in short term. However, in long term, the innovation and creativity factor become more and more important in a country where the population is already familiar with ICTs in the education sector. This application helps to generate new/in-house technologies to help to reduce the digital divide according to the country's own needs. It also reduces technology dependency on other countries for their human capital and technologies.

11.3.5 Impact of Applications on the Reduction of the Digital Divide in the Economic Sector

Figure 11.7 represents the impacts of the ICT applications on the reduction of the digital divide in the economic sector for the short term and long term.

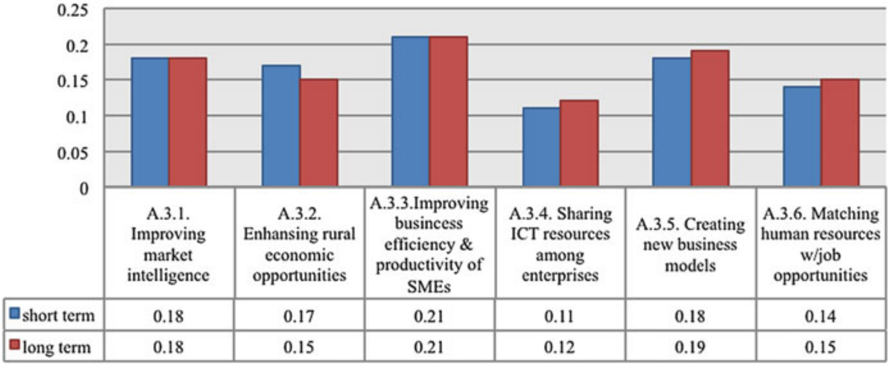


Fig. 11.7 Impacts of ICT applications on the economic sector for short term and long term

Grouping the applications in the economic sector by the level of impact on the reduction of the digital divide in the economic sector in short term, the groups are as follows:

• High impact:	A36: Creating a database to match the availability of human resources with job opportunities A34: Sharing ICT resources among enterprises
• Medium impact:	A31: Improving market intelligence available to every business in the country
• Low impact:	A33: Improving business efficiency and productivity of SMEs through ICTs A35: Creating new business models based on information networks A32: Enhancing rural economic opportunities

In long term the application of enhancing rural economic opportunities becomes part of the group with medium impact on the reduction of the digital divide of the economic sector as shown below:

• High impact:	A36: Creating a database to match the availability of human resources with job opportunities A34: Sharing ICT resources among enterprises
• Medium impact:	A31: Improving market intelligence available to every business in the country
	A32: Enhancing rural economic opportunities
• Low impact:	A33: Improving business efficiency and productivity of SMEs through ICTs A35: Creating new business models based on information networks

Costa Rica should use its existing human and ICT resources effectively in short term. In long term the focus should be on improving the economic opportunities and the available market intelligence.

11.3.6 *Impact of Applications on the Reduction of the Digital Divide in the Government Sector*

Figure 11.8 represents the impacts of the ICT applications on the reduction of the digital divide in the government sector for the short term and long term.

Grouping these applications according to their impact on the reduction of the digital divide in the government sector in short term, we have three groups:

• High impact:	A43: Improving public administration throughout the country
• Medium impact:	A42: Providing universal access to information and online services to empower people
• Low impact:	A41: Facilitating participation of the public in democratic processes

For the year long term we have two groups:

• High impact:	A43: Improving public administration throughout the country
• Medium impact:	A42: Providing universal access to information and online services to empower people A41: Facilitating participation of the public in democratic processes

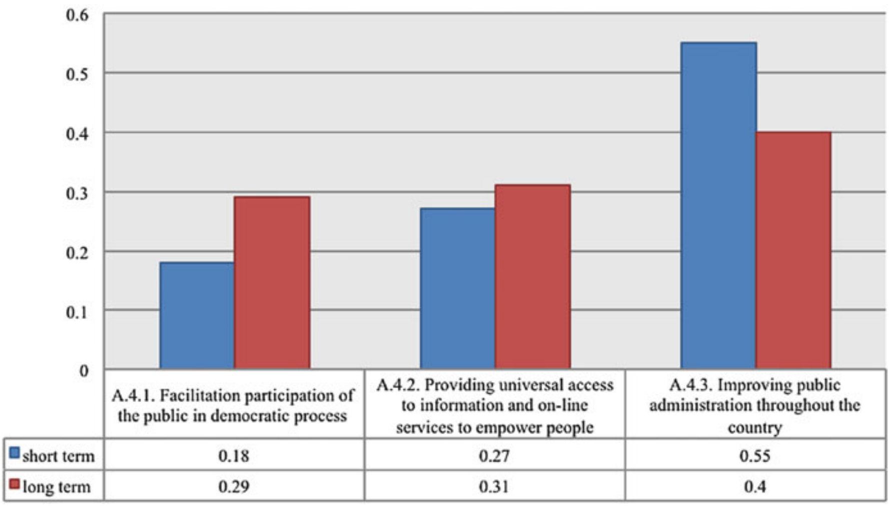


Fig. 11.8 Impacts of ICT applications on the government sector for short term and long term

Improving public administration is the key area that needs major improvements to reduce the digital divide in the government sector. It is expected that the public administration will improve by long term, and the other applications related to empowering the people and providing universal access will gain more weight. Basically, we have the same pattern in short term and long term, but the relative impact of the applications in the medium and low impact groups will be higher in long term.

11.3.7 Impact of Application on the Reduction of the Digital Divide in the Environmental Sector

Figure 11.9 represents the impacts of the ICT application on the reduction of the digital divide in the environmental sector for the short term and long term.

Grouping the applications in the environmental sector by their impacts on the reduction of the digital divide on that sector in short term, we have:

• High impact:	A54: Promoting biodiversity and sustainable development
	A52: Promoting public awareness of environmental issues throughout the country
• Medium impact:	A55: Disseminating information about the best practices
• Low impact:	A53: Monitoring and responding to environmental disasters A51: Monitoring and disseminating information on ecological conditions

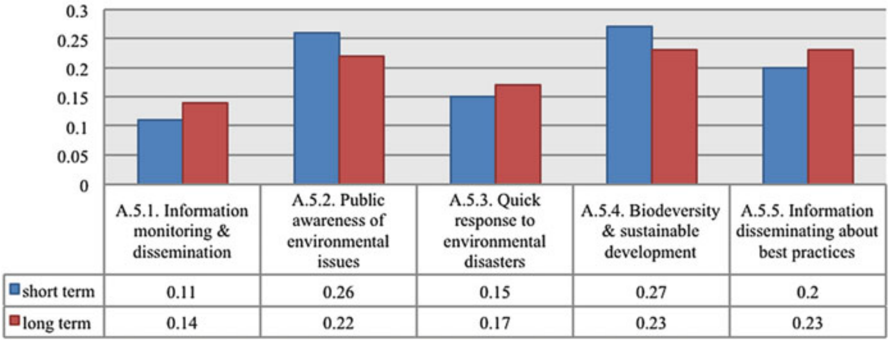


Fig. 11.9 Impacts of ICT applications on the environmental sector for short term and long term

For the year long term, the groups are as follows:

• High impact:	A54: Promoting biodiversity and sustainable development A55: Disseminating information about the best practices A52: Promoting public awareness of environmental issues throughout the country
• Medium impact:	A53: Monitoring and responding to environmental disasters
• Low impact:	A51: Monitoring and disseminating information on ecological conditions

It is important for Costa Rica to promote awareness of environmental issues, biodiversity, and sustainable development; in time, disseminating information about best practices becomes more and more important.

11.3.8 Impact of Information and Communication Technologies on the Reduction of the Internal Digital Divide

Figure 11.10 represents the impacts of ICTs on the reduction of the digital divide in Costa Rica for the short term and long term.

Grouping the ICTs by their impacts on the reduction of the digital divide in short term, we have:

• High impact:	T1: General-purpose software T3: Internet content and infrastructure T5: Land-based devices and infrastructure
• Medium impact:	T2: Mobile devices and infrastructure T6: Country-specific software
• Low impact:	T4: Collaborative tools T7: Mass communication systems

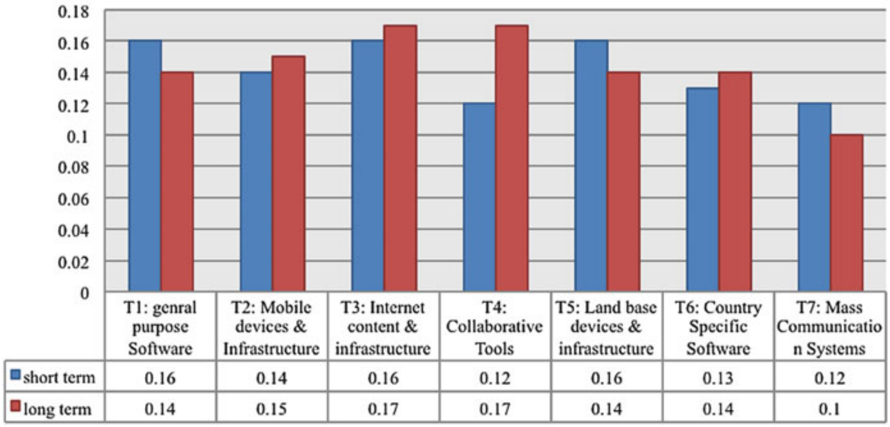


Fig. 11.10 ICTs impact on the reduction of the digital divide in short term and long term

For the long term, the groups are as follows:

• High impact:	T4: Collaborative tools T3: Internet content and infrastructure
• Medium impact:	T2: Mobile devices and infrastructure T5: Land-based devices and infrastructure T1: General-purpose software T6: Country-specific software
• Low impact:	T7: Mass communication systems

Land-based devices, general-purpose software, the Internet content, and infrastructure have the highest impact on the overall reduction of the internal digital divide in short term. It is expected that in the long term the installed base of land-based devices, such as PCs, general-purpose software, and mass communication systems, will have arrived at a level where continued investment in these ICTs will not yield as significant reduction on the internal digital divide as investments in other ICTs.

The impact of collaborative tools increases dramatically from the short term to the long term. Whilst collaborative tools were very important for applications in the education sector in both short term and long term, there is a significant increase of importance of the technology in the economic sector in long term.

The Internet content and infrastructure as well as mobile devices increase their impact in long term, leading us to conclude that the role of technology in the long term will be distinctively oriented toward Internet, mobile, and collaboration.

11.3.9 Summary of Results

The key results can be summarized at three levels:

(a) Relative impacts of the reduction of digital divide in key sectors on the overall reduction of the internal digital divide.
(b) Relative impacts of ICT applications on the reduction of the digital divide in the key sectors.
(c) Relative impacts of ICTs on the overall reduction of the internal digital divide.

Each result is discussed below.

11.3.9.1 Relative Impacts of the Reduction on Digital Divide in Key Sectors on the Overall Reduction of the Internal Digital Divide

The reduction of the digital divide in the education sector has a major impact followed by the reduction of the digital divide in the economic, government, and health sectors in both short term and long term. In both times, the reduction of the digital divide in the environmental sector has the lowest impact on the reduction of the internal digital divide, but it is nevertheless a significant impact, representing 13 % of the total in short term and 15 % in long term.

For the year short term, it is perceived by some of the experts that the reduction of the digital divide on the education sector is in some way at a different level than the other sectors. It is a necessary condition that will impact the reduction of the digital divide in other sectors. According to those expert panel members:

(a) The education sector in Costa Rica is one of the most expensive among all sectors, not only for the equipment but also for the number of people working in that sector.
(b) The reduction of the digital divide in the education sector has a multiplying effect on other sectors' future. For example, re-training professionals from other disciplines in the use of ICTs will lead to innovative applications in all sectors.

The results obtained for the long term generated questions and comments in the expert panel. The panel members indicated that any policies implemented in short term to reduce the digital divide would have dramatic impacts on the reduction of the digital divide in several sectors by long term. In fact, even if the impacts are not very high, the experts believe that many people will have to jump into the technology boat sooner or later.

11.3.9.2 Relative Impacts of ICT Applications on the Reduction of the Digital Divide in the Key Sectors

Figure 11.11 represents the relative impact of all the applications of all the sectors on the reduction of the internal digital divide for the year short term.

Grouping the applications by the level of impact on each sector, we have five groups for the year short term:

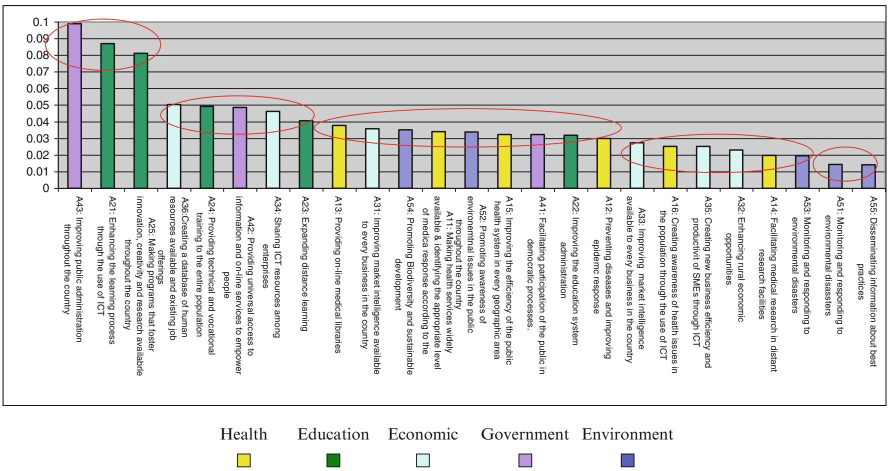


Fig. 11.11 ICT applications on the reduction of the digital divide in short term

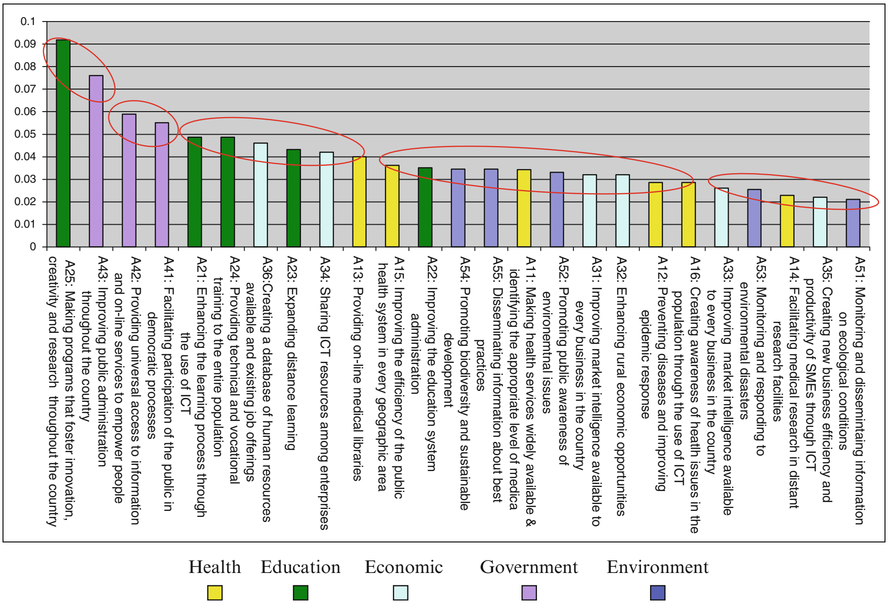


Fig. 11.12 ICT applications on the reduction of the digital divide in long term

- Very high impact: This group consists of three applications, one from the government and two from the education sectors. Those applications are improving public administration, enhancing the education process through ICTs, and fostering innovation and creativity.
- High impact: This group consists of a mix of applications in economic, education, and government sectors, applications that focus on making effective use of human resources and ICT resources.
- Medium impact: This group has a mix of applications from all the groups with a focus on diffusion of information of different topics in different sectors. Most of the health applications are in the medium impact group.
- Low impact: This group is focused on applications on new businesses and rural areas. The applications are mainly from the health and economic sectors.
- Very low: This group consists of applications in the environmental sector with a focus on dissemination of information and prevention in environmental problems.

This can be interpreted as a gradual approach. First, focus on what will have a major impact now and in the future. Then, as second priority, focus on what resources we have now and what our current needs are, matching them together to generate economic and social empowerment. As third priority, grow more horizontally and focus on the health and well-being of the people, and other areas of knowledge. As fourth priority extend the area of action to access rural areas and to reduce the gap in the economic and health sectors. Finally as the fifth priority, consider the environmental applications in the country.

Figure 11.12 represents the impact of the applications of all the sectors on the reduction of the internal digital divide for the long term.

Grouping the applications according to their impact on the reduction of the digital divide in long term, we will have five groups as follows:

- Very high impact: This group consists of one application from the government and one from the education sectors. Innovation and creativity become more and more important as well as improving the efficiency of public administration.
- High impact: This group consists of two applications of the government sector. Applications focus on the empowerment of the citizens.
- Medium impact: This is a mix of applications in education, economic, and health sectors, focused on making effective use of human resources and ICT resources as well as expanding education.
- Low impact: This group is a mix of applications in various sectors. They are primarily related to improving efficiency in education and health system administration, improving rural and economic opportunities, and creating biodiversity awareness. The medium impact level is where the environmental application first appears.
- Very low impact: This group includes applications in health, economic, and environmental sectors with a focus on dissemination of economic, health, and environmental information, in addition to applications on medical research, new business models, and environmental issues.

Fostering innovation and creativity is the leading application followed by improving the public administration through the use of ICTs. It is expected that if the public administration is improved in short term, then in long term it will have a lesser impact. However, fostering creativity and innovation will have a larger impact in long term than in short term, with a society more dependent on technology, the need for innovation, and creativity increases. After that, applications that look for empowerment of the population to participate in public and government processes, followed by improving the public services in health and education. The next group of applications focus on improving the situation in rural areas, and finally applications of awareness and prevention in the environmental sector and health.

11.3.9.3 Impacts of ICTs on the Reduction of the Digital Divide

Table 11.1 presents a comparison of the impact of information and communication technologies on the overall reduction of the digital divide in short term and long term.

The ICTs with the highest relative impacts in short term are land-based devices, Internet content and infrastructure, and general-purpose software. As we move toward long term, the role of technology becomes distinctively oriented toward

Table 11.1 Ranking of relative impacts of ICTs on reducing the internal digital divide in Costa Rica

short term		long term	
ICTs	Rank	Rank	ICTs
T1: General purpose Software	1	1	T3: Internet content & infrastructure
T3: Internet Content & Infrastructure	1	1	T4: Collaborative tools
T5:Land-based devices & Infrastructure	1	3	T2: Wireless devices & infrastructure
T2: Wireless devices & Infrastructure	4	4	T1: General purpose software
T6: Country specific software	5	4	T5:Land-based devices & infrastructure
T4: Collaborative tools	6	4	T6: Country specific software
T7: Mass communication systems	6	7	T7: Mass communication systems

the Internet, mobility, and collaboration. The difference between the impact of wireless devices and land-based devices is small by long term. In both cases the mass communication systems are the last group. They have an impact on the reduction of the digital divide, but their relative impact does not grow from short term to long term; in fact it is slightly reduced.

11.4 Conclusions, Contributions, and Future Work

11.4.1 Conclusions

Four major conclusions are derived from the results of this study.

1. Reduction of the digital divide in the education sector will have the highest impact on reducing the overall internal digital divide in Costa Rica. The ICT applications with major impact on the reduction of the digital divide of this sector are "enhancing the learning process through the use of ICTs" and "making programs that foster innovation, creativity, and research." The top-ranked technologies for these applications are "collaborative tools" and "country-specific software."
2. ICT applications in the government and education sectors have the greatest impact on the overall reduction of the internal digital divide in Costa Rica.

These are applications focused on improving public administration and fostering innovation and creativity.

3. The relative impact of “Internet content and infrastructure” and “collaborative tools” on reducing the internal digital divide will grow from short term to long term. The relative impacts of the “general-purpose software” and “land-based devices” will diminish in the same time frame. Technologies can be clustered into three priority levels in terms of each technology’s impact on the overall reduction of the internal digital divide in short term and long term.

	Short term	Long term
High impact	T1: General-purpose software T3: Internet content and infrastructure T5: Land-based devices and infrastructure	T3: Internet content and infrastructure T4: Collaborative tools
Medium impact	T2: Wireless devices and infrastructure T6: Country-specific software	T2: Wireless devices and infrastructure T1: General-purpose software T5: Land-based devices and infrastructure T6: Country-specific software
Low impact	T4: Collaborative tools T7: Mass communication systems	T7: Mass communication systems

4. The most effective ways to reduce the overall internal digital divide in Costa Rica are to:

   (a) Enhance the learning process through the use of ICTs in the education sector.
   (b) Develop ICT-enabled educational programs that foster innovation, creativity, and research.
   (c) Focus on using ICTs to improve public administration.

11.4.2 Contributions to the State of Knowledge

This research establishes a decision-making process and model for the reduction of the digital divide and identifies, assesses, and selects the appropriate ICTs, ICT application, and sectors for the reduction of the internal digital divide in a developing economy.

There is a substantial amount of information in terms of case studies and policy-level recommendations about the digital divide. The model operationalizes UNDP concepts, providing a generalized model for developing countries to reduce the digital divide by using ICTs. In other words, this research provides a tool to make educated policy decisions in terms of ICTs and the digital divide.

This model and its methodology can be generalized to different countries to identify the ICTs, technology applications, and sectors and their impacts on the reduction of the digital divide. The general objective is applicable in any developing country, and the sectors studied are present in any society. The results may have different relative weights in different countries. ICT applications and technologies are mostly constant for all countries at a given time but may also have different weights in different countries. The model can be applied to other technologies too.

The research presents another application of AHP at the policy-making level for the reduction of the digital divide. It also presents policy modeling as a series of impact relationships among technologies, applications, key sectors, and the country's objective. Finally, systems perspectives can be applied to the decisions related to the digital divide by identifying the appropriate systems and the different perspectives.

Research in developing countries is usually done by people from abroad. A frequent problem with this research is the lack of a real link between the research and the country of origin [6]. In this research, the panel of experts is formed by people who are related to the country and have an active participation in Costa Rican society.

This research provides Costa Rica with a decision-making tool to reduce its digital divide through a participative decision process using expert opinions to prioritize the reduction of the digital divide of the sectors, ICT application and ICTs.

11.4.3 Contributions to Costa Rica

This research contributes to Costa Rica by:

1. Applying the model to a critical policy decision involving key people at high levels of national decision making.
2. Providing an in-depth understanding of the relative impacts of reducing the digital divide in key sectors.
3. Identifying the top-ranked ICT applications and ICTs in each sector for both short term and long term.
4. Enabling the decision makers in Costa Rica to select the areas on which to focus. Table 11.2 presents top-ranked sectors, ICT applications and ICTs, for short term and long term. This table could be used in many different decision scenarios. For example: (a) the decision maker who is responsible for reducing the digital divide in the country should focus on columns one and two, (b) the decision maker responsible for reducing the digital divide in a specific sector

Table 11.2 Top-ranked sectors, ICT applications and ITCs, for short term and long term

		Short term		Long term	
Priority	Sector	Top-ranked ICT applications	Top-ranked ICTs	Top-ranked ICT applications	Top-ranked ICTs
1	Education	A.2.1. Enhancing the learning process through the use of ICTs	T4, T6	A.2.5. Making programs that foster innovation, creativity, and research	**T4**, T6, T3
		A.2.5. Making programs that foster innovation, creativity, and research	**T4**, T6		
2	Economic	A.3.6: Creating a database to match the availability of human resources with job opportunities	**T1**, T2	A.3.6. Creating a database to match the availability of human resources with job opportunities	T4, T3
		A.3.4. Sharing ICT resources among enterprises	T3, T1, T5	A.3.4: Sharing ICT resources among enterprises	T4, T2
3	Government	A.4.3. Improving public administration throughout the country	**T1**, T5, T2-T3	A.4.3. Improving public administration throughout the country	T5, T3
4	Health	A.1.3. Providing online medical libraries	T3	A.1.3. Providing online medical libraries	T3
5	Environment	A.5.4. Promoting biodiversity and sustainable development	T3	A.5.5. Disseminating information about best practices	**T6**, T3
		A.5.2. Promoting public awareness of environmental issues throughout the country	T7	A.5.4. Promoting biodiversity and sustainable development	**T3**, T1
				A.5.2. Promoting public awareness of environmental issues throughout the country	T7

should focus on the rows corresponding to the sectors, respectively, or (c) the decision maker who wants to determine which technologies will have the highest impact on a top-ranked application should focus on the application row and the top technologies listed in that row.

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Part IV
Decision Making Tools

Chapter 12
Decision-Making Tools: University Technology Transfer Effectiveness

Thien Anh Tran

Abstract Academic knowledge and technology transfer has been growing in importance both in academic research and practice. A critical question in managing this activity is how to evaluate its effectiveness. The literature shows an increasing number of studies done to address this question; however, it also reveals important gaps that need more research. One novel approach is to evaluate the effectiveness of this activity from an organizational point of view, which is to measure how much knowledge and technology transfer from a university fulfills the mission of the institution. This research develops a hierarchical decision model to measure the contribution values of various knowledge and technology transfer mechanisms to the achievement of the mission. The performance values obtained from the university under investigation are applied to the model to develop a Knowledge and Technology Transfer Effectiveness Index for that university. The Index helps an academic institution assess the current performance of its knowledge and technology transfer with respect to its mission. This robust model also helps decision makers discover areas where the university is performing well, or needs to pay more attention. In addition, the university can benchmark its own performance against its peers in order to set up a roadmap for improvement. It is proved that this is the first index in the literature which truly evaluates the effectiveness of university knowledge and technology transfer from an organizational perspective. Practitioners in the area of academic technology transfer can also apply this evaluation model to quantitatively evaluate the performance of their institutions for strategic decision-making purposes.

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12.1 Introduction

University knowledge and technology transfer (UKTT) has been growing in importance both in academic research and practice. A critical question in managing this activity is how to evaluate its effectiveness. The literature shows an increasing number of studies done to address this question; however, it also reveals important gaps that need more research. One novel approach is to evaluate the effectiveness of this activity from an organizational point of view, which is to measure how much knowledge and technology transfer from a university fulfills the mission of the institution. This research develops a hierarchical decision model (HDM) to measure the contribution values of various knowledge and technology transfer mechanisms to the achievement of the mission. The performance values obtained from the university under investigation are applied to the model to develop a Knowledge and Technology Transfer Effectiveness Index for that university. The Index helps an academic institution assess the current performance of its knowledge and technology transfer with respect to its mission. This robust model also helps decision makers discover areas where the university is performing well, or needs to pay more attention. In addition, the university can benchmark its own performance against its peers in order to set up a roadmap for improvement. It is proved that this is the first index in the literature which truly evaluates the effectiveness of university knowledge and technology transfer from an organizational perspective. This evaluation method incorporates both hard data of academic technology transfer and the judgments of the experts in the field including the university administrators into the problem. Practitioners in the area of academic technology transfer can also apply this evaluation model to quantitatively evaluate the performance of their institutions for strategic decision-making purposes.

12.2 Research Scope

The general goal of this research is to develop a new approach to the evaluation of effectiveness of technology transfer from university to industry. This study approaches the problem by examining a comprehensive list of university technology transfer mechanisms, not just one mechanism or a group of mechanisms, and sees how they help contribute to the achievement of the university's mission. Due to the large amount of data that need to be collected and some uncontrollable challenges in accessing and obtaining those data from the entire university, the study is developed and applied only to science, technology, engineering, and medical schools within the university. The model, however, can be modified and applied to the entire university following the same procedure. In addition, though the model can be applied to make comparison among universities in a group, this study evaluates the effectiveness of a single university to demonstrate the model.

12.3 Terminology

The topic of the study is technology transfer from university to industry. In practice, the term "university technology transfer" is often used to refer to the activities for which the Technology Transfer Office is in charge of at a university, particularly licensing and technological start-ups. This conventional understanding of the term is also used in research although the scope of technology transfer has gone beyond technology licensing from universities to include other means such as research publications, conferences, and training. In fact many scholars point out that technology transfer from universities is not just about licensing but involves many other forms of knowledge transfer. Some researchers use the term knowledge transfer to study the subject, implying a broader sense of the activity. Though there are studies trying to differentiate between knowledge transfer and technology transfer from universities, no norm has been developed in the literature regarding how the terms should be used by researchers to reflect the true nature of the activity. More often than not, the terms technology transfer and knowledge transfer are used at the convenience of the researcher.

This study adopts the broader sense of knowledge transfer from universities to include the conventional technology transfer definition; yet it does not aim to solve this terminology problem in the literature. Instead a compromised term will be used which includes both knowledge transfer and technology transfer, "UKTT." This term may not be neat but we believe that it appeals to the research community in the field. However, the term "university technology transfer" (UTT) is used in the literature review section to refer to what has been used in the literature. The term "knowledge and technology transfer" emphasizes the broader scope of the research, while the term "technology transfer" helps readers relate to what is familiar to them.

12.4 Literature Summary

A comprehensive literature review was conducted on topics related to the evaluation of university knowledge and technology transfer effectiveness. Combinations of keywords were used to search for materials including university, academic, knowledge transfer, technology transfer, university industry relations, effectiveness, evaluation, and assessment. Most relevant articles in leading international journals and other publications were retrieved and reviewed. The literature review has provided a picture of how university knowledge and technology transfer is implemented and evaluated. It spans a number of topics including the debate on the economic mission of research universities, the interplay between knowledge transfer and technology transfer, technology transfer mechanisms to UTT effectiveness evaluation.

Though there is still some skepticism most of the researchers have come to the agreement that research universities have taken on a third mission which is capitalizing on intellectual capital generated by research at universities in addition to the two traditional missions in the nineteenth century and first half of the twentieth century. This "capitalization of knowledge" is at the heart of a new mission for research universities [1]. Universities now promote knowledge and technology transfer to improve local business competitiveness, the regional economy, and innovation as well as for financial recuperation from increasing research expenditures.

However as an emerging field of research in the 1980s this branch of management poses a dispersion of topics, approaches, and terminologies taken by the researchers. There is no consensus among the research community with regard to what technology transfer, knowledge transfer, various transfer mechanisms, and so on are. There is a need to clarify the interplay between knowledge transfer and technology transfer as these two concepts often go hand in hand. When a physical technology is transferred, intangible knowledge is also transferred [2]. European researchers often use the term knowledge transfer to investigate a broad spectrum of the activities involved in transferring research results to industry, while their American counterparts tend to use the term technology transfer, which reflects a focus on patenting, licensing, spin-offs, and the role of the TTOs at American universities. There is a concern about what the scope of technology transfer at universities in America should be. Should it be confined to what the TTO is institutionalized for or be more than just that? In fact many researchers have pointed out that a focus on patents, licensing, and spin-offs provides an incomplete picture [3]. Gopalakrishnan and Santoro [4] posit that technology transfer is a much narrower construct than knowledge transfer. Few technology transfer studies include conferences and publications as transfer mechanisms while knowledge transfer research often incorporate patents, licensing, and spin-offs among many others. While the taxonomy of terms is not yet available it is suggested that researchers should adopt a broader perspective when assessing the transfer of research outputs from universities to industry in particular and society in general.

Figure 12.1 depicts the knowledge and technology transfer from universities to society including industry. The process starts with the expenditures by universities on research every year. The researchers or faculty conduct research and come up with new findings and knowledge from the research which is then either patented or not. In fact, only a small fraction of the generated knowledge can be codified in patents [3], and not all researchers patent their inventions [5]. According to knowledge management theory, knowledge can be classified as either explicit knowledge or tacit knowledge [6]. Explicit knowledge has been or can be articulated, codified, and stored in certain media. By contrast, tacit knowledge is difficult to transfer from one person to another by means of written or spoken language. Thus only the explicit aspects of new knowledge generated from university research can be codified in the form of patents or publications[1].

[1] A typical example is the Bessemer steel process. Bessemer sold a patent for his advanced steel making process and was sued by the purchasers who couldn't get it to work. In the end, Bessemer

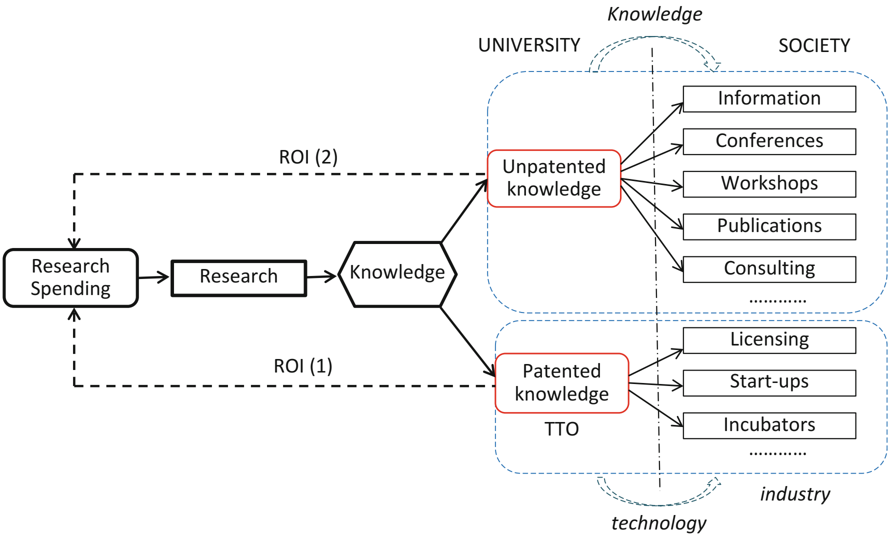


Fig. 12.1 Knowledge and technology transfer from university to society

Then only a small share of the total codifiable knowledge is filed for patents by the researchers (10–20 % at MIT, [5]). Some tacit knowledge is codifiable, but most (also called sticky knowledge) is not and remains with the researchers. Tacit knowledge can only be transferred effectively by means of personal contacts such as consulting, workshops, personal exchange, and joint research. Previous studies which are focused on the TTOs only take into account the patented portion of the total new knowledge generated by university research from the total research expenditures. As a result, they face a dilemma of underestimating the return on investment of university research as only the returns, often in monetary terms, from legal instruments (patents) are accounted for (ROI (1) in Fig. 12.1). This explains why the ROIs of US university technology transfer reported in some research are strikingly low. For instance, the Johns Hopkins University, the top research spending university in the USA, consistently receives licensing income of less than 2 % of its research expenditures for many years[2], while it has been rated among leading universities in research impact [7]. The question here is where the rest of the university's research outputs go to besides those legal instruments, or how the total knowledge generated from research gets transferred from the university to society. Figure 12.1 illustrates the answer to this question. The portion of the

set up his own steel company because he knew how to do it, even though he could not convey it to his patent users. Bessemer's company became one of the largest in the world and changed the face of steel making (source: wikipedia.org).

[2] In 2007, the university spent $1.1 billion in research expenditures and received $1,026,000 of licensing income for the corresponding year (source: AUTM report, 2007).

knowledge generated which is not patented will be transferred to the society via several other channels, ranging from the basic activities such as provision of technological information to the interested parties to more personal interactive means such as consulting. Through these researcher-centric mechanisms, a significant portion of the new knowledge, often tacit in nature, can be effectively transferred to the users. Therefore any study that aims to evaluate UTT should incorporate the impact of the informal knowledge and technology transfer channels into the analysis. By adding the missing link—ROI (2) in Figure 12.1—the large investments in university research can be better justified. Obviously this is not an easy task, but it highlights the dilemma when only hard data such as research expenditures and licensing incomes are used to evaluate UTT.

In close relation to the knowledge vs. technology transfer problem, the transfer mechanisms or activities considered in the studies also vary greatly depending on the researcher's perspective—the narrow technology transfer perspective or the broad knowledge transfer perspective. Even among the knowledge transfer studies it can be seen that different papers introduce different sets of knowledge transfer activities. Again, the researcher community has not yet provided a common set of knowledge and technology transfer mechanisms. While technology transfer activities involve new tools, methodologies, and processes, knowledge transfer activities often engage broader learning [4]. Other researchers, e.g., Link et al., classify transfer mechanisms into formal and informal mechanisms. Formal mechanisms are those directly resulting in a legal instrument such as a patent, license, or royalty agreement. Informal mechanisms focus on non-contractual interactions of the agents involved.

Only 10 % of new knowledge is transferred from the research labs through patents, as estimated by researchers at MIT. That is in addition to the fact that only about 10–20 % of faculty members file for patents as opposed to 60 % publishing in a given year during the 15-year period under investigation [5].

Most of the existing research has focused on formal TT mechanisms, while only a few studies have investigated informal mechanisms. In fact formal and informal technology transfers mutually reinforce each other [8]. Agrawal concludes that non-patent channels are economically important, and there is a need for further research to specifically examine the nature of those transfer channels less studied in the literature [9].

Another observation from the literature review is that most studies do not pay attention to and focus on delineating the indicators or metrics of the technology transfer mechanisms to an adequate extent. Most papers only describe or discuss the mechanisms or investigate the impact of the mechanisms. An exception is the work by Geisler and Rubenstein [10], in which the authors propose a list of potential indicators for evaluating university industry interactions. However since the introduction of this study in 1989 its result has not been adopted in any other studies. Most studies employ common sense indicators such as number of patents, number of publications, amount of licensing income but this use is still not consistent across the studies. The Milken report by DeVol et al. [7] is the only study that looks at the citations of research publications as indicators of the quality of publications used as a knowledge transfer mechanism. In short, there is a need for researchers to develop a comprehensive list of indicators and metrics of the knowledge and technology transfer mechanisms.

The striking finding from the literature review is that there are very few studies which directly address the issue of evaluating university technology transfer effectiveness. Some studies mention the effectiveness of UTT from a distant angle such as a literature review [11] or propose models to improve the effectiveness of UTT [12]. Some even claim that they address the UTT effectiveness problem while in fact they present a different issue [13]. This is partly due to the fact that there is no universal definition of UTT effectiveness and thus researchers may use this term at their discretion. Many studies can be classified into the innovation- or process-based approach; that is, they aim to investigate the effectiveness of the transfer process and its factors. Therefore these studies can take on subjects other than effectiveness evaluation, e.g., impact analysis, determinant analysis, and success factor assessment. They share the same purpose which is to improve the success of the technology transfer process. In addition since they tackle the transfer process and its factors they tend to focus on the role of the TTO as the facilitator of the process.

Future research should look at data sources other than AUTM and NSF used in this study, and include the role of university administrators in the examination of university technology transfer effectiveness [14].

Only two studies found in the literature directly address and measure the effectiveness of UTT. One takes the TTO as the study object, and the other research centers. Both of these studies were led by E.M. Rogers and define technology transfer effectiveness as the degree to which an organization fulfills its objectives through TT.[3] Interestingly, E. Rogers is the theorist of *diffusion of innovation* [16]; yet he and his colleagues adopt the organizational effectiveness definition in their studies of UTT effectiveness, while the majority of researchers in the field adopt the process based on the innovation theory approach.

Nevertheless both studies of Rogers et al. have a major drawback. Both studies obtain TT effectiveness scores by using averaging method on the TT effectiveness indicators. In their 1999 paper [14], the data are derived from interviewing the research centers. In their 2000 paper [15], the indicators are based on the steps of the suggested TT process. The authors then use correlation analysis to justify the relationship between the indicators and the effectiveness score. In fact, the resulting effectiveness scores have no relation to the organization's objective as claimed by

[3] Rogers et al. [14]: see page 692 for definition.
Rogers et al. [15]: see footnote 4 in his paper for definition.

Table 12.1 The distinction among the related topics in technology transfer evaluation

Research problem	Description
Process evaluation	The evaluation of the phases, stages, antecedents, determinants, etc. These are influential factors that help improve the success of the TT process
Performance evaluation	Evaluation of the outputs of TT activity
Efficiency evaluation	Evaluation of how well the TT activity is performed, measured by the ratio between the outputs and inputs of the process
Effectiveness evaluation	Evaluation of the degree to which TT activity is achieving the organization's desired result

Definition of effectiveness: "Effectiveness is the degree to which something is successful in producing a desired result" (Oxford Dictionary)

their definition since they are merely averaged scores of the indicators' values. The former paper has no upper limit for the effectiveness score while the latter sets the experts' maximum ratings, which do not represent the university's objectives, the upper limit of the effectiveness score. Hence these studies can only rank the organizations on their TT effectiveness scores, but can make no conclusion about how effective each organization is relative to its own objective. The mismatch between the definition and the measurement of UTT effectiveness is the main shortcoming of these two studies. In addition the latter paper was restrained by the data available only from AUTM, and thus the effectiveness score was biased.

In an attempt to make a distinction among the many related research problems found in the literature concerning evaluation of university technology transfer, this study presents a description of research topics that are different but often confused with each other, including process evaluation, performance evaluation, efficiency evaluation, and effectiveness evaluation. Many studies in the literature fail to recognize the differences among these concepts and thus they often confuse the terms. For instance a paper claiming to address the effectiveness problem of technology transfer may in fact simply examine the outputs or performance of the activity. This distinction is necessary for this study as well as future research in defining the focus of the research problem. This categorization also covers most problems concerning UTT evaluation in particular or technology transfer evaluation in general (Table 12.1).

From the above discussion of the literature, some major gaps with respect to the research interest of this study are identified as follows:

12.4.1 Gap 1: There Is No Organizational Mission-Oriented Study to Evaluate UKTT Effectiveness

A large number of studies in the literature measure UTT effectiveness by an innovation diffusion, or process-based, approach. These studies aim to analyze and improve the UTT process, and they are often descriptive in nature. Some of them focus on process productivity while claiming to address the effectiveness of UTT. Only two studies by Rogers directly measure the UTT effectiveness and claim to adopt an organizational effectiveness definition. However both of them actually come up with TT effectiveness scores that do not relate to the organizational mission. In addition, one study by Rogers only examines TTOs; the other is targeted at university-based research centers. Thus there is a need to extend the group of organizational effectiveness studies for UTT which define UTT effectiveness as the degree to which the university's mission is achieved through UTT activities.

12.4.2 Gap 2: There Is No Common Set of Mechanisms and Metrics for UKTT Research

It is easily seen in the literature that every UTT study uses a convenient set of TT mechanisms, mostly involving legal instruments such as patents, licensing, and spin-offs. As pointed out earlier, this narrow set of TT mechanisms may represent a biased view of university TT since legal TT instruments only constitute part of the knowledge transferred from a university to industry. Some studies introduce wider ranges of UTT means; yet these sets of UTT means are different from one study to another. In particular the two papers by Rogers only examine limited TT mechanisms, mostly involving legal instruments. Thus there is a need for a comprehensive set of transfer mechanisms which best represents the wide spectrum of UKTT and serves as a reference for future research in the field.

12.4.3 Gap 3: There Is Limited Use of Available Research Methods in Previous Studies

A large number of studies are explorative such as literature review, case studies, and discussion. This reflects the developing status of the UTT field. Another group of studies quantitatively examine the topic, albeit using simple research methods such as descriptive statistics and correlation analysis. While a variety of research methods for technology management studies are available [17], only a few have been employed to study UTT effectiveness. This represents an opportunity for future research to apply other research methods because they can help solve different problems in the field. Particularly for organizational effectiveness analysis, a judgment quantification method should be applied as these studies often entail the subjective judgments of experts to measure the degree to which the organization's mission is achieved.

12.5 Research Objectives

Having reviewed the literature on the topic of research and identified the gaps in the literature, this study aims to achieve the following objectives:

12.5.1 Objective 1: To Evaluate Organizational Effectiveness of UKTT at the University Level

As mentioned in Gap 1, most research on UKTT effectiveness looks at analyzing and improving the UKTT process without actually measuring the effectiveness of the work. Only two studies by Rogers adopt the organizational effectiveness definition and aim to measure the UKTT effectiveness by developing UKTT effectiveness scores. However both fail to conform to their definition of UKTT effectiveness. This study fills that gap by developing an organizational mission-oriented approach to measure UKTT effectiveness. It aims to determine to what degree UKTT contributes to a university's mission. The study takes into consideration the entire spectrum of knowledge and technology transfer activities taking place across the university rather than being confined to the TTO or a similar unit in the university. This is to ensure the comprehensiveness and significance of the research.

12.5.2 Objective 2: To Compile a Common Set of Mechanisms for UKTT Research

Gap 2 says that no previous study has offered a common set of mechanisms representing the entire range of UKTT activities. Each study in the literature presents a different compilation of UKTT mechanisms. Many only look at those means related to legal instruments such as patents. Thus the second objective of this study is to compile a comprehensive collection of various UKTT mechanisms which include both technology and knowledge transfer means. Together with this mechanism list the research also develops a set of metrics for each of the UKTT mechanisms in order to measure their performances. It is hoped that this comprehensive list of UKTT mechanisms with their metrics will serve as a reference for future research in the field of UKTT research.

12.5.3 Objective 3: To Apply a New Research Method for UKTT Effectiveness Study

This study resolves the weakness of previous studies in evaluating UKTT effectiveness, particularly the two by Rogers, by applying a novel research method that can determine the contribution of UKTT means or mechanisms to the overall mission of the organization. To measure the organizational effectiveness of UKTT, subjective judgments or ratings from experts who have in-depth knowledge and hands-on experience of the matter must be sought. Therefore the study develops a research model that utilizes a judgment quantification method to achieve a measure of the UKTT effectiveness. It is the first research in the field to demonstrate the contribution of each UKTT means to the overall effectiveness score. This novel approach also allows evaluating UKTT effectiveness of individual universities as well as comparing a group of universities.

12.6 Approaches to Evaluation of UKTT Effectiveness Research

The literature has seen a plethora of approaches to evaluate UKTT effectiveness. However most studies did not provide a clear definition of the research problem, i.e., effectiveness of technology transfer. As a result, these studies in fact discuss related issues such as impact analysis, determinant analysis, and success factor assessment. Some claim that they address the UKTT effectiveness problem while in fact they present a different issue, e.g., efficiency of UKTT. This is partly due to the fact that there is no common definition of UTT effectiveness and thus researchers may use this term at their discretion. After a thorough examination of the literature, the researcher of this study categorizes the research on UKTT effectiveness into two major approaches as follows:

Innovation diffusion theory approach	Organizational theory approach
The degree to which research results are moved from the research institutions to external parties	The degree to which tech transfer activity helps a research institution achieve its institutional goals

Most prior studies in the literature took the first approach, innovation diffusion theory approach, as they aim to analyze the technology transfer process. The purpose of the technology transfer process in the first approach is to achieve a better transfer process and a higher number of transfer outcomes, e.g., number of licenses and number of start-ups. As a result, the better numerical outcomes are achieved the more effectiveness the technology transfer at the university is. The second approach defines UKTT effectiveness from an organizational perspective.

It is not the numerical outcomes of the transfer process that decides but how much the organizational mission is achieved through knowledge and technology transfer.

Most prior studies adopted the innovation diffusion approach; only two studies conducted by E. Rogers claimed that they adopted the organizational definition for measuring UKTT effectiveness. However these two studies stopped short of measuring the true organizational effectiveness of technology transfer due to their approach and limited data sources. This gap in the research literature paves the way for this study in adopting the organizational definition to address the evaluation of UKTT effectiveness by developing an appropriate research method that reflects the achievement of the organizational mission. Therefore the research problem of this study is defined as "develop an index to indicate the achievement of mission of the university through knowledge and technology transfer."

> Future research should look at data sources other than AUTM and NSF used in this study, and include the role of university administrators in the examination of university technology transfer effectiveness, [14].

12.7 Development of Research Model

In order to determine the contributions of various UKTT mechanisms to the economic development mission of the university, an HDM was developed. The model comprises four levels, including the overall mission of the university in transferring knowledge and technology to public, the specific UKTT objectives, groups of UKTT mechanisms, and specific mechanisms within the groups. The elements in the model were drawn from a thorough literature research and published information. Five UKTT objectives, 10 groups of UKTT mechanisms, and 26 different UKTT mechanisms were identified. These elements in the model were verified by the experts in the field through a rigorous Delphi process. 35 experts participated in the process, including 3 vice presidents for research at US universities, 22 academic researchers who are professors at universities in the USA, Europe, and South America, and 10 technology managers who are from entrepreneurship centers, technology commercialization centers, and technology transfer offices at US universities. These groups of experts helped in different parts of the model verification and model quantification.

After the model was verified, the experts quantified the contribution values of the elements on a level to the next upper level through a pairwise comparison process. Then these matrixes of contribution values were aggregated to come up with the contribution values of each UKTT mechanism at the bottom level to the mission on the top level. These contribution values to the mission of the UKTT mechanisms will be combined with their performance values to determine the effectiveness of knowledge and technology transfer for the university. In this study, instead of using the actual performance values of the mechanisms, e.g., number of patents, the

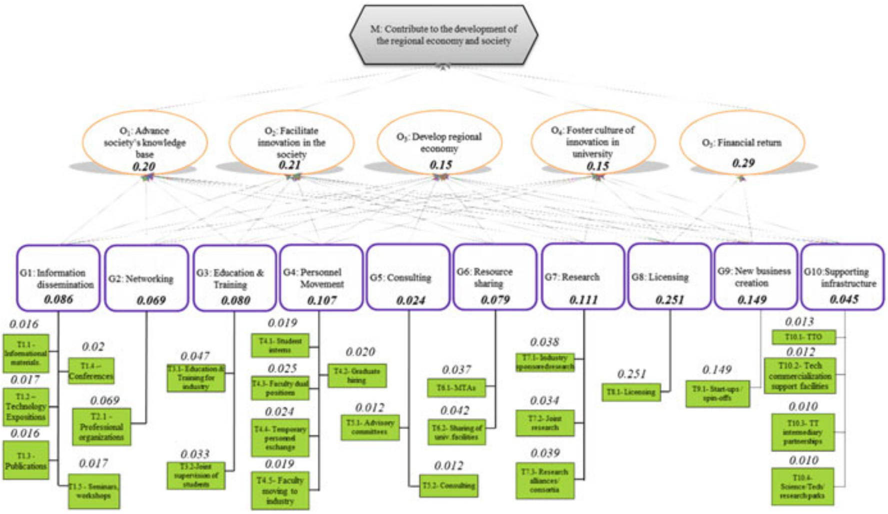


Fig. 12.2 Hierarchical decision model for UKTT effectiveness evaluation

concepts of desirability values and desirability curves of the metrics were applied. The desirability value of a metric reflects the degree of its desirability to the user of the model, the university in this case. For instance, having too much consulting hours may not be desirable to the university as they may take away productive time from the faculty. Thus using desirability values for the metrics represents the "desired achievement" of the university better than the actual values. In this study, a desirability curve was developed with the inputs from the experts for all UKTT metrics. The final UKTT Effectiveness Index for the university is calculated as follows:

$$0 \leq \text{UKTTEI} = \sum_{k,j}^{K,J} \tau_{kj} \, x \, \mathrm{P}\left(\mathrm{T}_{kj}\right) \leq 100$$

τ_{kj}: contribution value of mechanism T_{kj} to the mission

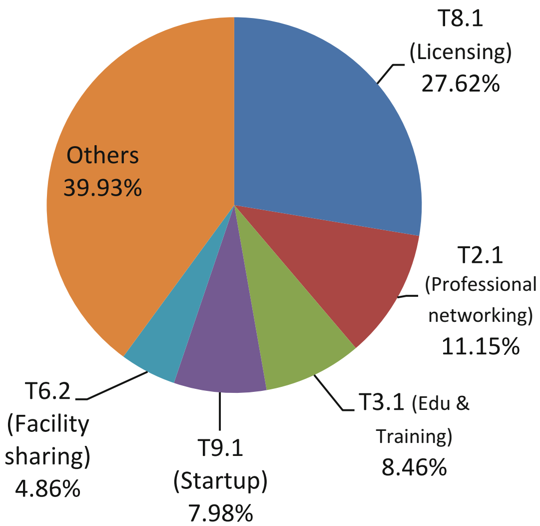
$\mathrm{P}(\mathrm{T}_{kj})$: Performance value of mechanism T_{kj}

A case study of Portland State University was conducted to demonstrate the model in Fig. 12.2.

In this figure, all the elements in the model and the contribution values of the UKTT mechanisms were developed generic to all universities, except for the contribution values of the UKTT objectives to the mission which are specific to PSU. The reason is that every university may have chosen a strategic orientation with regard to knowledge and technology transfer. For instance a university can focus on knowledge generation while another university emphasizes on revenues from technology commercialization. Actual values of UKTT metrics were collected from PSU, and then the desirability values were determined. As a result, the UKTT

Effectiveness Index for Portland State University is 47.4. While 100 points represents a hypothetical university which excels on all mechanisms, this result indicates an average effectiveness level for PSU.

In addition, the model identifies the most important UKTT mechanisms to the university. If the university aims to improve its effectiveness in knowledge and technology transfer, it should focus its resources on these important mechanisms. If two or more universities are compared, the model can point out areas where a university is underperforming its peers so that managerial actions can be taken.



The five most important UKTT mechanisms for Portland State University

12.8 Summary of the Study

An HDM was developed to measure the effectiveness of UKTT in this study. There were many attempts to evaluate the effectiveness of UKTT in the literature; yet those studies have shortcomings. Some did not look at the problem from the big picture. They only focused on a few legal instruments and ignored the important informal channels to disseminate technological information and knowledge from the university to the public. They suffer from the limited availability of hard data for university technology transfer, for instance AUTM data. This study aimed to approach the problem comprehensively to include all major knowledge and technology transfer mechanisms and examine the contribution of these mechanisms to knowledge and technology transfer effectiveness of the university.

The study adopted an organizational definition of effectiveness, which is the degree of achievement of the university's goal in knowledge and technology transfer. A hierarchy of the problem was constructed with the inputs from the experts in the field. Relative contributions of the elements to the overall UKTT mission of the university were also determined through a judgment quantification process. A new concept of desirability curves was applied to convert the actual measurements of the metrics into desirability values as inputs of the evaluation model. This conversion is necessary as it better reflects the usefulness of the numbers in decision making, and it also enables the aggregation of different measurement units. With these inputs the model is capable of producing a composite index to represent the effectiveness of knowledge and technology transfer at university(ies).

Various analyses were conducted to explore the behavior of the research model, including a disagreement analysis to see the impact of the disagreement of the experts' judgments on the final result, a strategic orientation analysis to explore the implication of the model for universities with different strategic UKTT positions, and a scenario analysis and sensitivity analysis to identify the key UKTT areas for improvement at the university.

The research results show that universities with different strategic UKTT objective prioritization are influenced by a different set of transfer mechanisms. Particularly there is a contrast between financial return seeking universities and public service-oriented universities. The former universities rely mostly on licensing and start-ups, while the latter universities are more balanced on a wide range of knowledge and technology transfer mechanisms, and thus enjoy a supplemental effect among these mechanisms in the overall effectiveness index.

The analysis of the university under investigation, Portland State University, reveals that the university still has much improvement to make in order to increase its UKTT Effectiveness Index. Licensing, start-ups, and research alliance are among the important activities that the university should pay attention to.

12.9 Contributions of the Research to the State of Knowledge

The first contribution of this research is to clarify the important concepts and approaches used in the literature on the topic of university knowledge and technology transfer effectiveness. Two main approaches used in prior studies are identified, the innovation diffusion approach and organizational theory approach. Most studies use the first approach while only two papers in the literature, pioneered by Everett Rogers, claim the second. A remarkable observation about the studies taking the innovation diffusion approach is that they do not clearly define what effectiveness is, so the evaluation approaches were loosely designed. On the other hand, the organizational theory approach gives a very clear definition of UKTT effectiveness, one that facilitates a sound evaluation method for the study. Unfortunately the two papers that adopted this definition in the literature failed to actually measure what is defined due to the limited data source and unsuitable research method. The categorization set forth by this research gives guidance for future research in defining the problem appropriately. The current study adopts the organizational effectiveness approach and becomes the third example in the literature on this approach for future studies.

The second contribution of this study to the literature is the expansion of the use of new research methods on the topic. Prior research is limited to a few traditional research methods such as material review, discussion, and statistical analysis. They only used hard data from a few sources, mainly AUTM, with common metrics such as the number of licenses, number of start-ups, licensing revenues, and research expenditures. This limitation in fact puts a curb on the freedom and diversity in academic research of the topic. The result is that there are not many breakthrough research ideas or approaches to the extent that a prominent researcher recommended that future research should look in data sources other than AUTM and NSF used in this study, and take the role of university administrators into the examination of university technology transfer effectiveness [18], and that the technology metrics should be shifted toward a more balanced metric focused on the mission of the research institution [19]. This study accomplished these quests by introducing HDM as a research method for the problem. By applying a judgment quantification method the study was able to draw upon a new source of data, expert judgments, to address the problem from a new perspective and come up with completely new results. The novel approach used in this study has shed new light on the topic and may open a new stream of research in the literature.

Most importantly this study answers one of the most critical research questions raised in the literature regarding evaluating UKTT effectiveness: “Can a measure of technology transfer effectiveness be developed for US research universities?” The study successfully developed a research model to address this question not only to research universities in the USA, but to universities anywhere. The measure is represented by a UKTT Effectiveness Index which is a quantitative indicator of the effectiveness of the university in transferring knowledge and technology to society. The model is robust enough to identify strategic areas for the university to improve its knowledge and technology transfer. In addition it enables comparison of the UKTT effectiveness among the universities so that individual universities can identify the benchmarks for their performances. It is the first time that the roles of various knowledge and technology transfer mechanisms are manifested by concrete numbers. This is also the first study in which a university’s priority of objectives with respect to the economic development mission is quantified with numbers and the relationships between the strategic UKTT orientation of the university and the key UKTT areas are demonstrated.

Last but not least, the approach introduced by this study can be applied to similar research in related fields, including government technology transfer, private sector technology transfer, and international technology transfer.

12.10 Implications of the Study

The study has a two-pronged implication for academic research and practitioners in academic knowledge and technology transfer. For the UKTT research community this study sets an example for exploring new research methods and data sources to approach the evaluation problem. Other researchers can employ the same method used in this study, or further develop the research method, to investigate the problem in different settings.

For UKTT administrators, managers, and practitioners this research provides them with a new way to assess their knowledge and technology transfer activity. It is hoped that the study sheds new understanding for the university administrators and technology transfer managers about the wide boundary of the knowledge and technology transfer activities taking place at their institutions. This boundary should not be viewed as confined to a few transfer mechanisms but rather encompassing the many more subtle and informal channels to transfer both knowledge and technologies from the university to the outside world. Therefore, a comprehensive evaluation of the activity entails the consideration of all these important transfer mechanisms to fully account for the impact of research and knowledge and technology transfer from universities. With this study, policy makers see the large and complex problem of measuring UKTT effectiveness broken down into a well-structured hierarchy of objectives and specific transfer mechanisms and the relationships among them. They can now see the big picture of academic knowledge and technology transfer.

Universities' research expenditures have been increasing at impressive rates in recent years, and there is rising compelling concern about the effectiveness of those large expenditures. This study will help university administrators answer this important question. Unlike prior evaluation methods, this evaluation model gives them a concrete number, the UKTT Effectiveness Index, to have a grasp of the situation. It is much better for people to work with specific numbers than qualitative statements. These quantified results allow convenient comparisons between the university and its peers, and identifying the areas where the university needs to improve. With this evaluation model UKTT practitioners will for the first time see their priorities worked out in specific numbers, i.e., the relative weights, and the dynamics in the contributions of the UKTT mechanisms to the overall performance of the university. These results are useful information for decision makers to plan and manage knowledge and technology transfer activities at their institutions.

The research approach in this study can be applied to other institutional levels or different types of organizations involving technology transfer. For example, it can be modified to evaluate the effectiveness of a Technology Transfer Office at a university. In this case, the top level of the HDM is the mission of the office, and the transfer mechanisms and metrics are those most appropriate to their works. Another example is AUTM. The association can conduct a comparative study among its members for ranking purposes, for instance. In this case the organization will develop a common hierarchical model and weights for its members, or different classes of members. The evaluation approach introduced in this research facilitates flexible applications in many circumstances.

In order to conduct a study of this comprehensiveness, it is recommended that universities, or any organization that wants to apply this research approach, set up a university-wide tracking system of the UKTT mechanism metrics. The university can decide what UKTT mechanisms are important to its mission and what metrics to use for the mechanisms, and then set up a tracking system to collect data of these metrics on a periodic basis. An important note is that the more knowledge and technology mechanisms are included in the evaluation, the more comprehensive the evaluation model is, and the more accurate the data that are made available the more reliable the final results are.

12.11 Limitations of the Study

The evaluation model is presented in this study as a novel and robust model to evaluate university knowledge and technology transfer, yet not without caveats. As in any subjective judgment quantification studies, the results of the research largely depend on the makeup of the expert groups involved. Experts are independent individuals and they may have conflicting opinions about the same problem. This study could not engage the most suitable experts for its purpose due to the lack of connections and the willingness of the invited persons to participate. However it is impossible to eliminate the subjectivity in a research of this nature. Even if the best experts are recruited according to the selection criteria described in this report their judgments are still considered relative.

Another shortcoming of the study is the incomplete data set of the metrics. Unlike most prior research that is based on available data only, this research ventured into areas where data have not been reported at the universities or by any sources. As a result this research assumes many estimated figures to demonstrate the model. That is one of the reasons why validation of the model results is difficult. With a complete and updated set of actual values of the UKTT mechanism metrics the final results would have been more justifiable.

Another limitation of the research is that it did not include all departments that are possibly doing research at the university. Even though the study examines the major science, technology, science, and math departments it does not represent the entire university.

It would have added much more information to the results if the study had included a comparative analysis among a group of universities to see how a particular university ranks in the group in terms of UKTT effectiveness. Due to time limits, this study only investigates a university's UKTT effectiveness, although it provides an analysis on the different strategic UKTT orientations of the universities. Nevertheless, the procedure to evaluate the UKTT effectiveness of a group of universities is laid out in this study.

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Chapter 13
Decision Making Tools: Sensitivity Analysis for the Constant Sum Pair-wise Comparison Method

Jingrui Li and Hongyi Chen

Abstract Every hierarchical decision modeling process starts with quantifying the contributions of decision elements through pair-wise comparisons. As subjective values, the pair-wise comparison judgments are seldom provided at a 100 % confidence level and are subject to variations. To increase the model's validity and ensure requisite decision making, it is important to know how sensitive the model result is to these inputs. In this chapter, a sensitivity analysis algorithm is developed to test a hierarchical decision model's robustness to the pair-wise comparison judgment inputs acquired from the constant sum method. It defines the allowable region of perturbation(s) induced to a judgment matrix at any level of a decision hierarchy to keep the current ranking of decision alternatives unchanged. An example will be presented to demonstrate the application of this algorithm in technology selection.

13.1 Introduction

Hierarchical decision modeling (HDM), including the well-known analytic hierarchy process (AHP) [31] and its variants, is widely used in multi-criteria decision makings. The method provides a simple yet effective way for decision makers to compare tangibles and intangibles side by side, synthesize a large number of information and data at different scales [32], and convert measurements and judgment into data for quantitative decision makings. Since its introduction, an

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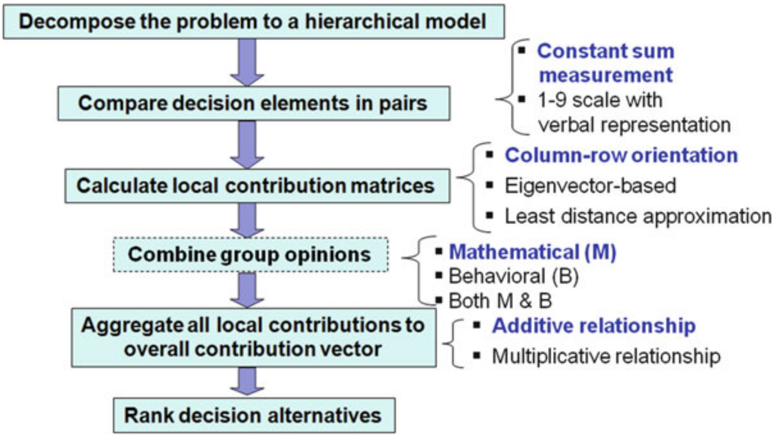

Fig. 13.1 Steps in hierarchical decision modeling

overwhelming amount of publications using HDM as the research method have been generated. Thousands of applications have been reported in social, economical, and environmental fields, such as technology forecasting and assessment, R&D portfolio development, energy choices, investment analysis, medical and health care decisions, and risk assessment [5, 6, 20, 25, 26, 35, 36]. Figure 13.1 shows the steps and the associated methods at each step in building a hierarchical decision model to evaluate decision alternatives.

Step 1—Decompose a problem to a hierarchical model: The HDM starts with understanding and analyzing the internal dynamics and cause-and-effect relationships within a complex decision problem [32]. Then the problem is decomposed into several levels of decision elements with the decision alternatives at the bottom and the criteria and sub-criteria in the middle. The "MOGSA" model originated from [8] and introduced in [7] gives a typical example of the HDM model structure, as shown in Fig. 13.2.

Depending on how much details are needed, the number of decision levels in the MOGSA model can be reduced or increased. As for the number of decision elements at each level, it is suggested that no more than nine should be used due to the limitation of human brains in processing information [29]. Therefore, a decision element on the hierarchy may represent a group of subelements clustered together for effective comparison. Each decision element should be preferentially independent from others on the same level.

Decision elements at one level contribute directly to those at the next higher level. At the bottom level of the hierarchy, actions, which are the decision alternatives, are evaluated and ranked based on their overall contributions to the mission through alignment with strategies, goals, and objectives. To determine the overall contributions of actions, local contributions for decision elements between every two immediate levels are acquired first through pair-wise comparisons.

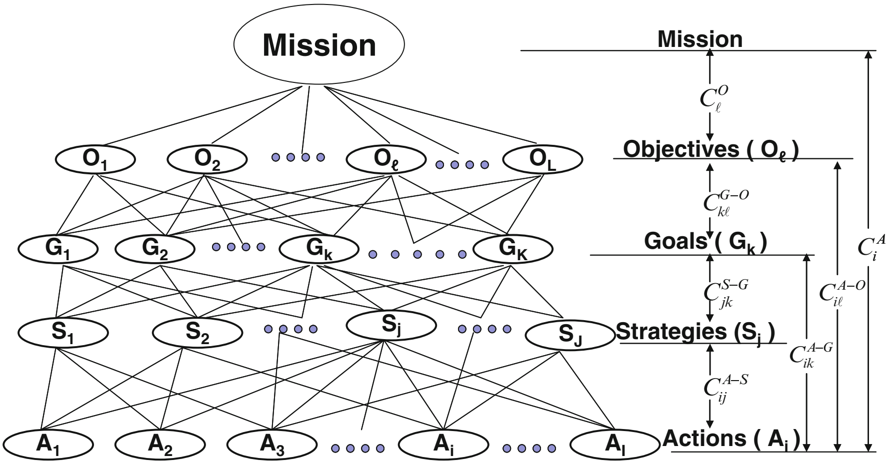

Fig. 13.2 HDM model structure [7]

Step 2—Pair-Wise Comparison: Two types of ratio scales are generally used at the pair-wise comparison step: the 1–9 scale with verbal representation developed by Saaty [31] and the constant sum measurement developed by Comrey [10] and Guilford [16] and refined by Kocaoglu [23]. Since most people are familiar with the 1–9 scale with verbal representation used in AHP [31], in this chapter we introduce the constant sum measurement with more details. The constant sum method asks the experts to distribute 100 points between a pair of decision elements to represent their judgment on the relative importance or contribution that each decision element makes to a higher level decision element. For example, if an expert believes that O_1 and O_2 contribute equally to the mission (M), then the points distributed to O_1 and O_2 will be 50 and 50. If the expert believes that O_1 makes three times contribution to the M as O_2 does, then the points distributed to O_1 and O_2 will be 75 and 25, respectively. The term "constant sum" refers to the procedure for expressing judgments as a constant value—100. Comparing to the 1–9 scale with verbal representation method, this method leads to relatively consistent results [30].

Using the MOGSA model in Fig. 13.1 as an example, $\left(\frac{L(L-1)}{2}+L\times\frac{K(K-1)}{2}+K\times\frac{J(J-1)}{2}+J\times\frac{I(I-1)}{2}\right)$ pair-wise comparisons need to be performed for a decision hierarchy with L objectives, K goals, J strategies, and I actions. As a result, $(1+L+K+J)$ judgment matrices will be created. Table 13.1 shows an example of the judgment matrix for decision elements E_1 through E_Y when they are pair-wise compared regarding their contributions to a higher level decision element. E_y represents any decision element at any level below the mission, such as O_l, G_k, S_j, or A_i in the MOGSA model.

Table 13.1 Constant sum pair-wise comparison judgment matrix $\mathbf{J_{E_x-E_y}}$ (matrix A)

	E_1	E_2	E_3	…	E_y	…	E_Y
E_1		$J_{E_2-E_1}$	$J_{E_3-E_1}$	…	$J_{E_y-E_1}$	…	$J_{E_Y-E_1}$
E_2	$J_{E_1-E_2}$		$J_{E_3-E_2}$	…	$J_{E_y-E_2}$	…	$J_{E_Y-E_2}$
E_3	$J_{E_1-E_3}$	$J_{E_2-E_3}$		…	$J_{E_y-E_3}$	…	$J_{E_Y-E_3}$
⋮	⋮	⋮	⋮		⋮	…	
E_y	$J_{E_1-E_y}$	$J_{E_2-E_y}$	$J_{E_3-E_y}$	…		…	$J_{E_Y-E_y}$
⋮	⋮	⋮	⋮	⋮	⋮		⋮
E_Y	$J_{E_1-E_Y}$	$J_{E_2-E_Y}$	$J_{E_3-E_Y}$	…	$J_{E_y-E_Y}$	…	

Table 13.2 Judgment quantification matrix B

	E_1	E_2	E_3	…	E_y	…	E_Y
E_1	1	J_{E_2/E_1}	J_{E_3/E_1}	…	J_{E_y/E_1}	…	J_{E_Y/E_1}
E_2	J_{E_1/E_2}	1	J_{E_3/E_2}	…	J_{E_y/E_2}	…	J_{E_Y/E_2}
E_3	J_{E_1/E_3}	J_{E_2/E_3}	1	…	J_{E_y/E_3}	…	J_{E_Y/E_3}
⋮	⋮	⋮	⋮	1	⋮	…	
E_y	J_{E_1/E_y}	J_{E_2/E_y}	J_{E_3/E_y}	…	1	…	J_{E_Y/E_y}
⋮	⋮	⋮	⋮	⋮	⋮	1	⋮
E_Y	J_{E_1/E_Y}	J_{E_2/E_Y}	J_{E_3/E_Y}	…	J_{E_y/E_Y}	…	1

An expert only needs to provide judgment values in the lower triangle and values in the up triangle can be calculated by using Eq. (13.1):

$$J_{E_y-E_x} = 100 - J_{E_x-E_y} \tag{13.1}$$

Step 3—Judgment Quantification: The next step is to convert the pair-wise comparison judgments into local contribution vector and matrices, denoted as $\mathbf{C_l^O}$, $\mathbf{C_{kl}^{G-O}}$, $\mathbf{C_{jk}^{S-G}}$, and $\mathbf{C_{ij}^{A-S}}$ in the MOGSA model. Ra summarized the judgment quantification techniques employed at this step into three groups [30]: (1) column-row orientation methods; (2) eigenvector-based methods; and (3) least distance approximation methods. The column-row orientation methods are associated with the constant sum ratio scales, and the eigenvector-based methods deal with the 1–9 scales. In this chapter, we introduce the column-row orientation method.

To calculate the contributions of E_y's, a pair-wise comparison judgment matrix is converted into two matrices, B and C, consequently, as shown in Tables 13.2 and 13.3. Elements in matrix B are calculated from the judgment matrix A based on Eq. (13.2):

Table 13.3 Judgment quantification matrix C

E_1/E_2	E_2/E_3	E_3/E_4	…	E_y/E_{y+1}	…	E_{Y-1}/E_Y
$\frac{1}{J_{E_2/E_1}} = J_{E_1/E_2}$	$\frac{J_{E_2/E_1}}{J_{E_3/E_1}} = J_{E_2/E_3}$	$\frac{J_{E_3/E_1}}{J_{E_4/E_1}} = J_{E_3/E_4}$	…	$\frac{J_{E_y/E_1}}{J_{E_{y+1}/E_1}} = J_{E_y/E_{y+1}}$	…	$\frac{J_{E_{L-1}/E_1}}{J_{E_L/E_1}} = J_{E_{Y+1}/E_Y}$
$\frac{J_{E_1/E_2}}{1} = J_{E_1/E_2}$	$\frac{1}{J_{E_3/E_2}} = J_{E_2/E_3}$	$\frac{J_{E_3/E_2}}{J_{E_4/E_2}} = J_{E_3/E_4}$	…	$\frac{J_{E_y/E_2}}{J_{E_{y+1}/E_2}} = J_{E_y/E_{y+1}}$	…	$\frac{J_{E_{Y-1}/E_2}}{J_{E_Y/E_2}} = J_{E_{Y+1}/E_Y}$
$\frac{J_{E_1/E_3}}{J_{E_2/E_3}} = J_{E_1/E_2}$	$\frac{J_{E_2/E_3}}{1} = J_{E_2/E_3}$	$\frac{1}{J_{E_4/E_3}} = J_{E_3/E_4}$	…	$\frac{J_{E_y/E_3}}{J_{E_{y+1}/E_3}} = J_{E_y/E_{l+1}}$	…	$\frac{J_{E_{Y-1}/E_3}}{J_{E_Y/E_3}} = J_{E_{Y+1}/E_Y}$
⋮	⋮	⋮	⋮	⋮	…	⋮
$\frac{J_{E_1/E_y}}{J_{E_2/E_y}} = J_{E_1/E_2}$	$\frac{J_{O_2/O_l}}{J_{O_3/O_l}} = J_{E_2/E_3}$	$\frac{J_{E_3/E_l}}{J_{E_4/E_l}} = J_{E_3/E_4}$	…	$\frac{1}{J_{E_{y+1}/E_y}} = J_{E_y/E_{y+1}}$	…	$\frac{J_{E_{Y-1}/E_y}}{J_{E_Y/E_y}} = J_{E_{Y+1}/E_Y}$
⋮	⋮	⋮	⋮	⋮	…	⋮
$\frac{J_{E_1/E_Y}}{J_{E_2/E_Y}} = J_{E_1/E_2}$	$\frac{J_{E_2/E_Y}}{J_{E_3/E_Y}} = J_{E_2/E_3}$	$\frac{J_{E_3/E_Y}}{J_{E_4/E_Y}} = J_{E_3/E_4}$	…	$\frac{J_{E_y/E_Y}}{J_{E_{y+1}/E_Y}} = J_{E_y/E_{y+1}}$	…	$\frac{1}{J_{E_Y/E_y}} = J_{E_{Y+1}/E_Y}$

$$J_{E_x/E_y} = \frac{J_{E_x - E_y}}{J_{E_y - E_x}} = \frac{J_{E_x - E_y}}{100 - J_{E_x - E_y}} \quad \text{for all} \quad x = 1, \ \dots Y \quad \text{and} \quad y = 1, \ \dots Y \tag{13.2}$$

Dividing the elements in one column by elements in the next column right to it for every column in matrix B leads to matrix C (note that the dimension of matrix C is Y*(Y − 1)).

For each column in matrix C, taking average of the $J_{E_y/E_{y+1}}$'s in all rows and going through a normalization process will calculate the contribution that each element makes to the higher level decision element under this current orientation.

It should be noted that when an expert provides pair-wise comparison judgments, he or she is asked to compare

$$\begin{array}{l}
E_1 \text{ to } E_2, \quad E_1 \text{ to } E_3, E_1 \text{ to } E_4, \dots E_1 \text{ to } E_y, \dots, E_1 \text{ to } E_Y \\
E_2 \text{ to } E_3, E_2 \text{ to } E_4, \dots E_2 \text{ to } E_y, \dots, E_2 \text{ to } E_Y \\
E_3 \text{ to } E_4, \dots E_3 \text{ to } E_y, \dots, E_3 \text{ to } E_Y \\
\dots \\
E_y \text{ to } E_{y+1}, \dots, E_y \text{ to } E_Y \\
\dots \\
E_{Y-1} \text{ to } E_Y
\end{array}$$

in terms of their relative contributions to a higher level decision element. If the expert is perfectly consistent, then the contributions of E_y' s calculated should be no different from the ones calculated when the expert compares the elements in different orders. However, since human beings are seldom perfectly consistent, the contribution values calculated from different orders of pair-wise comparison will be different. To accommodate the inconsistencies, the column-row orientation method enumerates all the (Y!) possible ways to arrange the order of elements in pair-wise comparisons and call each way as an orientation. Averaging the values calculated from the matrix C under all orientations, we get the final result of the local contributions. The calculation process can be summarized as follows: Let ${}_{[w]}c_{xy}$ denote an element in the x^{th} row and y^{th} column of matrix C under the w$^{\text{th}}$ orientation; then

$$\begin{aligned}
&{}_{[\mathrm{w}]}\mathrm{c}_{\mathrm{xy}} = \frac{{}_{[\mathrm{w}]}J_{E_y/E_x}}{{}_{[\mathrm{w}]}J_{E_{y+1}/E_x}} = {}_{[w]}J_{E_y/E_x} \times {}_{[w]}J_{E_x/E_{y+1}} = \frac{{}_{[w]}J_{E_y - E_x}}{{}_{[w]}J_{E_x - E_y}} \times \frac{{}_{[w]}J_{E_x - E_{y+1}}}{{}_{[w]}J_{E_{y+1} - E_x}} \\
&(\mathrm{x} = 1, 2 \dots \mathrm{Y}; \quad \mathrm{y} = 1, 2 \dots \mathrm{Y} - 1.)
\end{aligned} \tag{13.3}$$

The contribution of each decision element under the w$^{\text{th}}$ orientation is

$$ {}_{[w]}C_y^E = \frac{\prod_y^Y \left(\sum_{x=1}^{Y} {}_{[w]}c_{xy} \right) / Y)}{\sum_{y=2}^{Y} \left(\prod_y^Y \left(\sum_{x=1}^{Y} {}_{[w]}c_{xy} \right) / Y \right) + 1} \tag{13.4} $$

Note that $\sum_y^Y {}_{[w]}C_y^E = 1$ for all $w = 1, 2 \ldots Y!$ since the ${}_{[w]}C_y^E$ values are normalized in Eq. (13.4).

Taking the average of ${}_{[w]}C_y^E$'s in all orientations, the local contribution value of a decision element E_y is calculated as

$$ C_y^E = \left(\sum_w^W {}_{[w]}C_{E_y} \right) / W, \quad \text{where} \quad W = Y! \tag{13.5} $$

This process applies to the calculation of local contributions between any two immediate levels in a decision hierarchy. For example, C_y^E can represent the local contribution values C_l^O, C_{kl}^{G-O}, C_{jk}^{S-G}, and C_{ij}^{A-S} in the MOGSA model.

To measure the inconsistency of a pair-wise comparison judgment matrix, an inconsistency index was defined in [2] as the standard deviation of the contribution values in all orientations $\left(\frac{\sqrt{\sum_{y=1}^{Y} \sum_{w=1}^{W} \left({}_{[w]}C_y^E - C_y^E \right)^2 / W}}{Y} \right)$. An inconsistency value exceeding 0.04 is regarded as unacceptable [2]. When this happens, the judgment provider will be asked to start over the pair-wise comparison process until his or her inconsistency degree drops below 0.04.

Step 4—Group Opinion Combination: When a group of people are involved in the decision, different approaches are used to synthesize individuals' opinions in calculating the local contribution values. Those approaches can be categorized into three basic groups [13]: (1) mathematical aggregation, such as simple or weighted arithmetic/geometric mean of individual's local contribution values [1, 13, 19]; (2) behavioral aggregation that requires discussion and agreement upon a value by the group, such as consensus [32] and majority rule [17]; and (3) a mixture of the previous two, such as *Delphi* developed by Norman Dalkey et al. and the "nominal group technique" investigated by Andre Delbecq et al. [13]. Among them, taking simple arithmetic mean of the local contributions calculated from each individual's judgment matrix is the method used the most.

Step 5—Calculating the Overall Contributions: In the next step, the local contribution vector and matrices are aggregated into global contribution matrices ($\mathbf{C_{kl}^{G-O}}$ and $\mathbf{C_{il}^{A-O}}$ in the MOGSA model in Fig. 13.2) and eventually an overall contribution vector ($\mathbf{C_i^A}$) to indicate the overall contributions of the actions to the mission. All of the methods, except the "row geometric mean method" developed by Barzilai and Lootsma [1] and refined by Lootsma [27] that assumes a multiplicative relationship among local contributions, use additive formulas to calculate the overall contributions [3, 23, 24, 30, 32]. Using the additive relationship, $\mathbf{C_i^A}$ is calculated as [7]

$$C_i^A = \sum\nolimits_{l=1}^{L} \sum\nolimits_{k=1}^{K} \sum\nolimits_{j=1}^{J} C_{ij}^{A-S} \times C_{jk}^{S-G} \times C_{kl}^{G-O} \times C_l^O$$
$$= \sum\nolimits_{l=1}^{L} \sum\nolimits_{k=1}^{K} C_{ik}^{A-G} \times C_{kl}^{G-O} \times C_l^O = \sum\nolimits_{l=1}^{L} C_{il}^{A-O} \times C_l^O \qquad (13.6)$$

Step 6—Rank Decision Alternatives: Finally, all the decision alternatives, the A_i's, are ranked based on the $\mathrm{C_i^A}$ values and decisions will be made accordingly.

13.2 Sensitivity Analysis for HDM to Pair-Wise Comparison Judgments

From the above introduction, it should be clear that a decision obtained by evaluating the final ranking of the decision alternatives depends mainly on the expert judgments. Since such judgments are seldom provided at a 100 % confidence level and are subject to variations as the environment changes, it is necessary to know how sensitive the model result is to these inputs. As noted in numerous literature, sensitivity analysis is critical in making any type of decision models requisite by providing insights that are otherwise not available or intuitively recognizable [5, 7, 9]. Therefore, it is important to conduct sensitivity analysis for any hierarchical decision models to help derive a complete solution and develop a comprehensive strategy that meets various contingencies. As a fundamental concept in the effective use and implementation of quantitative decision models [11, 12], sensitivity analysis has several important roles and serves different purposes in the decision-making process. For the HDM process, knowing the tolerance of their pair-wise comparison judgments can also help the experts reach consensus [38].

Three main methods, mathematical deduction [7, 21, 28, 33], numerical incremental analysis [37, 38], and simulation [4, 18], have been employed in sensitivity analysis (SA) in general and for hierarchical decision models. Among them, mathematical deduction was identified to be superior if the relationships among the variables can be expressed in a close-formed function [7]. Utilizing mathematical deduction, a sensitivity analysis algorithm called HDM SA was developed in [5, 7] to evaluate a hierarchical decision model's robustness to changes in the local contribution values. The algorithm defines the allowable region of perturbation (s) induced on local contribution(s), tolerance of a local contribution, operating point sensitivity coefficient, total sensitivity coefficient, probability of rank change, and the most critical decision element at a certain level. In this chapter, we extend the HDM SA algorithm to study a model's sensitivity to its direct input—the pair-wise comparison judgments. The research question is the following:

> How sensitive the ranks of the decision alternatives are to perturbation(s) induced to a judgment matrix $\boldsymbol{J}_{\boldsymbol{E}_x-\boldsymbol{E}_y}$ at any level of a decision hierarchy?

The constant sum ratio scales and the column-row orientation method are assumed to be the judgment quantification technique in this chapter. Sensitivity analysis for models using the 1–9 scale with verbal representation and its eigenvector-based technique will be discussed in future research. As for the group opinion combination method, an example using the simple arithmetic mean is presented in Sect. 13.3. The same logic can be followed to modify the calculation when other group opinion combination methods are used. Next, we briefly summarize the HDM SA algorithm developed in [5, 7].

13.2.1 The Original HDM SA Algorithm

In the HDM SA algorithm [5, 7], the allowable region of M perturbations induced to the local contribution values to keep the ranking of any pair of decision alternatives, A_r and A_{r+n}, unchanged is defined by a group of inequalities in the format as

$$C_r^A - C_{r+n}^A \geq P_{l_1^*}^O \times \lambda_{l1}^O + P_{l_2^*}^O \times \lambda_{l2}^O + \ldots + P_{l_m^*}^O \times \lambda_{lm}^O + \ldots + P_{l_M^*}^O \times \lambda_{lM}^O \tag{13.7a}$$

$$C_r^A - C_{r+n}^A \geq P_{k_1^* l^*}^{G-O} \times \lambda_{k_1 l}^{G-O} + P_{k_2^* l^*}^{G-O} \times \lambda_{k_2 l}^{G-O} + \ldots + P_{k_m^* l^*}^{G-O} \times \lambda_{k_m l}^{G-O} + \ldots + P_{k_M^* l^*}^{G-O} \times \lambda_{k_M l}^{G-O} \tag{13.7b}$$

When changes take place at the top level that alter the contributions of the objectives to the mission, Eq. (13.7a) will be followed to derive the allowable region of perturbations. When perturbations are induced to any middle-level contribution matrix, Eq. (13.7b) will be used instead. In both inequalities, C_r^A and C_{r+n}^A are the overall contributions of the decision alternatives A_r and A_{r+n} that rank as the rth and (r + n)th in the current result; P's are the contribution perturbations. $P_{l_m^*}^O$ represents the mth perturbation and it is induced on the contribution of the lth objective to the mission. $P_{k_m^* l^*}^{G-O}$ represents the mth perturbation, and it is induced on the contribution of the kth goal to the lth objective. The "*" sign on a subscript indicates that the corresponding decision element is involved in perturbations. The λ's are numeric values to be calculated based on certain theorems and corollaries in the HDM SA algorithm. For perturbations induced to the bottom-level contribution matrix (the actions to the strategies), several situations are discussed and the allowable region of the contribution perturbations is defined in a similar format. Tolerance of a contribution is its base value plus and minus the upper and lower bounds of the allowable range of its perturbations. When certain contribution values change uniformly within their feasible region, the probability of rank changes equals to the allowable region of these contributions' perturbations divided by their feasible region [5, 7].

Utilizing the developed theory, we answer the research question by first defining the allowable region of perturbation(s) induced to the pair-wise comparison judgment (s). Once such allowable region is identified, the tolerance of a pair-wise comparison judgment and the probability of rank changes can be calculated in the same manner. To make the logic clear, two situations are discussed: one deals with consistent pair-wise comparison judgment matrices and the other with inconsistent ones.

13.2.2 HDM SA for Pair-Wise Comparison Under Perfect Consistency

By definition, if the pair-wise comparison judgment values of any three decision elements, E_x, E_y, and E_z, in a judgment matrix satisfy the condition defined in Eq. (13.8), the judgment matrix is perfectly consistent:

$$\frac{J_{E_x-E_y}}{J_{E_y-E_x}} \cdot \frac{J_{E_z-E_x}}{J_{E_x-E_z}} = J_{E_x/E_y} \cdot J_{E_z/E_x} = J_{E_z/E_y} = \frac{J_{E_z-E_y}}{J_{E_y-E_z}} \tag{13.8}$$

Even though perfect consistency rarely exists, it does happen, especially when the judgments are based on well-known facts or objective data. For example, in an experiment that one of the authors participated, it has been observed that people show perfect consistency when they are asked to give pair-wise comparison judgments on topics such as populations and geographic areas that they are familiar with. Applied in technology management, HDM models are often used to compare technology performance and costs (i.e., [14, 15]). Since people can usually base their judgments on objective data and facts, one or several consistent judgment matrices may be present in the model. Conducting sensitivity analysis for consistent pair-wise comparison judgment matrices is much simpler than performing it under inconsistency.

When one or several judgments in a consistent matrix are perturbed, all the related values in that matrix will be changed passively according to the relationships defined in Eqs. (13.1) and (13.8). This further leads to changes in the local contribution values, which are the $P_{m^*}^{E}$'s in the HDM SA algorithm. Since the allowable region of the $P_{m^*}^{E}$'s have been defined in [7], by replacing the $P_{m^*}^{E}$'s with expressions containing the pair-wise comparison judgments and the induced judgment perturbations, we can derive inequalities to define the allowable region for the judgment perturbations. It should be noted that, in order to maintain consistency, perturbations can only be induced to certain groups of pair-wise comparison judgments at the same time, and the rest of the judgment values can only be passively changed according to their relationships with the perturbed ones. For example, if judgment perturbations $P_{E_1-E_2}$ and $P_{E_1-E_3}$ are induced on two judgments $J^*_{E_1-E_2}$ and $J^*_{E_1-E_3}$, the value of $J_{E_2-E_3}$ can only be changed in the amount of

$$\Bigg(\Big(100 - J^*_{E_1-E_2} - P_{E_1-E_2}\Big) \frac{\Big(J^*_{E_1-E_3} + P_{E_1-E_3}\Big)(100 - J_{E_2-E_3}) - \Big(J^*_{E_1-E_2} + P_{E_1-E_2}\Big)\Big(100 - J^*_{E_1-E_3} - P_{E_1-E_3}\Big)J_{E_2-E_3}}{\Big(J^*_{E_1-E_2} + P_{E_1-E_2}\Big)\Big(100 - J^*_{E_1-E_3} - P_{E_1-E_3}\Big) + \Big(100 - J^*_{E_1-E_2} - P_{E_1-E_2}\Big)\Big(J^*_{E_1-E_3} + P_{E_1-E_3}\Big)\Big]}\Bigg)$$

based on the consistency relationships (the deduction process is shown in Appendix A). Since there are three decision elements, we can only perturb $J^*_{E_1-E_2}$ and $J^*_{E_1-E_3}$, or $J^*_{E_1-E_2}$ and $J^*_{E_2-E_3}$, or $J^*_{E_1-E_3}$ and $J^*_{E_2-E_3}$ at the same time and let the remaining

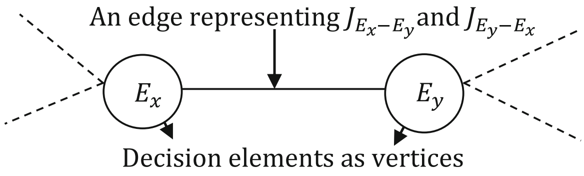

Fig. 13.3 Representing the pair-wise comparison relationship with a graph

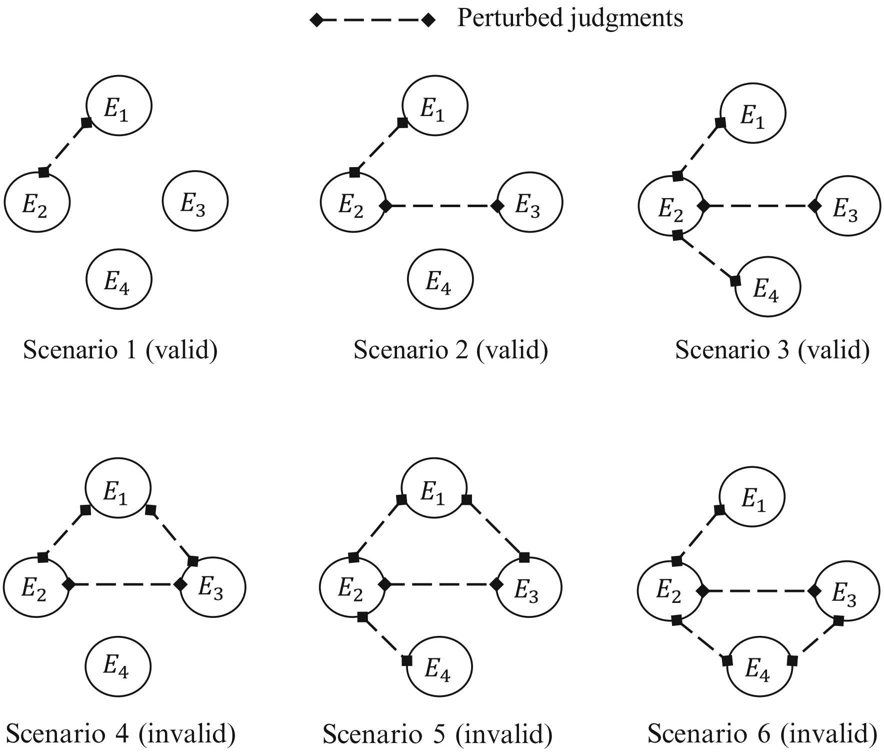

Fig. 13.4 An example of valid and invalid ways to perturb judgments

judgment value change passively. We cannot perturb all three judgments at the same time.

Therefore, in determining the sensitivity of multiple judgment perturbations, we should keep in mind that only up to Y − 1 perturbations can be induced to a judgment matrix with Y decision elements, and the perturbed judgments should not violate the consistency rule. To better illustrate this rule, we transfer the judgment matrix into a graph by representing decision elements as vertices and the judgment between each pair of decision elements as an edge connecting the two vertices, as shown in Fig. 13.3.

To maintain the consistency relationship, judgment perturbations can only be induced on edges that do not connect the vertices into a loop. Using a judgment matrix with four decision elements as an example, Fig. 13.4 shows three valid ways

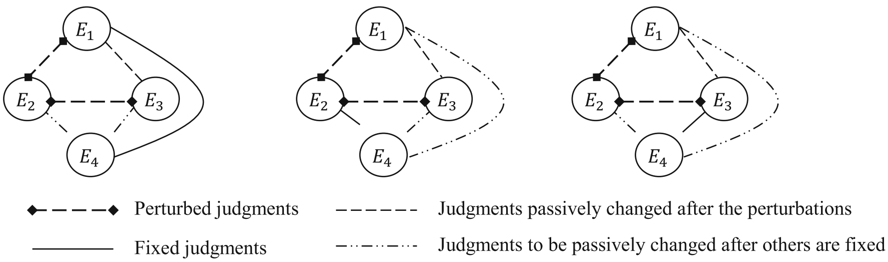

Fig. 13.5 Three different ways to calculate the judgment matrix when $\boldsymbol{J}^*_{E_1-E_2}$ and $\boldsymbol{J}^*_{E_2-E_3}$ are perturbed

to perturb the pair-wise comparison judgment in scenarios 1 through 3 and three invalid ways in scenarios 4 through 6.

Scenarios 4 and 5 in the second row are invalid since E_1, E_2, and E_3 are connected into a loop, and scenario 6 is invalid since E_1, E_2, and E_3 are connected into a loop. All three cases violate the consistency rule discussed earlier.

Suppose T perturbations are induced to a judgment matrix with Y decision elements, if $(T = Y - 1)$, then all the judgment values will be changed since all decision elements are involved in the perturbations. A completely new judgment matrix will be calculated based on Eqs. (13.1) and (13.5) using the perturbed new values. In the other case, if $(T < Y - 1)$, then additional $(Y - 1 - T)$ unperturbed judgments that help connect all Y decision elements into a tree need to be fixed at their original values in order to create the new matrix. In Fig. 13.5, we illustrate the three different ways to choose the fixed judgments and show how other values in the new judgment matrix would change. As it shows, when two perturbations are induced on $\mathrm{J}^*_{E_1-E_2}$ and $\mathrm{J}^*_{E_2-E_3}$, $J_{E_1-E_3}$ will be changed passively for sure since it connects both elements involved in the perturbation. Depending on which value among $J_{E_1-E_4}$, $J_{E_2-E_4}$, and $J_{E_3-E_4}$ we fix, $J_{E_2-E_4}$ and $J_{E_3-E_4}$, or $J_{E_1-E_4}$ and $J_{E_3-E_4}$, or $J_{E_1-E_4}$ and $J_{E_2-E_4}$ will be changed passively according to Eqs. (13.1) and (13.5).

Under perfect consistency, the new judgment matrix should be the same regardless of which judgments are to be fixed. The judgment provider should make the choice and fix the judgments that are most unlikely to be changed. In practice, to make sure that the perturbed judgments and the fixed judgments involve all the Y decision elements and fully connect them into a tree without loops, the following steps can be followed to test the connectivity:

1. In a judgment matrix A, fill the known judgments, including the perturbed ones and the ones chosen to be fixed, and leave the other cells blank. Let a_{xy} denote the element in the x$^{\text{th}}$ row and the y$^{\text{th}}$ column in this matrix.
2. Let $V = \{\mathrm{E}_1\}$, check a_{1y} for $y = 2, \ldots, \mathrm{Y}$. If a_{1y} is not blank, then $V = V \cup \{\mathrm{E}_y\}$, set $V^- = \{\mathrm{E}_1\}$.

3. For $E_y \in V - V^-$, check a_{yz} for $z = 1, \ldots, Y$. If a_{yz} is not blank, then $V = V \cup \{E_z\}$, set $V^- = V^- \cup \{E_z\}$.
4. Repeat step (3).

When V is exhausted, check V. If $V = \{E_1, \ldots, E_Y\}$, we can conclude that the decision elements are connected. Next, check the number of judgments in the lower triangle of matrix A. If it equals to $(Y-1)$, then the tree generated has $(Y-1)$ edges. In this way, we can be sure that no loops are involved and any two vertices of the tree are connected by only one path. This guarantees that the relative importance ratio of any two elements, J_{E_x/E_y}, can be derived through one and only one way to create new values in judgment matrices B and C. Since we are dealing with a consistent situation, there is only one orientation. The new local contribution values can be calculated directly from the new matrix C, and the changes to the contribution values can be represented as

$$P^E_{m^*} = C_m^{E(new)} - C_m^E = \frac{J^{(new)}_{E_m/E_Y}}{\sum_{y=1}^{Y} J^{(new)}_{E_y/E_Y}} - \frac{J_{E_m\ /E_Y}}{\sum_{y=1}^{Y} J_{E_y/E_Y}} \tag{13.9a}$$

where $\forall\ y = 1, 2 \ldots Y$, $m \in \{y | y = 1, 2 \ldots Y\}$,

$$J^{(new)}_{E_y/E_Y} = J_{E_y/E_{(1)}} \times J_{E_{(1)}/E_{(2)}} \times J_{E_{(2)}/E_{(3)}} \times \ldots \times J_{E_{(v)}/E_Y} \tag{13.9b}$$

if the path from E_y to E_Y does not include any perturbed edges, and $E_{(1)}, E_{(2)} \ldots E_{(v)}$ are decision elements on the path from E_y to E_Y;

$$\begin{aligned}
&J^{(new)}_{E_y/E_Y} = J_{E_y/E_{(1)}} \times J_{E_{(1)}/E_{(2)}} \times J_{E_{(2)}/E_{(3)}} \times J^{*(new)}_{E_{(3)}/E_{(4)}} \times J_{E_{(4)}/E_{(5)}} \times \ldots \times J^{*(new)}_{E_{x_t}/E_{y_t}} \times \ldots \times \\
&J^*_{E_{x_T}/E_{y_T}} \times \ldots \times J_{E_{(v)}/E_Y} = J_{E_y/E_{(1)}} \times J_{E_{(1)}/E_{(2)}} \times J_{E_{(2)}/E_{(3)}} \times \left(J^*_{E_{(3)}-E_{(4)}} + P_{E_{(3)}-E_{(4)}}\right)/ \\
&\left(J_{E_{(4)}-E_{(3)}} - P_{E_{(3)}-E_{(4)}}\right) \times J_{E_{(4)}/E_{(5)}} \times \ldots \times \left(J^*_{E_{x_t}-E_{y_t}} + P_{E_{x_t}-E_{y_t}}\right)/ \\
&\left(J_{E_{y_t}-E_{x_t}} - P_{E_{x_t}-E_{y_t}}\right) \times \ldots \times \left(J^*_{E_{x_T}-E_{y_T}} + P_{E_{x_T}-E_{y_T}}\right)/ \\
&\left(J_{E_{y_T}-E_{x_T}} - P_{E_{x_T}-E_{y_T}}\right) \times \ldots \times J_{E_{(v)}/E_Y}
\end{aligned} \tag{13.9c}$$

If the path from E_y to E_Y includes one or more perturbed edges, $J^*_{E_{x_t}-E_{y_t}}$'s. $E_{(1)}$, $E_{(2)} \ldots E_{(v)}$ are decision elements on the path from E_y to E_Y.

Since we are dealing with a consistent judgment matrix, the relationship defined in Eqs. (13.8), (13.9b), and (13.9c) can be further simplified to be

$$J^{(new)}_{E_y/E_Y} = J_{E_y - E_Y} / J_{E_Y - E_y} \tag{13.9d}$$

and

$$\begin{aligned} J_{E_y/E_Y}^{(new)} &= J_{E_y/E_3} \times \left(J_{E_3-E_4}^{*} + P_{E_3-E_4}\right) / \left(J_{E_4-E_3} - P_{E_3-E_4}\right) \times J_{E_4/E_{x_t}} \\ &\times \left(J_{E_{x_t}-E_{y_t}}^{*} + P_{E_{x_t}-E_{y_t}}\right) / \left(J_{E_{y_t}-E_{x_t}} - P_{E_{x_t}-E_{y_t}}\right) \times J_{E_{y_t}/E_{E_{x_T}}} \\ &\times \left(J_{E_{x_T}-E_{y_T}}^{*} + P_{E_{x_T}-E_{y_T}}\right) / \left(J_{E_{y_T}-E_{x_T}} - P_{E_{x_T}-E_{y_T}}\right) \times J_{E_{y_T}/E_Y} \end{aligned} \tag{13.9e}$$

Substituting the contribution perturbations in the HDM SA algorithm with the above expression containing the judgment perturbations and simplifying the calculation of the λ's based on the fact that all the contributions will be changed regardless of the number of judgments being perturbed, we can extend the HDM SA algorithm to the pair-wise comparison step. (The simplification process is included in Appendix B.)

Next, we discuss the situation when the judgment matrix is inconsistent.

13.2.3 HDM SA for Pair-Wise Comparison Under Inconsistency

As introduced in Sect. 13.1, step 3, to accommodate the inconsistency of judgment providers, the column-row orientation method calculates the contributions from all orientations and uses the arithmetic mean as the final value of the local contributions. The most straightforward way to link the HDM SA to the inconsistent pair-wise comparisons would be to represent the new judgment values symbolically with the induced judgment perturbation(s) and go through the same calculation steps, so that the changes to the local contribution values can be represented by the judgment perturbation(s). However, the complexity of this method increases dramatically as the number of decision elements, Y, increases: Y! orientations need to be included in the calculation. It also becomes too complex and even impossible to express the new values of C_{E_y}'s symbolically using $J_{E_x-E_y}$'s and $P_{E_x-E_y}$'s when Y goes above three. To decrease the computational complexity, tree theory is employed. Representing each orientation as a tree that connects all Y decision elements and a perturbed judgment as a fixed edge on the tree, we can generate up to $2Y^{Y-3}$ trees, each representing a unique orientation, to calculate the new contribution values.

This tree-based method builds on discussions in the previous section by assuming consistent relationship among the judgments on each tree and calculates the arithmetic mean of the new contribution values from all trees. When $(T < Y - 1)$ perturbations are induced to an inconsistent judgment matrix with Y decision elements, all possible ways to fix any $(Y - 1 \ - T)$ judgments and connect the decision elements into a tree will be enumerated. This becomes a classic problem of determining the number of different undirected trees with Y-labeled vertices in graph theory. It is also a major research area called "analysis of algorithms" in the field of computer science. According to the Cayley theorem [34], there exist N^{N-2} different undirected trees if

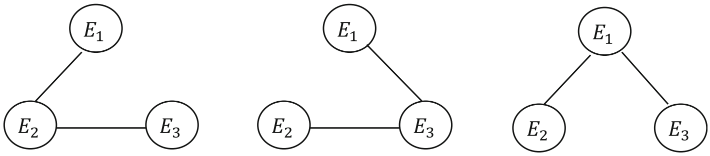

Fig. 13.6 An example of three different ways to connect three decision elements

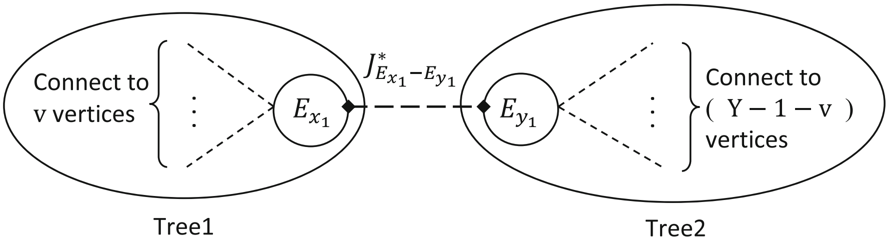

Fig. 13.7 Splitting a judgment matrix tree into two trees after one of the $\boldsymbol{J}_{E_x-E_y}$'s is perturbed

one tries to connect N vertices. Therefore, we can identify Y^{Y-2} different orientations in a pair-wise comparison matrix with Y decision elements. For example, a judgment matrix with three elements, E_1, E_2, and E_3, has $\left(3^{3-2}=3\right)$ different orientations, or three different ways to connect all elements into a tree, as shown in Fig. 13.6.

When a judgment perturbation is induced, the perturbed judgment is viewed as a fixed edge with the new value being $\left(J^{*(new)}_{E_{x_1}-E_{y_1}} = J^*_{E_{x_1}-E_{y_1}} + P_{E_{x_1}-E_{y_1}}\right)$. E_{x_1} and E_{y_1} are the decision elements involved in the perturbation and we call the remaining decision elements the "free elements." Since the connection between E_{x_1} and E_{y_1} is fixed, the number of possible ways to connect all the decision elements into a tree equals to the number of ways to connect the free elements to E_{x_1} and E_{y_1} with $(\mathrm{Y}-2)$ edges. Let v denote the number of free decision elements connecting to E_{x_1} to form a tree; since there are $(\mathrm{Y}-2)$ free elements in total, v can take any value from 0 to $(\mathrm{Y}-2)$. For every v value, there exist $(\mathrm{v}+1)^{\mathrm{v}-1}$ ways to form the tree (tree 1 in Fig. 13.7). Then the remaining free elements that are not included in tree 1 need to be connected to E_{y_1} and form tree 2. The number of vertices in tree 2 is, therefore, $(\mathrm{Y}-1-\mathrm{v})$. With $(\mathrm{Y}-1-\mathrm{v})$ vertices, there are $(\mathrm{Y}-1-\mathrm{v})^{\mathrm{Y}-\mathrm{v}-3}$ possible ways to generate tree 2. Therefore, there are

$$W=\sum\nolimits_{\mathrm{v}=0}^{\mathrm{Y}-2}\binom{\mathrm{Y}-2}{\mathrm{v}}(\mathrm{v}+1)^{\mathrm{v}-1}(\mathrm{Y}-1-\mathrm{v})^{\mathrm{Y}-\mathrm{v}-3}=2\mathrm{Y}^{\mathrm{Y}-3} \tag{13.10}$$

possible ways in total to form new trees around the fixed edge $J^*_{E_{x_1}-E_{y_1}}$ and connect all the Y decision elements with $(\mathrm{Y}-1)$ edges. This means that $2\mathrm{Y}^{\mathrm{Y}-3}$ orientations need to be included to calculate the new contribution values when one perturbation is induced to an inconsistent judgment matrix with Y decision elements. Under each

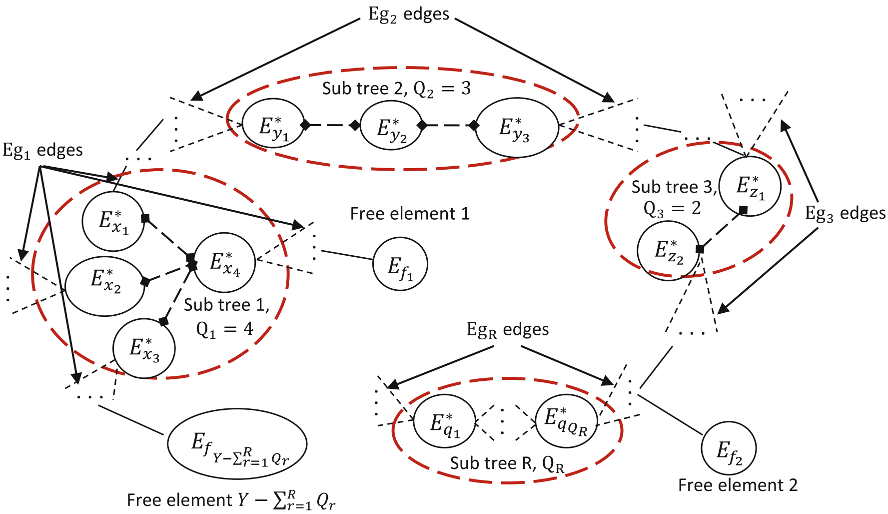

Fig. 13.8 Connecting Y decision elements into a tree around the perturbed subtrees

orientation, a new judgment matrix will be calculated based on Eqs. (13.1) and (13.8) using the perturbed judgment $J^{*(new)}_{E_{x_1}-E_{y_1}}$ and the fixed judgments that serve as edges in the connected tree.

When ($T > 1$) judgments are perturbed, all the T perturbed judgments are viewed as fixed edges with new values being $J^{*(new)}_{E_{x_t}-E_{y_t}} = J^*_{E_{x_t}-E_{y_t}} + P_{E_{x_t}-E_{y_t}}$, t = 1, 2...T). In a general situation as the one shown in Fig. 13.8, some of the decision elements may be involved in more than one perturbed judgments, such as $E^*_{y_2}$ and $E^*_{x_4}$ in the figure. This creates some clusters of decision elements connected by fixed edges, and we call them perturbed subtrees. A fixed edge connecting two decision elements can be viewed as a special case of perturbed subtree—one with only one edge, such as the subtree 3 in Fig. 13.8. Assuming that there exist R ($R \le T$) perturbed subtrees in total and they involve Q ($Q \le 2T$) decision elements, then there are $(\mathrm{Y}-\mathrm{Q})$ free elements not involved in any perturbations. To connect the R perturbed subtrees and the $(\mathrm{Y}-\mathrm{Q})$ free elements into a complete tree, there are $(\mathrm{R}+\mathrm{Y}-\mathrm{Q})^{\mathrm{R}+\mathrm{Y}-\mathrm{Q}-2}$ ways based on the Cayley theorem [34]. Next, suppose in a certain connection, a perturbed subtree r involving $\mathrm{Q_r}\left(\sum_{\mathrm{r}=1}^{\mathrm{R}} \mathrm{Q_r} = \mathrm{Q}\right)$ decision elements is connected to the complete tree through Eg_r edges, then $\left(\mathrm{Q_r^{Eg_r}}\right)$ ways exist to attach the edges to the different decision elements inside the subtree. (This represents the way when additional judgments are chosen to be fixed as edges to connect the Y decision elements into a tree.) Since the number of edges, Eg_r, for each subtree r varies when the complete tree is generated, we use $_{[j]}\mathrm{Eg_r}$ to represent the number of edges that connect the perturbed subtree r under the $\mathrm{j^{th}}$ $\left(\mathrm{j}=1,\ 2\ldots(\mathrm{R}+\mathrm{Y}-\mathrm{Q})^{\mathrm{R}+\mathrm{Y}-\mathrm{Q}-2}\right)$ tree connection. With $(\mathrm{R}+\mathrm{Y}-\mathrm{Q})^{\mathrm{R}+\mathrm{Y}-\mathrm{Q}-2}$ complete tree connections, R perturbed subtrees, and $\left(\mathrm{Q_r^{Eg_r}}\right)$ ways to attach the edges inside each subtree r, there exist

$$W = \sum_{j=1}^{(R+Y-Q)^{R+Y-Q-2}} \sum_{r=1}^{R} Q_r^{[j]\,Eg_r} \tag{13.11}$$

ways in total to form new trees around the fixed edges $J^{*}_{E_{x_t}-E_{y_t}}$ (t = 1, 2...T) and connect all the Y decision elements with (Y-1) edges.

It should be noted that as the number of perturbations increases, the number of fixed edges in the trees increases and the degree of freedom decreases. The available ways to generate the orientation trees will thus decrease and leads to decreased W value. Therefore, using the proposed method, the more perturbations that are induced to the judgment matrix, the less orientations will be generated in the calculation. This is very different from using the numerical incremental analysis or simulation methods in which the number of orientations remains constant regardless of the T value, and the calculation process becomes complex as the T value increases.

After the W trees or orientations are enumerated, the new contribution values under each orientation, ${}_{[w]}C_y^E$, can be calculated. Then the changes brought to the local contribution values can be represented as

$$P^E_{m^*} = C_m^{E(new)} - C_m^E = \left[\sum_{w=1}^{W}\left(\frac{{}_{[w]}J^{(new)}_{E_m/E_Y}}{\sum_{y=1}^{Y} {}_{[w]}J^{(new)}_{E_y/E_Y}} - \frac{{}_{[w]}J_{E_m/E_Y}}{\sum_{y=1}^{Y} {}_{[w]}J_{E_y/E_Y}}\right)\right]/W \tag{13.12}$$

Under each orientation, the ${}_{[w]}J^{(new)}_{E_y-E_Y}$ values can be calculated based on Eqs. (13.9b) and (13.9c). The simplified Eqs. (13.9d) and (13.9e) won't work since in an inconsistent judgment matrix, the relationship defined in Eq. (13.8) does not hold, and as a result, $J_{E_1/E_2} \times J_{E_2/E_3} \times J_{E_3/E_4} \neq J_{E_1/E_4}$. To calculate any ${}_{[w]}J_{E_y-E_Y}$ value, all the edges (the pair-wise comparison judgments) that connect the decision element E_y to E_Y in the w^{th} tree need to be involved.

Summarizing the analysis under perfect consistency and inconsistency, we present the proposed algorithm in the next section to conduct sensitivity analysis for hierarchical decision models to their pair-wise comparison judgment input.

13.2.4 HDM SA Algorithm for Pair-Wise Comparison

Mathematical deductions based on the above discussion lead to the following theorem. It defines the allowable region of perturbation(s) induced to any judgment matrix for decision elements at any level of a decision hierarchy to keep the current model result unchanged.

Theorem 1 Let $\boldsymbol{J_{E_x-E_y}}$ denote a pair-wise comparison judgment matrix for Y decision elements at any level of a decision hierarchy,

$P_{E_{x_t}-E_{y_t}}\left(-J^*_{E_{x_t}-E_{y_t}} \le P_{E_{x_t}-E_{y_t}} \le 100 - J^*_{E_{x_t}-E_{y_t}},\ x_t \ne y_t,\ \ t = 1, \ldots, T\right)$ denote judgment perturbations induced on T $(T \le Y - 1)$ of the $J_{E_x - E_y}$'s that connect all the Y decision elements into a tree with (Y − 1) edges, C^A_r and C^A_{r+n} denote the overall contribution of the decision alternatives that ranked as the rth and the (r + n)th. The rank order of decision alternatives A_n and A_{n+r} will not reverse if

$$C^A_r - C^A_{r+n} \ge P^E_{1^*} \times \lambda^E_1 + P^E_{2^*} \times \lambda^E_2 + \cdots P^E_{m^*} \times \lambda^E_m + \cdots + P^E_{M^*} \times \lambda^E_M \quad (13.13a)$$

where

$$\lambda^E_m = C^{A-O}_{r+n,m^*} - C^{A-O}_{r,m^*} - C^{A-O}_{r+n,L} + C^{A-O}_{r,L} \quad (13.13b)$$

(if $E_x = O_l$, which means the perturbed judgment matrix is used to quantify the local contributions of decision elements at the second-level to the top-level decision element. In this case, Y = L, and M = L − 1. $C^{A-O}_{x,y}$ denotes the xth action's contribution to the yth objective.)

Or

$$\lambda^E_m = C^O_{l^*} \times \left(C^{A-G}_{r+n,m^*} - C^{A-G}_{r,m^*} + C^{A-G}_{r,K} - C^{A-G}_{r+n,\ K}\right) \quad (13.13c)$$

(if $E_x = G_k$ or any middle-level decision elements, which means the perturbed judgment matrix is used to quantify the local contributions of decision elements in the middle levels of the decision hierarchy, for example, the contributions of the G_k's to a specific objective O_{l^*}. In this case, Y = K and M = K − 1. $C^{A-G}_{x,y}$ is the xth action's contribution to the yth goal.)

Or

$$\lambda^E_m = \left\{\begin{array}{ll} 0, & \text{when } m \ne r \text{ or } (r+n) \\ -\mathrm{C}^{\mathrm{S}}_{\mathrm{j}^*}, & \text{when } m = r \\ \mathrm{C}^{\mathrm{S}}_{\mathrm{j}^*}, & \text{when m} = \text{r} + \text{n} \end{array}\right\} \quad (13.13d)$$

where (if $E_x = A_i$, which means the perturbed judgment matrix is used to quantify the local contributions of the decision alternatives to a specific strategy S_{j^*}. In this case, Y = I. C^S_j is the jth strategy's contribution to the mission.)

$$P^E_{m^*} = \left[\sum\nolimits_{w=1}^{W}\left(\frac{{}_{[w]}J^{(new)}_{E_m/E_Y}}{\sum\nolimits_{y=1}^{Y}{}_{[w]}J^{(new)}_{E_y/E_Y}} - \frac{{}_{[w]}J_{E_m\ /E_Y}}{\sum\nolimits_{y=1}^{Y}{}_{[w]}J_{E_y\ /E_Y}}\right)\right]\Big/ W \quad (13.13e)$$

where $\forall\ y = 1,\ 2 \ldots Y \text{ and } m \in \{y\}$, let $E_{(v)}\ (v = 1 \ldots V,\ V \in \{0,\ 1,\ 2 \ldots Y - 2\})$ denote the vth decision element on the path from E_y to E_Y in the corresponding

$\mathrm{w^{th}}$ connection, if the path from $\mathrm{E_y}$ to $\mathrm{E_Y}$ does not include any perturbed edges ${}_{[w]}J^{*}_{E_{x_t}-E_{y_t}}$'s, then

$$\begin{aligned}&{}_{[w]}\mathrm{J}^{(new)}_{E_y/E_Y} = {}_{[w]}\mathrm{J}_{E_y\ /E_Y} = {}_{[w]}\mathrm{J}_{\mathrm{E_y/E_{(1)}}} \times {}_{[w]}\mathrm{J}_{\mathrm{E_{(1)}/E_{(2)}}} \times {}_{[w]}\mathrm{J}_{\mathrm{E_{(2)}/E_{(3)}}} \times {}_{[w]}\mathrm{J}_{\mathrm{E_{(3)}/E_{(4)}}} \times \ldots \times\\ &{}_{[w]}\mathrm{J}_{\mathrm{E_{(v-1)}/E_{(v)}}} \times \ldots \times {}_{[w]}\mathrm{J}_{\mathrm{E_{(V)}\ /E_Y}};\end{aligned} \tag{13.13f}$$

Or if the path from $\mathrm{E_y}$ to $\mathrm{E_Y}$ includes one or more perturbed edges, ${}_{[w]}J^{*}_{E_{x_t}-E_{y_t}}$'s, which means E_{x_t} and $E_{y_t} \in \{E_{(v)}\}$, then
where

$$\begin{aligned}&{}_{[w]}\mathrm{J}^{(new)}_{\mathrm{E_y-E_Y}}/{}_{[w]}\mathrm{J}^{(new)}_{\mathrm{E_Y-E_y}} = {}_{[w]}J_{E_y/E_{(1)}} \times {}_{[w]}J_{E_{(1)}/E_{(2)}} \times {}_{[w]}J_{E_{(2)}/E_{(3)}} \times\\ &\left({}_{[w]}J^{*}_{E_{x_1}-E_{y_1}} + P_{E_{x_1}-E_{y_1}}\right)\Big/\left({}_{[w]}J_{E_{y_1}-E_{x_1}} - P_{E_{x_1}-E_{y_1}}\right) \times {}_{[w]}J_{E_{(4)}/E_{(5)}} \times \ldots \times\\ &\left({}_{[w]}J^{*}_{E_{x_t}-E_{y_t}} + P_{E_{x_t}-E_{y_t}}\right)\Big/\left({}_{[w]}J_{E_{y_t}-E_{x_t}} - P_{E_{x_t}-E_{y_t}}\right) \times \ldots \times {}_{[w]}\mathrm{J}_{\mathrm{E_{(v-1)}/E_{(v)}}} \times \ldots \times\\ &\left({}_{[w]}J^{*}_{E_{x_T}-E_{y_T}} + P_{E_{x_T}-E_{y_T}}\right)\Big/\left({}_{[w]}J_{E_{y_T}-E_{x_T}} - P_{E_{x_T}-E_{y_T}}\right) \times \ldots \times {}_{[w]}J_{E_{(V)}/E_Y}\end{aligned} \tag{13.13g}$$

$$W = 1 \tag{13.13h}$$

$W = 1$ (13.13h), if judgment matrix $\boldsymbol{J_{E_x-E_y}}$ is perfectly consistent or if $\boldsymbol{J_{E_x-E_y}}$ is inconsistent and $\mathrm{T} = \mathrm{Y} - 1$;

$W = 2\mathrm{Y}^{\mathrm{Y}-3}$ (13.10), if judgment matrix $\boldsymbol{J_{E_x-E_y}}$ is inconsistent and $\mathrm{T} = 1$;

$W = \sum_{\mathrm{j=1}}^{(\mathrm{R+Y-Q})^{\mathrm{R+Y-Q-2}}} \sum_{\mathrm{r=1}}^{\mathrm{R}} \mathrm{Q_r}^{{}_{[j]}\mathrm{Eg_r}}$ (13.11), if judgment matrix $\boldsymbol{J_{E_x-E_y}}$ is inconsistent and $1 < T < Y - 1$. (R is the total number of perturbed subtrees, Q is the total number of decision elements involved in perturbations, $\mathrm{Q_r}$ is the number of decision elements involved in perturbed subtree r $\left(\mathrm{Q} = \sum_{\mathrm{r=1}}^{\mathrm{R}} \mathrm{Q_r}\right)$, and ${}_{[j]}\mathrm{Eg_r}$ is the number of edges that connect subtree r to the complete tree generated in the $\mathrm{j^{th}}$ way.)

The top choice will remain at the top rank if all the above conditions are satisfied for all r = 1 and n = 1, 2...I − 1. The original ranking of all $\mathrm{A_i}$'s will remain unchanged if all the above conditions are satisfied for all r = 1, 2...I − 1, and n = 1.

The proposed algorithm was verified using data from several HDM models. Tests show that whenever the induced judgment perturbation(s) go beyond the allowable region and violate the inequalities defined in the theorems, the ranking of the concerned decision alternatives will be changed; otherwise, they will remain to be the same. (Due to limited space, results of the verification test are not included in this chapter.) The proposed method is also evaluated against the numerical incremental analysis, which is an iteration-based method, in conducting sensitivity analysis for

Table 13.4 Calculation steps involved in two sensitivity analysis methods for HDM

# of decision elements	Numerical incremental analysis (T perturbations, accurate to 1)	Proposed tree-based method					
			T = 2 perturbations		T = 3 perturbations		
			# of overlaps (2T-Q)		# of overlaps (2T-Q)		
		T = 1 perturbation	0	1	0	1	2
3	(6*T + 2)*100	2 + 2		1 + 2			
4	(24*T + 2)*100	8 + 3	4 + 3	3 + 3			1 + 3
5	(120*T + 2)*100	50 + 4	20 + 4	15 + 4		6 + 4	4 + 4
6	(720*T + 2)*100	432 + 5	144 + 5	108 + 5	48 + 5	36 + 5	24 + 5
7	(5,040*T + 2)*100	4,802 + 6	1,372 + 6	1,029 + 6	392 + 6	294 + 6	196 + 6
8	(40,320*T + 2)*100	65,536 + 7	16,384 + 7	12,288 + 7	4,096 + 7	3,072 + 7	2,048 + 7
9	(3.63E5*T + 2)*100	1,062,882 + 8	236,196 + 8	177,147 + 8	52,488 + 8	39,366 + 8	26,244 + 8

Computational complexity decreases

hierarchical decision models. Table 13.4 shows the calculation steps involved in each method to define the allowable region of judgment perturbation(s). Since nine is the maximum number of decision elements suggested to be included in a pair-wise comparison [29], we calculated the measurements using up to nine decision elements.

When one employs the proposed method to conduct HDM SA, the number of calculation steps decreases as the number of perturbations increases. Therefore, we only list data in situations with up to three judgment perturbations, knowing that the numbers will further decrease when the T value continues to increase. Comparing to the numerical incremental analysis, the proposed method has lower computational complexity in every case. Offering the same level of accuracy and generality, our method is superior overall in terms of performance, computational complexity, and generality, which are the three measurements to be compared while evaluating systems methods [22]. Comparing to the simulation method, the proposed algorithm also has better performance by offering accurate allowable range(s) of perturbations at lower computational complexity instead of a probability based on large quantity of experiments. Therefore, we propose the algorithm as the preferred method to conduct sensitivity analysis for HDM models.

13.3 Examples

To demonstrate the application of the algorithm, we present three examples using data from a research [6, 19] that evaluated five emerging technologies in Taiwan's semiconductor foundry industry using HDM.

The HDM model in the example contains four levels. In deciding the contributions of decision elements at the second level, which are the O_l's, to the mission, two experts, A and B, provided judgments. Table 13.5 shows expert A's judgment matrix, denoted as $\boldsymbol{J}_{\boldsymbol{O}_x-\boldsymbol{O}_y}(\boldsymbol{A})$.

After all experts' judgments were converted to local contribution vector and matrices, simple arithmetic mean was used as the group opinion combination method. Tables 13.6 and 13.7 summarize the local contribution vector $\boldsymbol{C}_1^{\mathrm{O}}$ and the global contribution matrix $\boldsymbol{C}_{il}^{\boldsymbol{A}-\boldsymbol{O}}$ calculated from aggregating the local contribution

Table 13.5 Expert A's pair-wise comparison judgment matrix $\boldsymbol{J}_{\boldsymbol{O}_x-\boldsymbol{O}_y}(\boldsymbol{A})$

Mission	O_1	O_2	O_3	O_4
O_1		30	20	50
O_2	70		40	50
O_3	80	60		60
O_4	50	50	40	

Table 13.6 First-level contribution vector $\boldsymbol{C}_1^{\mathrm{O}}$

C_l^O	O_1	O_2	O_3	O_4
Mission	0.36	0.25	0.21	0.18

Table 13.7 Aggregated global contribution matrix $\boldsymbol{C}_{il}^{A-O}$

C_{il}^{A-O}	A_1	A_2	A_3	A_4	A_5
O_1	0.19	0.24	0.13	0.19	0.24
O_2	0.27	0.22	0.13	0.18	0.20
O_3	0.21	0.24	0.13	0.19	0.22
O_4	0.22	0.24	0.13	0.19	0.21

Table 13.8 Overall contribution vector $\boldsymbol{C}_{\mathrm{i}}^{\mathrm{A}}$ and final rankings

	A_1	A_2	A_3	A_4	A_5
C_i^A	0.2196	0.235	0.1321	0.1929	0.2204
Rank	**(3)**	**(1)**	**(5)**	**(4)**	**(2)**

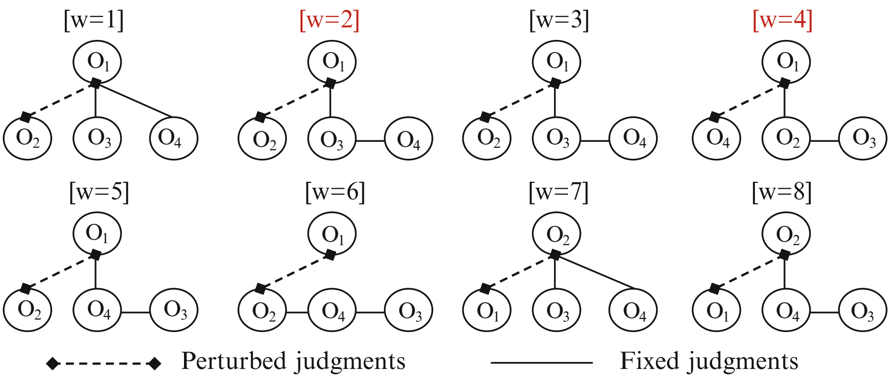

Fig. 13.9 Scenario trees for Y = 4 and T = 1

matrices between O and A levels. Table 13.8 summarizes the model results regarding the overall contributions and the ranks of the decision alternatives.

13.3.1 One-Way SA

A one-way sensitivity analysis is first conducted to study changes to $J_{O_1-O_2}^*$, which is the judgment value given to O_1 when it is compared with O_2 in regard of their contributions to the mission. Denoting perturbations given to this judgment provided by experts A and B with $P_{O_1-O_2}(A)$ and $P_{O_1-O_2}(B)$, respectively, we calculate the allowable range of $P_{O_1-O_2}(A)$ when expert B's judgments remain constant.

When inducing one perturbation to an inconsistent judgment matrix, based on Eq. (13.10), $\left(W = 2\mathrm{Y}^{\mathrm{Y}-3} = 2 \times 4^{4-3} = 8\right)$, scenarios need to be included in the calculation. Figure 13.9 shows the eight different orientation trees.

To determine the allowable range of the judgment perturbation $P_{O_1-O_2}(A)$, we first calculate the ${}_{[w]}P^{O}_{m^*}(A)$ (m = 1, 2, 3) values under each orientation based on theorem 1. Using (w = 1) and (m = 1) as an example, we illustrate in detail how Eqs. (13.13e)–(13.13g) are applied.

Judging from Fig. 13.9, in scenario 1, there is no perturbed edge on the path from O_1 to O_4, and only one edge, $J_{E_1-E_4}$, connects the two elements. Therefore, based on Eq. (13.13f),

$$
{}_{[1]}J^{(new)}_{O_1/O_4} = {}_{[1]}J_{O_1/O_4} = {}_{[1]}J_{O_1-O_4}/{}_{[1]}J_{O_4-O_1} = {}^{50}\!/_{50} = 1 \tag{13.14a}
$$

The perturbed edge $J^*_{O_1-O_2}$ is on the path from O_2 to O_4; therefore,

$$
\begin{aligned}
{}_{[1]}J^{(new)}_{O_2/O_4} &= {}_{[1]}J^{(new)}_{O_2/O_1} \times {}_{[1]}J_{O_1/O_4} = \frac{{}_{[1]}J_{O_2-O_1} - {}_{[1]}P_{O_1-O_2}}{{}_{[1]}J_{O_1-O_2} - {}_{[1]}P_{O_1-O_2}} \times {}_{[1]}J_{O_1/O_4} \\
&= \frac{30 - P_{O_1-O_2}}{70 + P_{O_1-O_2}} \times \frac{50}{50} = \frac{30 - P_{O_1-O_2}}{70 + P_{O_1-O_2}}
\end{aligned} \tag{13.14b}
$$

based on Eq. (13.13g). For ${}_{[1]}J^{(new)}_{O_3/O_4}$, two edges, ${}_{[1]}J_{O_3-O_1}$ and ${}_{[1]}J_{O_1-O_4}$, connect O_3 to O_4 and neither are perturbed. This leads to

$$
{}_{[1]}J^{(new)}_{O_3/O_4} = {}_{[1]}J_{O_3/O_4} = {}_{[1]}J_{O_3-O_1}/{}_{[1]}J_{O_1-O_3}\,{}_{[1]}J_{O_1-O_4}/{}_{[1]}J_{O_4-O_1} = \frac{20}{80} \times \frac{50}{50} = \frac{1}{4}. \tag{13.14c}
$$

Finally, we have

$$
\left({}_{[1]}J^{(new)}_{O_4/O_4} = {}_{[1]}J_{O_4/O_4} = 1\right) \tag{13.14d}
$$

Now we can calculate ${}_{[1]}P_{1^*(A)}$ using Eq. (13.13e) as

$$
\begin{aligned}
{}_{[1]}P^{O}_{1^*}(A) &= {}_{[1]}\frac{J^{(new)}_{O_1/O_4}}{\sum_{y=1}^{4} {}_{[1]}J^{(new)}_{O_y/O_4}} - {}_{[1]}\frac{J_{O_1/O_4}}{\sum_{y=1}^{4} {}_{[1]}J_{O_y/O_4}} = \frac{1}{1 + \frac{30 - P_{O_1-O_2}}{70 + P_{O_1-O_2}} + \frac{1}{4} + 1} \\
&- \frac{1}{1 + \frac{30}{70} + \frac{1}{4} + 1} = \frac{4(70 + P_{O_1-O_2})}{5(150 - P_{O_1-O_2})} - \frac{28}{75} \quad = \frac{32P_{O_1-O_2}(A)}{75(150 + P_{O_1-O_2}(A))}
\end{aligned} \tag{13.14e}
$$

By going through the same process, ${}_{[w]}P^{O}_{m^*}(A)$ values can be calculated for all w = 1, 2...6 and m = 1, 2, 3. Table 13.9 summarizes the results.

Table 13.9 The results of ${}_{[w]}P^{O}_{m^*}(A)$ values

	${}_{[w]}P^{O}_{1^*}(A)$	${}_{[w]}P^{O}_{2^*}(A)$	${}_{[w]}P^{O}_{3^*}(A)$
$w=1$	$\frac{32P_{O_1-O_2}(A)}{75\left(150+P_{O_1-O_2}(A)\right)}$	$-\frac{24P_{O_1-O_2}(A)}{25\left(150+P_{O_1-O_2}(A)\right)}$	$\frac{8P_{O_1-O_2}(A)}{75\left(150+P_{O_1-O_2}(A)\right)}$
$w=2$	$\frac{1120P_{O_1-O_2}(A)}{59\left(4130+19P_{O_1-O_2}(A)\right)}$	$-\frac{1880P_{O_1-O_2}(A)}{59\left(4130+19P_{O_1-O_2}(A)\right)}$	$\frac{280P_{O_1-O_2}(A)}{59\left(4130+19P_{O_1-O_2}(A)\right)}$
$w=3$	$\frac{128P_{O_1-O_2}(A)}{115\left(230+P_{O_1-O_2}(A)\right)}$	$-\frac{208P_{O_1-O_2}(A)}{115\left(230+P_{O_1-O_2}(A)\right)}$	$\frac{32P_{O_1-O_2}(A)}{115\left(230+P_{O_1-O_2}(A)\right)}$
$w=4$	$\frac{70P_{O_1-O_2}(A)}{25270+171P_{O_1-O_2}(A)}$	$-\frac{160P_{O_1-O_2}(A)}{25270+171P_{O_1-O_2}(A)}$	$\frac{20P_{O_1-O_2}(A)}{25270+171P_{O_1-O_2}(A)}$
$w=5$	$\frac{18P_{O_1-O_2}(A)}{65\left(130+P_{O_1-O_2}(A)\right)}$	$-\frac{48P_{O_1-O_2}(A)}{65\left(130+P_{I_1-I_2}(A)\right)}$	$\frac{12P_{O_1-O_2}(A)}{65\left(130+P_{O_1-O_2}(A)\right)}$
$w=6$	$\frac{14P_{O_1-O_2}(A)}{15\left(210+P_{O_1-O_2}(A)\right)}$	$-\frac{8P_{O_1-O_2}(A)}{5\left(210+P_{O_1-O_2}(A)\right)}$	$\frac{4P_{O_1-O_2}(A)}{15\left(210+P_{O_1-O_2}(A)\right)}$
$w=7$	$\frac{14P_{O_1-O_2}(A)}{15\left(210+P_{O_1-O_2}(A)\right)}$	$-\frac{8P_{O_1-O_2}(A)}{5\left(210+P_{O_1-O_2}(A)\right)}$	$\frac{4P_{O_1-O_2}(A)}{15\left(210+P_{O_1-O_2}(A)\right)}$
$w=8$	$\frac{14P_{O_1-O_2}(A)}{15\left(210+P_{O_1-O_2}(A)\right)}$	$-\frac{8P_{O_1-O_2}(A)}{5\left(210+P_{O_1-O_2}(A)\right)}$	$\frac{4P_{O_1-O_2}(A)}{15\left(210+P_{O_1-O_2}(A)\right)}$

From Eq. (13.13e), we have $P^{O}_{m^*}(A) = \frac{\sum_{w=1}^{W} {}_{[w]}P^{O}_{m^*}(A)}{W} = \sum_{w=1}^{8} {}_{[w]}P^{O}_{m^*}(A)/8$ (m = 1, 2, 3). Therefore,

$$P^{O}_{1^*}(A)=\frac{1}{8}\left[\frac{32P_{O_1-O_2}(A)}{75(150+P_{O_1-O_2}(A))}+\frac{1120P_{O_1-O_2}(A)}{59(4130+19P_{O_1-O_2}(A))}+\frac{128P_{O_1-O_2}(A)}{115(230+P_{O_1-O_2}(A))}\right.$$
$$\left.+\frac{70P_{O_1-O_2}(A)}{25270+171P_{O_1-O_2}(A)}+\frac{18P_{O_1-O_2}(A)}{65(130+P_{O_1-O_2}(A))}+\frac{3\times 14P_{O_1-O_2}(A)}{15(210+P_{O_1-O_2}(A))}\right] \tag{13.15a}$$

$$P^{O}_{2^*}(A)=\frac{1}{8}\left[-\frac{24P_{O_1-O_2}(A)}{25(150+P_{O_1-O_2}(A))}-\frac{1880P_{O_1-O_2}(A)}{59(4130+19P_{O_1-O_2}(A))}-\frac{208P_{O_1-O_2}(A)}{115(230+P_{O_1-O_2}(A))}\right.$$
$$\left.-\frac{160P_{O_1-O_2}(A)}{25270+171P_{O_1-O_2}(A)}-\frac{48P_{O_1-O_2}(A)}{65(130+P_{O_1-O_2}(A))}-\frac{3\times 8P_{O_1-O_2}(A)}{5(210+P_{O_1-O_2}(A))}\Bigg)\right] \tag{13.15b}$$

$$P^{O}_{3^*}(A)=\frac{1}{8}\left[\frac{8P_{O_1-O_2}(A)}{75(150+P_{O_1-O_2}(A))}+\frac{280P_{O_1-O_2}(A)}{59(4130+19P_{O_1-O_2}(A))}+\frac{32P_{O_1-O_2}(A)}{115(230+P_{O_1-O_2}(A))}\right.$$
$$\left.+\frac{20P_{O_1-O_2}(A)}{25270+171P_{O_1-O_2}(A)}+\frac{12P_{O_1-O_2}(A)}{65(130+P_{O_1-O_2}(A))}+\frac{4P_{O_1-O_2}(A)}{15(210+P_{O_1-O_2}(A))}\right] \tag{13.15c}$$

Expert B's judgments are assumed to be unchanged; therefore, $P^{O}_{1^*}(B)=P^{O}_{2^*}(B)=P^{O}_{3^*}(B)=P^{O}_{4^*}(B)=0$. Since simple arithmetic mean was used in Ho's model to combine the judgments from the two experts, the contribution perturbations can be represented as

$$P_{m^*}^O = \frac{P_{m^*}^O(A) + P_{m^*}^O(B)}{2} = \frac{P_{m^*}^O(A)}{2}, \quad \forall\, \mathrm{m} = 1,\ 2,\ 3. \tag{13.15d}$$

As a result, the inequality defined by Eq. (13.13a) can be rewritten as

$$2\left(C_r^A - C_{r+n}^A\right) \geq P_{1^*}^O(A)\lambda_1^O + P_{2^*}^O(A)\lambda_2^O + P_{3^*}^O(A)\lambda_3^O \tag{13.15e}$$

When r = 1, n = 1,

$$C_r^A - C_{r+n}^A = C_{(1)}^A - C_{(2)}^A = C_2^A - C_5^A = 0.235 - 0.2204 = 0.0146 \tag{13.15f}$$

Based on Eq. (13.13b), we calculate the λ_m^E's as

$$\lambda_1^O = C_{5,1^*}^{A-O} - C_{2,1^*}^{A-O} - C_{5,4}^{A-O} + C_{2,4}^{A-O} = 0.24 - 0.24 - 0.21 + 0.24 = 0.03 \tag{13.15g}$$

$$\lambda_2^O = C_{5,2^*}^{A-O} - C_{2,2^*}^{A-O} - C_{5,4}^{A-O} + C_{2,4}^{A-O} = 0.20 - 0.22 - 0.21 + 0.24 = 0.01 \tag{13.15h}$$

$$\lambda_3^O = C_{5,3^*}^{A-O} - C_{2,3^*}^{A-O} - C_{5,4}^{A-O} + C_{2,4}^{A-O} = 0.22 - 0.24 - 0.21 + 0.24 = 0.01 \tag{13.15i}$$

Therefore, we have

$$2 \times 0.0146 \geq 0.03P_{1^*}^O(A) + 0.01P_{2^*}^O(A) + 0.01P_{3^*}^O(A) \tag{13.15j}$$

Substituting Eqs. (13.15a)–(13.15d) for $P_{1^*}^O$, $P_{2^*}^O$, and $P_{3^*}^O$ in Eq. (13.15j) and solving it, we get

$$P_{O_1-O_2}(A) \geq -130 \tag{13.15k}$$

Repeating the same steps for n = 1 and r = 2, 3, 4, we get the following inequalities:

$$P_{O_1-O_2}(A) \geq -2.3306, \quad (\text{when } \mathrm{r} = 2,\ \mathrm{n} = 1) \tag{13.15l}$$

$$P_{O_1-O_2}(A) \geq -130, \quad (\text{when } \mathrm{r} = 3,\ \mathrm{n} = 1) \tag{13.15m}$$

$$P_{O_1-O_2}(A) \geq -130, \quad (\text{when } \mathrm{r} = 4,\ \mathrm{n} = 1) \tag{13.15n}$$

Combining with the feasibility constraint, $(-70 \leq P_{O_1-O_2}(A) \leq 30)$, that prevents the new $J_{O_1-O_2}(A)$ value to go below 0 or above 100, the allowable range of $P_{O_1-O_2}(A)$

is [−2.33, 30]. Since the base value of $J_{O_1-O_2}(A)$ is 70, its tolerance is [67.67, 100]. This means that as long as expert A's judgment value given to O_1 when it is compared with O_2 in terms of their contributions to the mission is between 67.67 and 100, the rank of all the decision alternatives will remain unchanged. From the Eqs. (13.15k) to (13.15n), we can tell that only the rank order of $A_{(2)}$ and $A_{(3)}$ is sensitive to decreases in the $J_{O_1-O_2}(A)$ value, and all the other pairs are very stable.

Since the length of $J_{O_1-O_2}(A)$'s tolerance is 27.33, and the total length of its feasible range is 100, we can conclude that there is (1–27.33 % = 72.67 %) chance that the current ranking of the decision alternatives will change when this pair-wise comparison judgment varies uniformly between 0 and 100.

13.3.2 Two-Way SA

If, besides $J^*_{O_1-O_2}$, expert A is also concerned with the judgment given to O_2 when it is compared with O_3, we can conduct a two-way sensitivity analysis on these two judgments. Again, we use $P_{O_1-O_2}(A)$ and $P_{O_2-O_3}(A)$ to denote the perturbations induced on the judgments given by expert A to $J^*_{O_1-O_2}$ and $J^*_{O_2-O_3}$. Applying theorem 1 and based on Eq. (13.11), we first generate $\left(W = \sum_{j=1}^{(1+4-3)^{1+4-3-2}} \sum_{r=1}^{1} Q_r^{[j]^{Eg_r}} = \sum_{j=1}^{2^0} 3^{[j]^{Eg_r}} = 3^1 = 3\right)$ labeled trees representing three scenarios, as shown in Fig. 13.10.

From tree [1], we get

$$_{[1]}P^O_{1^*}(A) = -\frac{7}{15} + \frac{2(70 + P_{O_1-O_2}(A))(60 + P_{O_2-O_3}(A))}{5P_{O_1-O_2}(A)(-40 + P_{O_2-O_3}(A)) + 10(360 + P_{O_2-O_3}(A))} \tag{13.16a}$$

$$_{[1]}P^O_{2^*}(A) = -\frac{1}{5} - \frac{2(-30 + P_{O_1-O_2}(A))\,(60 + P_{O_2-O_3}(A))}{5P_{O_1-O_2}(A)\,(-40 + P_{O_2-O_3}(A)) + 10(360 + P_{O_2-O_3}(A))} \tag{13.16b}$$

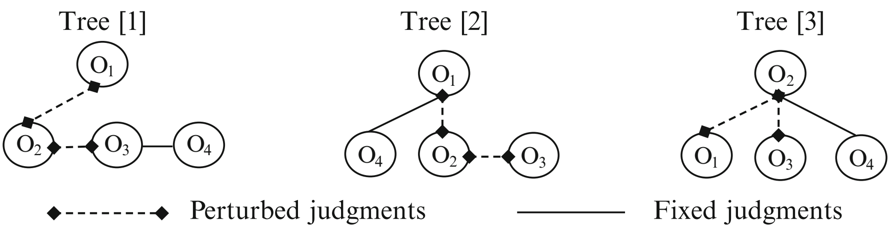

Fig. 13.10 Scenario trees for Y = 4, T = 2, and Q = 3

$$ {}_{[1]}P^{O}_{3^*}(A) = -\frac{2}{15} + \frac{2(-30 + P_{O_1-O_2}(A))\,(-40 + P_{O_2-O_3}(A))}{5P_{O_2-O_3}(A)(-40 + P_{O_1-O_2}(A)) + 10(360 + P_{O_2-O_3}(A))} \tag{13.16c} $$

From tree [2], we get

$$ {}_{[2]}P^{O}_{1^*}(A) = -\frac{7}{19} + \frac{\left(70 + P_{O_1-O_2}(A)\right)\left(60 + P_{O_2-O_3}(A)\right)}{2(5700 + 70P_{O_2-O_3}(A) + P_{O_1-O_2}(A))\,(10 + P_{O_2-O_3}(A))} \tag{13.16d} $$

$$ {}_{[2]}P^{O}_{2^*}(A) = -\frac{3}{19} - \frac{\left(-30 + P_{O_1-O_2}(A)\right)\left(60 + P_{O_2-O_3}(A)\right)}{2\left(5700 + 70P_{O_2-O_3}(A) + P_{O_1-O_2}(A)\,(10 + P_{O_2-O_3}(A)\right)} \tag{13.16e} $$

$$ {}_{[2]}P^{O}_{3^*}(A) = -\frac{2}{19} + \frac{\left(-30 + P_{O_1-O_2}(A)\right)\left(-40 + P_{O_2-O_3}(A)\right)}{2(5700 + 70P_{O_2-O_3}(A) + P_{O_1-O_2}(A))(10 + P_{O_2-O_3}(A))} \tag{13.16f} $$

From tree [3], we get

$$ {}_{[3]}P^{O}_{1^*}(A) = -\frac{7}{15} - \frac{\left(70 + P_{O_1-O_2}(A)\right)\left(60 + P_{O_2-O_3}(A)\right)}{100(-90 + P_{O_1-O_2}(A) - P_{O_2-O_3}(A))} \tag{13.16g} $$

$$ {}_{[3]}P^{O}_{2^*}(A) = -\frac{1}{5} + \frac{\left(-30 + P_{O_1-O_2}(A)\right)\left(60 + P_{O_2-O_3}(A)\right)}{100(-90 + P_{O_1-O_2}(A) - P_{O_2-O_3}(A))}\Bigg) \tag{13.16h} $$

$$ {}_{[3]}P^{O}_{3^*}(A) = -\frac{2}{15} - \frac{(-30 + P_{O_1-O_2}(A))(-40 + P_{O_2-O_3}(A))}{100(-90 + P_{O_1-O_2}(A) - P_{O_2-O_3}(A))}\Bigg) \tag{13.16i} $$

Taking the average of the perturbations calculated in all the orientations, we get

$$ P^{O}_{l}(A) = \sum_{w=1}^{3} {}_{[w]}P^{O}_{l}(A)/3, \quad \forall\, l = 1,\ 2,\ 3. \tag{13.16j} $$

Expert B's judgments are assumed to be unchanged; therefore,

$$ P^{O}_{m^*} = \frac{P^{O}_{m^*}(A) + P^{O}_{m^*}(B)}{2} = \frac{P^{O}_{m^*}(A)}{2}, \quad \forall\, \mathrm{m} = 1,\ 2,\ 3 \tag{13.16k} $$

Based on Eqs. (13.13a) and (13.13b) in theorem 1, when r = 1, and n = 1,

$$C_r^A - C_{r+n}^A = 0.0146 \quad [\text{E14l}], \;\; \lambda_1^O = 0.03 \quad [\text{E14m}], \;\; \lambda_2^O = 0.01 \quad [\text{E14n}], \;\; \lambda_3^O = 0.01 \tag{13.16l}$$

This leads to

$$0.0146 \geq 0.03P_{1^*}^O + 0.01P_{2^*}^O + 0.01P_{3^*}^O \tag{13.16m}$$

Substituting Eqs. (13.16a) through (13.16k) for $P_{1^*}^O$, $P_{2^*}^O$, and $P_{3^*}^O$ in Eq. (13.16m), we get

$$\begin{aligned}&3\times 2\times 0.0146 \geq\\&(156+0.8x+2.1y+0.03xy)\left[\frac{2}{5P_{O_1-O_2}(A)(-40+P_{O_2-O_3}(A))+10(360+P_{O_2-O_3}(A))}+\right.\\&\left.\frac{1}{2(5700+70P_{O_2-O_3}(A)+P_{O_1-O_2}(A))(10+P_{O_2-O_3}(A))}-\frac{1}{100(-90+P_{O_1-O_2}(A)-P_{O_2-O_3}(A))}\right]\\&-0.04836\end{aligned} \tag{13.16n}$$

Repeating the same steps for r = 2, 3, 4 and n = 1, we get the following group of inequalities:

$$\begin{aligned}&3\times 2\times 0.0008 \geq\\&(-336-0.8x-6.6y+0.02xy)\left[\frac{2}{5P_{O_1-O_2}(A)(-40+P_{O_2-O_3}(A))+10(360+P_{O_2-O_3}(A))}+\right.\\&\left.\frac{1}{2(5700+70P_{O_2-O_3}(A)+P_{O_1-O_2}(A)(10+P_{O_2-O_3}(A)))}-\frac{1}{100(-90+P_{O_1-O_2}(A)-P_{O_2-O_3}(A))}\right]\\&+0.1041\end{aligned} \tag{13.16o}$$

$$\begin{aligned}&3\times 2\times 0.0266 \geq\\&(246-2.2x+3.6y-0.02xy)\left[\frac{2}{5P_{O_1-O_2}(A)(-40+P_{O_2-O_3}(A))+10(360+P_{O_2-O_3}(A))}+\right.\\&\left.\frac{1}{2(5700+70P_{O_2-O_3}(A)+P_{O_1-O_2}(A))(10+P_{O_2-O_3}(A))}-\frac{1}{100(-90+P_{O_1-O_2}(A)-P_{O_2-O_3}(A))}\right]\\&-0.0093\end{aligned} \tag{13.16p}$$

$$\begin{aligned}&3\times 2\times 0.0061 \geq\\&(18-0.6x+0.3y-0.01xy)\left[\frac{2}{5P_{O_1-O_2}(A)(-40+P_{O_2-O_3}(A))+10(360+P_{O_2-O_3}(A))}+\right.\\&\left.\frac{1}{2(5700+70P_{O_2-O_3}(A)+P_{O_1-O_2}(A))(10+P_{O_2-O_3}(A))}-\frac{1}{100(-90+P_{O_1-O_2}(A)-P_{O_2-O_3}(A))}\right]\\&-0.0056\end{aligned} \tag{13.16q}$$

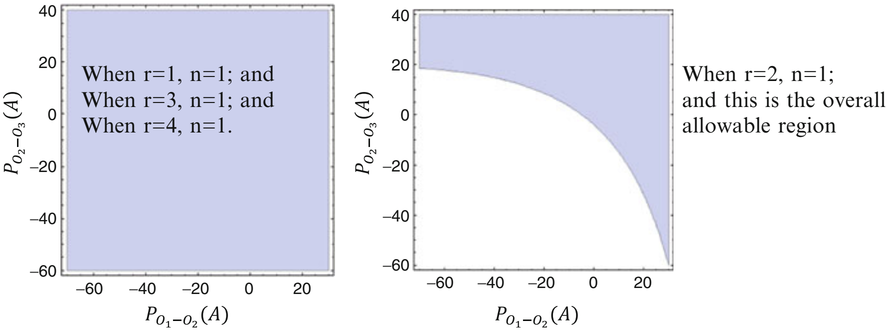

Fig. 13.11 The allowable region of $\boldsymbol{P_{O_1-0_2}(A)}$ and $\boldsymbol{P_{O_2-0_3}(A)}$ for all the $\boldsymbol{A_r}$'s to remain unchanged

Inequalities Eqs. (13.16n)–(13.16q) therefore define the allowable region for $P_{O_1-0_2}(A)$ and $P_{O_1-0_2}(A)$ in order to keep the rank of all decision alternatives unchanged. Figure 13.11 shows the allowable regions graphically.

Again, all the other rank orders are very robust to the perturbations except for the actions that ranked as the second and the third. With the given inequalities, Eqs. (13.16n)–(13.16q), we can also calculate the area of the allowable region to be 3,951.77. Since the total area of the feasible region of the two perturbations is 10^4, we can conclude that there is (1–39.5 % = 60.5 %) chance that the current ranking of decision alternatives will be changed when judgments $J^*_{O_1-0_2}(A)$ and $J^*_{O_2-0_3}(A)$ vary uniformly between 0 and 100.

13.3.3 Three-Way SA

If all the judgments given by expert A to the O_l's are concerned, theorem 1 can be applied to test the sensitivity of all $J^*_{O_l-O_{l'}}(A)$'s. Since there are four objectives under comparison, only up to $(4-1=3)$ judgments can be perturbed in this judgment matrix. With four decision elements and three judgment perturbations, only one orientation exists (when $T=Y-1,\ W=1$). Assuming that the judgments $J^*_{O_1-O_2}$, $J^*_{O_2-O_3}$, and $J^*_{O_3-O_4}$ given by expert A involve the most uncertainties, we determine the allowable region of the perturbations induced on these three judgments. Based on Eqs. (13.13e) and (13.13g) in theorem 1, we get

$$P^O_{1^*}(A) = -\frac{7}{15} + \frac{\left(70+P_{O_1-O_2}(A)\right)\left(60+P_{O_2-O_3}(A)\right)\left(40+P_{O_3-O_4}(A)\right)}{\begin{array}{c}[100(P_{O_2-O_3}(A)(-20+P_{O_3-O_4}(A))+30(120+P_{O_3-O_4}(A))\\ +P_{O_1-O_2}(A)(-40+2P_{O_2-O_3}(A)+P_{O_3-O_4}(A)))]\end{array}} \tag{13.17a}$$

$$P^O_{2^*}(A) = -\frac{1}{5} - \frac{\big(-30+P_{O_1-O_2}(A)\big)\big(-40+P_{O_2-O_3}(A)\big)\big(-60+P_{O_3-O_4}(A)\big)}{\begin{array}{c}[100(P_{O_2-O_3}(A)(-20+P_{O_3-O_4}(A))+30(120+P_{O_3-O_4}(A))\\ +P_{O_1-O_2}(A)(-40+2P_{O_2-O_3}(A)+P_{O_3-O_4}(A)))]\end{array}} \tag{13.17b}$$

$$P^O_{3^*}(A) = -\frac{2}{15} + \frac{\big(-30+P_{O_1-O_2}(A)\big)\big(-40+P_{O_2-O_3}(A)\big)\big(40+P_{O_3-O_4}(A)\big)}{\begin{array}{c}[100(P_{O_2-O_3}(A)(-20+P_{O_3-O_4}(A))+30(120+P_{O_3-O_4}(A)))\\ +P_{O_1-O_2}(A)(-40+2P_{O_2-O_3}(A)+P_{O_3-O_4}(A)))]\end{array}} \tag{13.17c}$$

Again, expert B's judgments are assumed to be unchanged. Therefore,

$$P^O_{m^*} = \frac{P^O_{m^*}(A)+P^O_{m^*}(B)}{2} = \frac{P^O_{m^*}(A)}{2}, \quad \forall\, \mathrm{m} = 1,\ 2,\ 3. \tag{13.17d}$$

Let r = 1, 2, 3, 4 and n = 1, we can get the allowable region of $P_{O_1-O_2}(A)$, $P_{O_2-O_3}(A)$, and $P_{O_3-O_4}(A)$ for the rank order of all decision alternatives to remain unchanged.

Based on Eqs. (13.13a) and (13.13b) in theorem 1, when r = 1, and n = 1,

$$C^A_r - C^A_{r+n} = 0.0146\ \ [\text{E15e}],\ \ \lambda^O_1 = 0.03\ \ [\text{E15 f}],\ \ \lambda^O_2 = 0.01\ \ [\text{E15g}],\ \ \lambda^O_3 = 0.01 \tag{13.17e}$$

This leads to

$$0.0146 \geq 0.03P^O_{1^*} + 0.01P^O_{2^*} + 0.01P^O_{3^*} \tag{13.17f}$$

Substituting Eqs. (13.17a) through (13.17d) for $P^O_{1^*}$, $P^O_{2^*}$, and $P^O_{3^*}$ in Eq. (13.17f), we get

$$2\times 0.0146 + 0.0173 \geq \frac{\begin{array}{c}[6240+126P_{O_3-O_4}(A)+P_{O_1-O_2}(A)[32+P_{O_2-O_3}(A)(2.2+0.03P_{O_3-O_4}(A))\\ +1.8P_{O_3-O_4}(A)]+P_{O_2-O_3}(A)(54+2.1P_{O_3-O_4}(A))]\end{array}}{\begin{array}{c}[100(P_{O_2-O_3}(A)(-20+P_{O_3-O_4}(A))+30(120+P_{O_3-O_4}(A)))\\ +P_{O_1-O_2}(A)(-40+2P_{O_2-O_3}(A)+P_{O_3-O_4}(A)))]\end{array}} \tag{13.17g}$$

Repeating the same steps for r = 2, 3, 4 and n = 1, we get the following group of inequalities:
When r = 2, n = 1

$$2\times 0.0008 - 0.0133 \geq \frac{\begin{array}{c}[-4800-P_{O_2-O_3}(A)(300+3P_{O_3-O_4}(A))+P_{O_1-O_2}(A)\\ [-320+P_{O_2-O_3}(A)(2-0.1P_{O_3-O_4}(A))-2P_{O_3-O_4}(A)]\\ -300P_{O_3-O_4}(A)]\end{array}}{\begin{array}{c}[100(P_{O_2-O_3}(A)(-20+P_{O_3-O_4}(A))+30(120+P_{O_3-O_4}(A))\\ +P_{O_1-O_2}(A)(-40+2P_{O_2-O_3}(A)+P_{O_3-O_4}(A)))]\end{array}} \tag{13.17h}$$

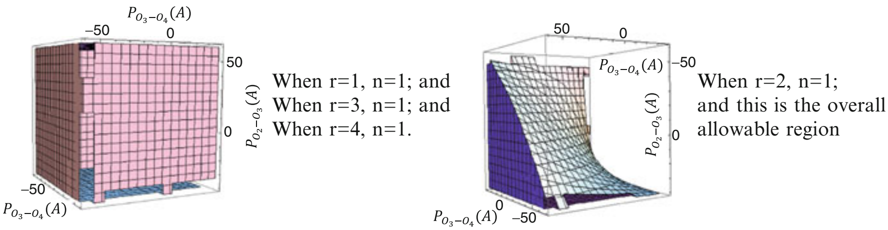

Fig. 13.12 The allowable region of $\boldsymbol{P_{O_1-0_2}(A)}$, $\boldsymbol{P_{O_2-0_3}(A)}$, and $\boldsymbol{P_{O_3-0_4}}$ for all $\boldsymbol{A_r}$'s to remain unchanged

When r = 3, n = 1

$$2 \times 0.0266 + 0.0273 \geq \frac{\begin{array}{c}[9840 + 66P_{O_3-O_4}(A) + P_{O_2-O_3}(A)(-36 + 3.6P_{O_3-O_4}(A)) + P_{O_1-O_2}(A) \\ [-88 + P_{O_2-O_3}(A)(5.2 - 0.02P_{O_3-O_4}(A)) + 3.8P_{O_3-O_4}(A)]]\end{array}}{\begin{array}{c}[100(P_{O_2-O_3}(A)(-20 + P_{O_3-O_4}(A)) + 30(120 + P_{O_3-O_4}(A)) \\ +P_{O_1-O_2}(A)(-40 + 2P_{O_2-O_3}(A) + P_{O_3-O_4}(A)))]\end{array}} \tag{13.17i}$$

When r = 4, n = 1

$$2 \times 0.0061 + 0.002 \geq -\frac{\left(-30 + P_{O_1-O_2}(A)\right)\left(-40 + P_{O_2-O_3}(A)\right)\left(-60 + P_{O_3-O_4}(A)\right)}{\begin{array}{c}[100(P_{O_2-O_3}(A)(-20 + P_{O_3-O_4}(A)) + 30(120 + P_{O_3-O_4}(A)) \\ +P_{O_1-O_2}(A)(-40 + 2P_{O_2-O_3}(A) + P_{O_3-O_4}(A)))]\end{array}} \tag{13.17j}$$

Representing the inequalities, Eqs. (13.17g)–(13.17j), graphically, we show the allowable space of the three perturbations in Fig. 13.12.

With the given inequalities that define the allowable space, we can calculate the volume of the allowable space to be 373,415. Since the total volume of the feasible space of the three perturbations is 10^6, we can conclude that there is (1–37.3 % = 62.7 %) chance that the current ranking of all decision alternatives will be changed when judgments $J^*_{O_1-O_2}(A)$, $J^*_{O_2-O_3}(A)$, and $J^*_{O_3-O_4}(A)$ vary uniformly between 0 and 100.

13.4 Concluding Remarks

In this chapter, we extended the HDM SA algorithm to help decision makers analyze how sensitive the results of a hierarchical decision model are to its input—the pair-wise comparison judgments. The HDM SA algorithm developed in early studies defines the allowable region of perturbation(s) induced on local contributions, the contribution tolerance, and the probability of rank changes.

Since the immediate input to any HDM model is the pair-wise comparison judgment values, the decision makers and the judgment providers are usually interested in knowing how changes to these input values affect the decisions. By linking the HDM SA algorithm to the pair-wise comparison step, we made it more comprehensive and straightforward. The theorem developed in this chapter defines the allowable region of judgment perturbation(s) induced to a pair-wise comparison judgment matrix at any level of a decision hierarchy to keep the current decision unchanged. Based on the length of the allowable range or the area or space of the allowable region of the judgment perturbation(s), the probability of rank change when certain judgment value(s) are perturbed can be calculated.

The proposed algorithm is applicable to hierarchical decision models that use the constant sum pair-wise comparison scale and the additive function to aggregate the local contributions. Examples illustrating the application of the algorithm also demonstrated how the algorithm can be used if group opinions are combined using the simple arithmetic mean. If other group opinion combination methods are used, the process can be easily modified following the same logic. Comparing to iteration-based methods such as the numerical incremental analysis, the algorithm enjoys lower computational complexity, better or equal accuracy, and equal generality.

To address the limitation of this work, the acceptable degree of inconsistency will be considered as an additional constraint while deriving the allowable change to the judgment values. To relieve general users from the cognitive burden in understanding the denotations and better assist decision makers, computer software based on the proposed algorithm is under development. Future work also includes developing sensitivity analysis for the 1–9 with verbal representation pair-wise comparison scale and its eigenvector-based judgment quantification technique.

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Chapter 14
Decision-Making Tools: Deleting Criteria Using Sensitivity Analysis

Fatima M. Albar and Dundar F. Kocaoglu

Abstract Research has shown that as the attractiveness of alternatives rises with more choices, individuals experience conflict between the alternatives, which causes them to defer their decision, search for new alternatives, or choose the default option. Having lesser attributes simplifies complex problems and the decision-making process. This chapter uses the sensitivity analysis in hierarchical decision model, developed by Hongyi Chen, to prove that we can reduce the size of a problem and make the decision easier with the future change of values of attributes, without affecting the final decision.

14.1 Introduction

As the world has become more complex and information flows from every direction with an easy access, decision problems must contend with increasingly complex relationships and interactions among the decision elements. Among a variety of decision-making fundamentals, models, and tools, the ability of individuals to estimate their needs and generate personal and organizational objectives for a given decision is critical to succeed. Management science and decision making research use different words like objectives, goals, criteria, or attributes to represent what the decision maker wants to achieve by making the decision [1]. In this research we choose "attributes" as a decision criteria or cue decision makers want to achieve in their decision.

Decision makers usually are attracted to choice, and sometimes they get disappointed when they do not have many alternative solutions [2, 3]. However, having more choices does not make the selection process easier [4] and often tends to yield to less confident about the choice [3]. Research shows that the percentage of

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positive judgments decreased with increasing complexity. When facing many choices, individuals experience conflict between the alternatives, which causes them to defer their decision, search for new alternatives, choose the default option, or simply not to choose [2], because goals shifted from maximizing benefits to minimizing the decision complexity and reaching a justifiable decision [3]. Malhotra [5] found that people experienced information overload when both the number of attributes and the number of options were increased. Research participants reported having too much information when the number of attributes was increased not when the number of options was increased [2]. When choosing among products described by more attributes, people reported feeling more confused and unsure of having made the right choice than when faced with fewer attributes [2].

Increasing number of attributes to be evaluated in making decision usually increases the cognitive costs associated with processing this information (Gigerenzer). The problems with having large assortments of data have been rooted in the ability of human cognitive system to compare and make a decision between several alternatives (psychology book). Cognitive system can process, remember, compare, and recognize up to seven variables—plus or minus two—at the same time. When people have more variance, they become ignorant about what is going to happen [6]. Process tracing studies have repeatedly shown that individuals employ simple strategies that minimize the amount of considered information and mental effort invested in the decision [7, 8].

To eliminate the effort decision makers might consider fewer choices, apply fewer attributes in the evaluation, and process a smaller fraction of the overall information available regarding their choices. Smith [9] found that smaller number of attributes were used to reach the desired decision in prescribing medication. Dhami [10] suggests that physicians use fewer attributes to make decision. Proctor & Gamble reduced the number of versions of Head and Shoulders shampoo from 26 to 15, and as a result sales increased by 10 % [2]. Bond et al. [1] found that the participants consistently omitted nearly half of their objectives even though they were perceived to be almost as important as the remaining ones. Despite omitting these objectives, decision makers were satisfied with their decisions.

Are all attributes important to the decision maker or important to the quality of the decision? Not always. The usefulness of the available attribute information is to help a decision maker in making decision; when the number of attributes increased, it does not always lead to increase in the quality of information. There is a point where more is not better, but harmful because the relation between level of accuracy and amount of information, computation, or time takes an inverse U shape. These facts raised many questions like the following: Should we reduce the number of attributes in strategic decisions? How can the number of attributes be reduced without affecting the quality of the decisions? This study uses sensitivity analysis of the attributes founded by Chen [11] to eliminate attributes without affecting the final decision in strategic planning decision making.

Sensitivity analysis (SA) is a fundamental concept that has been used and implemented in quantitative decision models. It provides information more significant and useful than simply knowing the model solution, and serves different purposes in the decision-making process.

Chen classified several benefits of applying sensitivity analysis to hierarchical decision models (HDM) including the following: (1) help visualize the impact of changes at the policy and strategy levels on decisions at the operational level; (2) test the robustness of the recommended decision; (3) identify the critical elements of the decision; (4) generate scenarios of possible rankings of decision alternatives under different conditions; (5) help judgment providers (the experts) reach consensus; and (6) offer answers to “what-if” questions. This research is adding another value of applying the sensitivity analysis, which is eliminating the ineffective decision criteria to reduce the complexity.

14.2 Eliminating Attributes in Literature

Many researches study the effect of eliminating information in the decision-making process on the quality of the decisions. The impact of using an incomplete set of the nine attributes on choice inaccuracy was measured in terms of the proportion of value lost (PVL) [12]. PVL is obtained by comparing the value of the option chosen using partial attribute information to the value of the option chosen using full attribute information. PVL ranges from 0, when the option chosen using partial information coincides with the best option determined by full information, to 1, when the option chosen coincides with the worst option determined by full information. Option values were computed using multi-attribute utility theory.

When attributes are negatively correlated, the results depend on the relative attributes’ importance; given that attributes are negatively correlated and equally important, choosing fewer attributes can lead to substantial increases in PVL, and it is necessary to use at least 80 % of attributes to make a choice at the 10 % PVL level [4, 12].

When weights are unequal, then it remains sufficient to know and use the most important attribute to make a choice within 10 % of the highest value possible [4].

When all attributes are considered, in the negative correlation, there are on average 95 % non-dominated options (s.d. = 5 %); earning that, with full information, the choice gets very complicated because about 20 of 21 options are most attractive regarding at least one attribute. Thus, considering fewer attributes has the benefit of making the choice less conflicted and less complicated.

Using unequal weight attributes—with positive correlation—Barbara [4] found that PVL was very low even when choice was based on a single attribute if attributes were positively correlated. Only one or two attributes are enough to make a choice at an acceptable 10 % PVL level. If attributes are unequally important to the decision maker, it is sufficient to use the most important one. We can still find the same relationship between the number of attributes and non-dominated options. In this case, about one-third of non-dominated options can be eliminated.

Gigerenzer and his research group tried to discover the power of one-reason decision making through applying the Take the Best algorithm [13–15]. Take the Best algorithm depends on the rule of thumb "take the best and ignore the rest."

Results [14] show that Take the Best performs as well as the regression model and has performed better than the linear models under lack of information. On average, the algorithm tested three attributes before it stopped searching and picked a choice, which it found to be acceptable.

14.3 Research Objective and Methodology

In this highly competitive and fast-changing environment, managers have to keep track of the changes in values of the criteria, which would cost money and effort.

This research used the sensitivity analysis to test the effect of deleting one or more attributes on the first (top) rank alternative decision in hierarchical decision model. In order to understand the impact of changes in the attribute value on the alternatives rank, we studied and analyzed the sensitivity of the attributes and tolerance values using Chen's doctoral dissertation and publications [11]. Tolerance is defined as "the allowable range in which a contribution value can vary without changing the rank order of the decision alternatives" [11]. To determine the tolerance of each attribute weight, the allowable range of perturbations on the contribution is used [11]. The allowable range of perturbations corresponds to "allowable increase and decrease," as used in the sensitivity analysis of linear programming.

14.3.1 Notations and Formulas

The classical notion of attributes implies on the [16] preference structure.

"P" denotes preference while "I" denotes indifference.

$a\ P\ b$ *iff* $C_a > C_b$.

$a\ I\ b$ *iff* $C_a = C_b$.

C_k represents the value given to criterion.

K is the number of attributes, then

A is the alternative technology.

$C_k(A)$ is the weight given to alternative A under criteria k.

$$\sum\nolimits_{k=1}^{K} C_k = 1.00 \tag{14.1}$$

$$\sum\nolimits_{k=1}^{K} C_k(A) = 1.00 \tag{14.2}$$

The total weight of alternative A is $R(A)$:

$$\begin{aligned} R(A) \; &= \sum_{k=1}^{K} \left(C_k \times C_{k(A)}\right) \\ A_1 P A_2 \; &\text{if}\, R\,(A_1) > R(A_2) \\ A_1 I A_2 \; &\text{if}\; R\;(A_1) = R(A_2) \end{aligned} \tag{14.3}$$

$R(A_1)I$, if no change happens to the A's rank even with changing the criteria weight.

14.3.2 Experiments and Results

To understand when the deletion of an attribute will not affect the decision, we studied simulated data where we randomly assigned four attributes different values keeping the condition that the sum of all attribute values equals one, Eq. (14.1).

We had two sets of alternatives: one had three different alternatives and a decision has to be done to choose one of them, and the other contained five different alternatives.

The weight of the alternatives regarding each attribute was randomly selected with keeping the total value of weights of each attribute equal to one, Eq. (14.2).

Then, alternatives were ranked depending on the rate value which was calculated using Eq. (14.3).

In order to find out when (at what point) deleting the attribute will not affect the first rank, we tried to change the value of each attribute C_k one at a time, keeping the weight of alternative's attributes C_k (A) without any change.

From studying many simulated values of four attributes with three and five alternatives and concerning only changes happened to the first rank alternative, we can classify our findings as follows:

Some attributes have C_k value that could go to 0.99 without changing the first rank. Others can go down to zero without changing the first rank.

When we change the C_k value of an attribute, in most of the cases, this change caused changing of the top rank at a certain point (we called it the break point), and then changing the C_a value will not cause changes to the decision until it reaches another break point; see Fig. 14.1.

Some attributes have one or two break points; others do not have any break points.

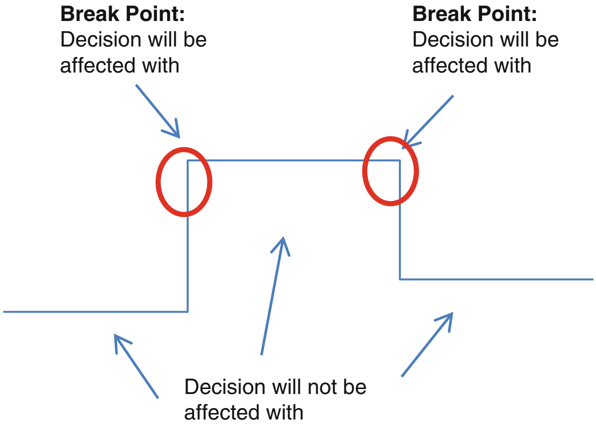

Fig. 14.1 When change of criterion's weight changes the top decision

We studied the sensitivity of each attribute and used the tolerance value to identify when we can delete the attribute without affecting the decision.

To calculate the tolerance of each attribute while keeping the first rank with no change, we need to calculate the perturbation value for criteria k^* (p_{k^*}), Eq. (14.4) [11].

Since we only care about the first rank we will set r in the following equations with value 1.

n is the variable which will take the value of criteria we want to test.

If $r = 1$. $n = 1, 2, \ldots K$, where K is the total number of all attributes, criteria are ranked from more important to less important, and technologies are ordered from the more important to less important. T_1 is the technology with higher $R(T)$ value.

$C_{r,k}$ is the weight value of technology that gains rank r under criterion k.

C_k is the weight of criterion k.

Equation (14.4) [11]:

$$p_{k^*} = \frac{y}{w} \tag{14.4}$$

$y = R(T_r - RT_{r+n})$ is the difference between the values of first rank and other rank values:

$$w = C_{r+n,k^*} - C_{r,k^*} - \sum_{k=1,\,k\neq K^*}^{K} C_{r+n,k} \times \frac{C_k}{\sum_{k=1,k\neq K^*}^{K} C_k} + \sum_{k=1}^{K} C_{r,k} \times \frac{C_k}{\sum_{k=1,k\neq K^*}^{K} C_k}$$

where

$$\sum_{k=1,\, k\neq K^*}^{K} C_k = C_2 + C_3 + \ldots.. + C_k$$

After calculating $p_{k*}\ for\ all\ values\ of\ n\ (from\ n=1,\ \ldots n=K)$

p_{l-} is the lower perturbation value of p_{k*}.

p_{l+} is the higher perturbation value of p_{k*}.

Equation (14.5) [11]:

$$Tolerance = \ p_{l-} + C_l, p_{l+} + C_l \tag{14.5}$$

From studying sensitivity analysis we can summarize our finding as follows:

- Top choice will remain at the first rank (the decision will not change) if for all criteria C_a has changed within the tolerance limit for each criterion:

$$R(A_1)\ \ I \text{ iff } \forall\ k\ C_k\ = C_k \pm p_k$$

- Once the value of a criterion goes beyond the tolerance range, the first rank will change and A_x will preference A_1, where x represents any alternative, and A_1 represents the first rank:

$$R(A_x)PR(A_1) \text{ iff } \exists\ k\mathbf{,}\ C_k < Tolerance(a)$$

- If the value of the criteria goes lower than the lower tolerance value, the value of the first rank will change and if it continues to go down until zero, this change will not affect the new change:

$$R(A_x)\ PR\ (A_1) \text{ iff } \exists\ k\mathbf{,}\ C_K < Tolerance(k)$$
$$R(A_x)\, I \text{ if } 0 \leq C_k < Tolerance(k)$$

- If the value of the criteria goes higher than the highest tolerance value, the value of the first rank will change and if it continues to go up until one, this change will not affect the new change:

$$R\ (A_x)PR(A_1) \text{ iff k}, C_K > Tolerance(k)$$
$$R(A_x)\, I\ \text{ if } Tolerance(k) < C_K \leq 1$$

14.4 Case Study

We are going to use a hierarchal decision model for the semiconductor foundry industry in Taiwan developed by Ho [17], and used by Chen [11], where the main goal is increasing the return on investment (ROI) rate for the company. Experts from the industry, research organizations, and the government identified four different criteria to reach the goal by choosing a technology among five different technology alternatives.

The four criteria with their weights of importance are displayed in the following Table 14.1.

The five different alternative technologies with their attributes weights are displayed in Table 14.2.

With current weight of criteria and alternatives, the rank of the alternatives is shown in Table 14.3 with R (A) values.

The tolerance value of all attributes to preserve the ranking of the top choice is calculated and summarized in Table 14.4.

Table 14.1 The four criteria and their weights

Criteria	Weight
Cost leadership1	0.36
Product leadership	0.25
Customer leadership	0.21
Market leadership	0.18

Table 14.2 Weight of different alternative technology criteria

	Alternatives				
Criteria	Increasing wafer size	Reducing line width	Hi K	Lo K	Factory integration
Cost leadership1	0.19	0.24	0.13	0.19	0.24
Product leadership	0.27	0.22	0.13	0.18	0.20
Customer leadership	0.21	0.24	0.13	0.19	0.22
Market leadership	0.22	0.24	0.13	0.19	0.21

Table 14.3 Alternative technologies in ranked orders with the contribution values

Technology	$R(A)$
Reducing line width	0.235
Factory integration	0.2204
Increasing wafer size	0.2196
Lo K	0.193
Hi K	0.132

Table 14.4 Tolerance of attributes for keeping the top-ranked alternative unchanged

Criteria	Tolerance range
Cost leadership1	0.75–1
Product leadership	0–0.427
Customer leadership	0–1
Market leadership	0–1

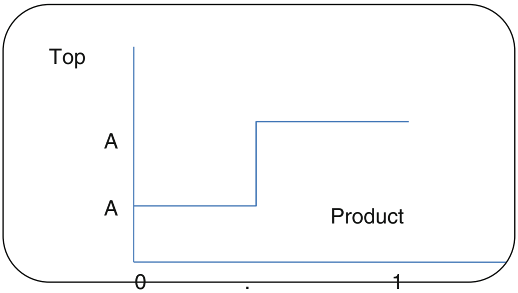

Fig. 14.2 Changing the decision depends on changing product attribute's weight

If the value of attribute changed within the tolerance ranges, this change will not affect the first rank (and our decision) but when it breaks this tolerance boundary, the first rank will change.

For example, if the value of production increases to 0.43, the first rank will change from *reducing line width* alternative to *increasing wafer size*. Moreover, we found that if the value of production increased more than that this increasing will not affect the new rank and *increasing wafer size* will stay as the top rank even if the production value reaches 100 %.

In this case, decision makers and strategic planners in companies don't need to forecast and track the increase of the production once it goes higher than the upper limit of tolerance (which is 0.43 for production attribute) (Fig. 14.2 and Table 14.5).

It is interesting to see that customer and market leadership has a wide tolerance range which tells us that if we do not consider the changes that will happen to these two criteria, we will still have the same top rank and the decision will not be affected with these changes. See Table 14.6.

Therefore, decision makers may delete these attributes from their considerations to simplify the problem.

14.5 Conclusion

Having fewer attributes simplifies complex problems and the decision-making process. This chapter shows that not including all the available information in the decision-making process can still lead to good decisions. Decision makers can reduce the number of criteria and simplify the problem without reducing the quality of the decision in many cases. This process should start with outlining the primary goals and important criteria needed to achieve the objective and eliminating the unnecessary ones. Depending on the problem and type of criteria, decision makers can apply fast and frugal algorithms if they need to make quick decisions. Or they can use sensitivity analyses when there is enough time to study and forecast the changing that could happen to criteria.

Table 14.5 Rate of technologies with different weights of product

Criteria		Increasing wafer size	Producing line width	Hi K	Lo K	Factory integration
Cost leadership1	0.443	0.19	0.24	0.13	0.19	0.24
Product leadership	0	0.27	0.22	0.13	0.18	0.2
Customer leadership	0.293	0.21	0.24	0.13	0.19	0.22
Market leadership	0.263	0.22	0.24	0.13	0.19	0.21
		0.204	0.240	0.130	0.190	0.226
Cost leadership1	0.3	0.19	0.24	0.13	0.19	0.24
Product leadership	0.43	0.27	0.22	0.13	0.18	0.2
Customer leadership	0.15	0.21	0.24	0.13	0.19	0.22
Market leadership	0.12	0.22	0.24	0.13	0.19	0.21
		0.231	0.231	0.130	0.186	0.216
Cost leadership1	0.29	0.19	0.24	0.13	0.19	0.24
Product leadership	0.46	0.27	0.22	0.13	0.18	0.2
Customer leadership	0.14	0.21	0.24	0.13	0.19	0.22
Market leadership	0.11	0.22	0.24	0.13	0.19	0.21
		0.233	0.231	0.130	0.185	0.216
Cost leadership1	0	0.19	0.24	0.13	0.19	0.24
Product leadership	1	0.27	0.22	0.13	0.18	0.2
Customer leadership	0	0.21	0.24	0.13	0.19	0.22
Market leadership	0	0.22	0.24	0.13	0.19	0.21
		0.270	0.220	0.130	0.180	0.200
Cost leadership1	0.43	0.19	0.24	0.13	0.19	0.24
Product leadership	0.32	0.27	0.22	0.13	0.18	0.2
Customer leadership	0	0.21	0.24	0.13	0.19	0.22
Market leadership	0.25	0.22	0.24	0.13	0.19	0.21
		0.223	0.234	0.130	0.187	0.220

(continued)

Table 14.5 (continued)

Criteria		Increasing wafer size	Producing line width	Hi K	Lo K	Factory integration
Cost leadership1	0	0.19	0.24	0.13	0.19	0.24
Product leadership	0	0.27	0.22	0.13	0.18	0.2
Customer leadership	1	0.21	0.24	0.13	0.19	0.22
Market leadership	0	0.22	0.24	0.13	0.19	0.21
		0.210	0.240	0.130	0.190	0.220

Table 14.6 Including or deleting the customer and market criteria does not affect the top rank

Criteria		Increasing wafer size	Producing line width	Hi K	Lo K	Factory integration
Cost leadership1	0.5	0.19	0.24	0.13	0.19	0.24
Product leadership	0.5	0.27	0.22	0.13	0.18	0.2
Customer leadership	0	0.21	0.24	0.13	0.19	0.22
Market leadership	0	0.22	0.24	0.13	0.19	0.21
		0.230	0.230	0.130	0.185	0.220

14.5.1 Limitations and Future Studies

This research considered reducing the number of criteria in one level of the hierarchal decision model and did not go through change in multiple levels. In addition, this study focused on changes to top rank and ignored changes that happened to the rest of the ranks. Future research could be done to study how to reduce the number of criteria in multiple levels of the hierarchical decision model without affecting the rank of all alternatives.

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Chapter 15
Decision-Making Tools: Innovation Measurement Framework

Kenny Phan

Abstract Innovation is one of the most important sources of competitive advantage. It helps a company to fuel the growth of new products and services, sustain incumbents, create new markets, transform industries, and promote the global competitiveness of nations. Because of its importance, companies need to manage innovation. It is very important for a company to be able to measure its innovativeness because one cannot effectively manage without measurement. A good measurement model will help a company to understand its current capability and identify areas that need improvement.

This chapter develops a framework to determine the innovativeness of a company in the semiconductor industry by using output indicators. Output indicators are used because they cannot be manipulated. A hierarchical decision model (HDM) was constructed for the framework. Expert judgments were quantified and incorporated into the model. The hierarchy consisted of three levels: innovativeness index, output indicators, and sub-factors.

According to the experts, the top three sub-factors to measure the innovativeness of a company are revenue from new products, market share of new products, and products that are new to the world.

15.1 Introduction

The past 30 years have shown that innovation is crucial to the sustainability of a business, and is critical for competitive advantage. Sustainable and profitable growth comes from new products, new services, new processes, new business models, or new organizational models [1]. Because of the importance of innovation, companies are expected to be able to manage their innovation optimally. However, being innovative is not easy. A company needs to assess and measure its

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innovativeness in order to manage it. Measuring innovativeness gives a company the ability to understand how to increase it.

Companies need a reliable framework for measuring and managing their innovation. With such a framework, they can track their innovation activities and review whether a learning loop is required to improve their innovativeness [2]. The measurement framework can provide information about the areas that need improvement, and help the company make strategic decisions, such as where investments should be made, how resources should be allocated, and how risks should be minimized.

A framework, measurement processes, and metrics to measure the innovativeness of a company are presented in this chapter. The framework shows how innovative a company is in comparison to its peers and helps the companies to improve the management of their innovation inputs in order to improve innovation outcomes.

15.2 Literature Review

The expression "innovate or die" has been an accepted phrase in the popular business environment [3]. Innovation is considered one of the most important business drivers for companies' growth and is also one of the important sources and enabler of competitive advantage [4–7]. Before a product or service reaches the maturity level or technological obsolescence (flat level on the top of the S curve), companies have to renew business opportunities, and improve product lines or service, to maintain growth and to stay ahead of competitors. Innovation helps to fuel the growth of new products or services, sustain incumbents, create new markets, transform industry, and promote the global competitiveness of nations [8–12]. History has proven that only those companies that innovate survive. The companies that do not innovate are not likely to survive let alone compete in the rapidly changing market [2].

Measuring innovation has attracted many researchers, using different methodologies and indicators. Some measure innovation based on a single indicator, and some consider several indicators. In addition to indicators, innovation indexes have also been proposed to measure innovation, but the innovation indexes in the literature are typically used at the national level, including environmental, social, and political variables in the measurement.

This research is focused on output indicators in companies because outputs are uncontrollable and unpredictable [1], while inputs and processes can be managed and controlled by the company. Measuring something that can be controlled and managed within the firm biases the results. For example, a company can increase the R&D expenditures as high as it wants; however, that increase does not necessarily assure that the company is highly innovative. Simply having high inputs may or may not produce high outputs. The innovativeness of a company is based on outputs of the innovation activities. Inputs define the scope, context, and structure of innovation. Inputs do not show the economic significance of the innovation output [13]. Outputs transform innovation activities into economic value for the company [2].

Several scholars agree with the use of output indicators to measure innovation. Kleinknecht and Bain [14] support the idea by using a literature-based methodology. They point out that counting output indicators will facilitate international comparisons. Output indicators are more viable because the data for outputs (number of new products, patents, publications, etc.) are available and thus verifiable. They can be objectively measured without creating unnecessary bias. Steward [13] agrees with Kleinknecht and Bain. Steward points out that the majority of innovation outputs are available to the public in some form. Because of their visibility, innovation outputs can be used for the development of useful indicators. Input indicators such as R&D expenditures will not be effective because obtaining such data from companies is not straightforward. Usually, input indicators are covered by accounting procedures [13]. Steward adds that measuring outputs uncovers the contributions of small firms. Output indicators show great potential for establishing innovation indicators that are internationally comparable and can be implemented and revisited on an annual basis.

Link [15] lists the advantages of measuring output, as:

- Appropriate: Output indicators are countable and can be evaluated at any given time.
- Complete: Output indicators perform as a market test for the success of the innovation process.
- Replicable: Output indicators are replicable and are from verifiable sources.

This chapter identifies a number of output indicators through literature review, such as number of new products, awards and honors, number of publication, and number of patents. There are also several sub-factors identified through literature review. The output indicators and sub-factors are combined in a framework to help a company determine its innovativeness.

15.3 Research Methodology

The innovation measurement research methodology is composed of three stages: hierarchical decision model development, indicator evaluation, and innovativeness evaluation.

Stage 1—Hierarchical Decision Model Development: Develop a hierarchical model to determine the innovativeness of a company.

Stage 2—Indicator Evaluation: Develop a measurement for a specific industry using the Delphi method.

Stage 3—Innovativeness Evaluation: Incorporate the values of the indicators obtained in a company into the model.

15.3.1 Hierarchical Decision Model

The HDM is one of the most recognizable methods for subjective approaches [16–18]. It is a tool that helps decision makers quantify and incorporate quantitative and qualitative judgments into a complex problem. It was developed from the analytic hierarchical process (AHP) by Saaty as a method for multi-criteria decision making [19, 20]. HDM has been applied in a wide range of applications in different fields for the last 25 years [21–23].

The underlying principle of HDM is decomposing problems into hierarchies. It is a comprehensive, logical, and structured framework that requires the subjective judgments of the experts to obtain weights for the criteria. Pairwise comparisons among criteria are the key step in the HDM to acquire the priority weights or relative importance of values for each criterion in the hierarchy [24]. The pairwise comparison method compares two criteria at a time and their relationship to each other. The process makes the experts more comfortable because their decisions are based on the relative preference of one criterion over another rather than an absolute preference [25]. The results of the pairwise comparisons from the experts can be verified by checking the consistency of the evaluations [18, 26].

Literature research reveals that innovation is complex and cannot be measured by a single attribute. We have identified multiple attributes associated with innovation outputs. In this regard, the problem of innovation measurement is a particularly suitable application for the HDM approach.

The output indicators and sub-factors can be evaluated by a series of calculation procedures. The results of judgment quantifications from the experts are used as the input in the calculations. The mathematical expression for calculating the contribution of output indicators and sub-factors to the innovativeness is expressed below:

$$S_{n,\,jn}^{IX} = \sum_{n=1}^{N} \sum_{jn=1}^{Jn} \left(O_n^{IX}\right)\left(S_{n,\,jn}^{O}\right) \tag{15.1}$$

where

$S_{n,jn}^{IX}$ Relative value of the jnth sub-factor under the nth output indicator with respect to the Innovation Index (IX).

O_n^{IX} Relative priority of the nth output indicator with respect to the Innovation Index (IX), n = 1, 2, 3, . . ., N.

$S_{n,jn}^{O}$ Relative contribution of the jnth sub-factor under the nth output indicator, jn = 1, 2, 3, . . ., Jn, and n = 1, 2, 3, . . ., N.

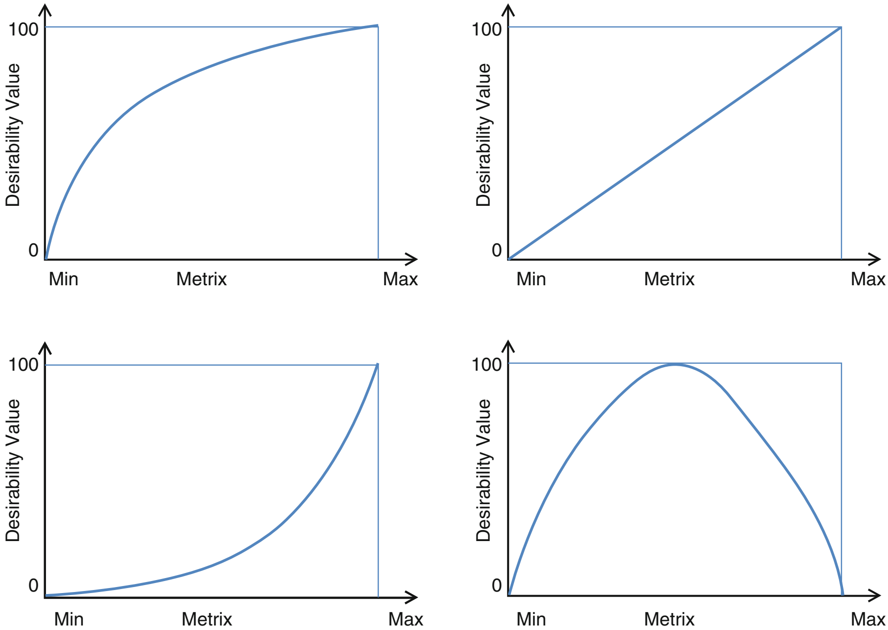


Fig. 15.1 Various shapes of desirability curves

15.3.2 Desirability Curve

The concept of the desirability curve is implemented in this chapter. It represents how desirable a metric is for the decision maker. In strategic decision making, decisions are often based not on numerical values of the variables but on the "goodness" or usefulness of those values. They are referred to as desirability values of the variables. The shape of the desirability curve could vary. The typical desirability curves are convex, concave, parabolic, or linear (straight line). Figure 15.1 depicts shapes of several typical desirability curves.

The experts express the desirability values of the various levels of the performance measures associated with the sub-factors under the output indicators. When the desirability values are obtained, the innovativeness index of a company can be calculated. The mathematical expression for calculating the innovativeness index is expressed below:

$$IX = \sum_{n=1}^{N} \sum_{jn=1}^{Jn} \left(S_{n,\,jn}^{IX} \right) \left(D_{n,\,jn} \right) \tag{15.2}$$

where

IX Innovation Index.

$S^{IX}_{n,jn}$ Relative value of the jnth sub-factor under the nth output indicator with respect to the Innovation Index (IX), jn = 1, 2, 3, . . ., Jn, and n = 1, 2, 3, . . ., N.

$D_{n,jn}$ Desirability value of the performance measure corresponding to the jnth sub-factor under the nth output indicator.

15.3.3 Delphi Method

The Delphi method is used when the availability of historical, economic, and technical information is inadequate. Delphi is a technique for structuring systematic communications among a panel of experts [27]. It is used as an opinion-taking procedure in many different areas of study such as sociology and economics. The Delphi method attempts to minimize an individual's knowledge limitations and possible individual biases.

The Delphi method is different from conventional face-to-face group integration. Three distinct characteristics of the Delphi method are the following [28, 29]:

- Anonymity: Group members do not know each other, preventing any one member from influencing the others. Also, the results are not revealed to any of the members to avoid biases.
- Iteration with controlled feedback: It is done in several iterations. Experts on the panel have the opportunity to reconsider and change their opinions and judgments between several successive iterations.
- Statistical group response: Statistical analysis for each round is performed by Delphi method moderators. Statistical information such as mean, median, and variations of the research is presented.

15.3.4 Expert Panel

This research has three expert panels to help construct a hierarchical model and to determine the value of each indicator. There are overlaps in the expert panels. The experts represent various sectors (education, government, and industry) and different areas of specialization (marketing, sales, legal, new product development, etc.) in the semiconductor industry. Each expert panel has a different role in this research.

15.3.4.1 Expert Panel 1

This expert panel comprises people from various sectors and different areas of specialization in a specific industry. The different areas of specialization (cross functional) provide different points of view on the output indicators. Examples of different areas of specialization include new product development, marketing, and sales. Members of expert panel 1 (EP1) are leaders in industry and government, and researchers whose work is focused on innovation strategies and measurements. The experts on this panel help to identify output indicators that are recognized as signs of innovativeness in a company.

15.3.4.2 Expert Panel 2

This expert panel also comprises people from various sectors and different areas of specialization in a specific industry. The experts in this panel provide quantified judgments on the relative importance of each indicator and sub-factor with respect to the innovativeness.

15.3.4.3 Expert Panel 3

This expert panel comprises people from various sectors and different areas of specialization in a specific industry. Expert panel 3 (EP3) develops desirability functions for the metrics used for the performance measures corresponding to each sub-factor. Therefore, it captures different points of view on what is perceived as innovativeness.

The summary of the expert panels formed in this study is shown in Table 15.1.

15.3.5 E. Data Collection

Four research instruments were developed in this research. They are shown in the Appendix. Research instrument 1 was sent to EP1 for model development. Research instrument 2 was used by expert panel 2 (EP2) to evaluate the relative importance of the output indicators with respect to the innovativeness. Research instrument 3 was used by EP2 to evaluate the relative importance of sub-factors with respect to the output indicators. Research instrument 4 was used by EP3 to express their desirability toward the metrics that contribute to the innovativeness of a company. The research instruments were tested and validated before being sent to the expert panels.

Table 15.1 Distribution and background of expert panel

	Industry	Government	Academia	Affiliation	Country
EXP1			×	Delft University of Technology	Netherlands
EXP2			×	INRS	Canada
EXP3			×	German Graduate School of Management and Law	Germany
EXP4			×	German Graduate School of Management and Law	Germany
EXP5			×	University of Bamberg	Germany
EXP6			×	University of Bamberg	Germany
EXP7			×	Korea University	South Korea
EXP8			×	University of Bologna	Italy
EXP9			×	Fuzhou University	China
EXP10			×	Erasmus University	Netherlands
EXP11			×	Indian Institute Technology	India
EXP12			×	University of Exeter	UK
EXP13			×	University of Manchester	UK
EXP14			×	Innovation IMS Instruction	USA
EXP15	×			Samsung Electronic Research Institute	South Korea
EXP16	×			Lattice Semiconductor	USA
EXP17	×			FEI Company	USA
EXP18	×			TOK America	USA
EXP19	×			Tektronix, Inc.	USA
EXP20	×			Tektronix, Inc.	USA
EXP21	×			Tektronix, Inc.	USA
EXP22	×			Tektronix, Inc.	USA
EXP23	×			Intel Corporation	USA
EXP24	×			Intel Corporation	USA
EXP25	×			Intel Corporation	USA
EXP26	×			Intel Corporation	USA
EXP27	×			TriQuint Semiconductor	USA
EXP28	×			TriQuint Semiconductor	USA
EXP29	×			TriQuint Semiconductor	USA
EXP30	×			PwC	USA
EXP31	×			Cascade Microtech	USA
EXP32	×			Novellus System	USA
EXP33	×			IPR & Innovation at Crompton Greaves Ltd	India
EXP34	×			Texas Instruments	USA
EXP35		×		Italian National Research Council	Italy
EXP36		×		Oregon Business Innovation Council	USA

15.4 Results and Analysis

15.4.1 Model Development

Figure 15.2 shows the HDM finalized by EP1 after research instrument 1 was sent to them for model development.

After the data collection and calculation, the relative contribution of each element of the decision model to innovativeness was calculated. The contribution values obtained from the quantified judgments of the experts are shown above each indicator and sub-factor in Fig. 15.2. Based on the experts, revenue from new products, market share of new products, and number of new products new to the world are in the top 3 with relative contributions of 0.280, 0.210, and 0.132, respectively. They are followed by the number of patents granted (0.084), number of new products that are new to the company (0.068), number of awards (0.045), number of honors (0.045), number of paper published in scientific publications (0.039), number of patents filed (0.036), number of patents cited (0.020), number of papers presented (0.019), and number of papers cited (0.012).

15.4.2 Maximum Innovativeness Value

The highest possible innovativeness index is not 100. The most desirable values for many of the sub-factors are not at the maximum score of 100. Thus, by taking the highest desirability value from each sub-factor and multiplying it with the relative weight of each sub-factor will bring the maximum innovativeness index to 76.5.

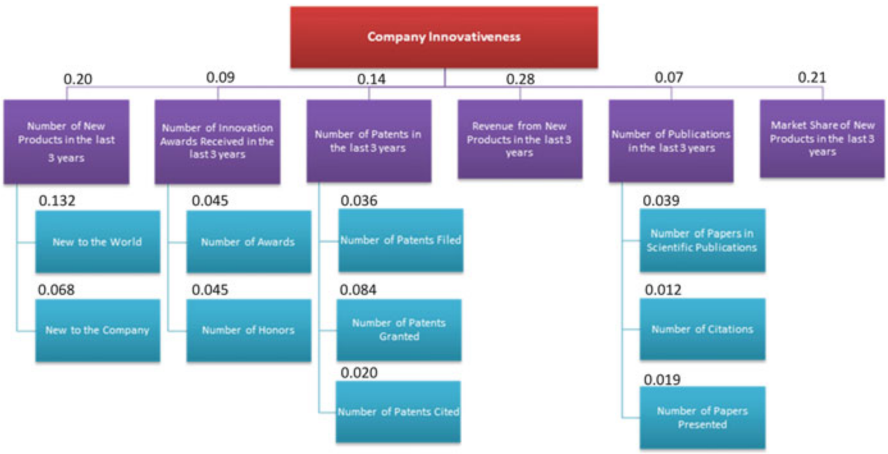


Fig. 15.2 Innovativeness index framework

15.4.3 Simulated Application of the Framework to Intel and AMD

The model was implemented in a case study to demonstrate it in the real situation. Intel and AMD were used for this purpose. Both companies are in the semiconductor industry. The data used for Intel and AMD included not all the product lines, but only notebook processors, desktop processors, and server processors to make a consistent comparison between the two companies. The characteristics of Intel and AMD are normalized. Without normalization, large companies lead in all aspects since they always have higher numbers compared to medium and small companies. The purpose of the normalization is to eliminate biases and ambiguity.

Table 15.2 shows the profiles of Intel and AMD. Some of the values are left empty because the data are unavailable.

The values of characteristics for both companies were normalized to eliminate biases. Table 15.3 shows the performance metrics of Intel and AMD after the normalization.

Intel shows strength in the revenue from new products and market share of new products. Those indicators are the top indicators according to the experts. AMD shows a slightly better performance in number of new products new to the world and number of innovation awards. The performance metrics were multiplied by the relative weights of the corresponding sub-factors to obtain the innovativeness index. Table 15.4 shows the innovativeness index of each company.

Although the maximum possible score for innovativeness index in this research is 76.5, because some of the data are not available evaluating the innovativeness of Intel and AMD, the highest possible value for this illustration is 70.9. In this case Intel's innovativeness index is at 80 % of the highest possible level, and AMD's is at 60 % of the highest possible level.

Table 15.2 Profiles of Intel and AMD

Company	Intel	AMD
Total products in the last 3 years [30]	530	275
Total researchers [31, 32]	1000	177
Total revenue (in thousands US$)	103.1 Billion	11.08 Billion
New products new to the world [30]	53	36
New products new to the company [30]	422	160
Number of awards [33, 34]	37	25
Number of honors [33, 34]	Data not available	Data not available
Number of patents granted [35]	550	100
Number of patents filed [35]	773	368
Number of patents cited [35]	Data not available	Data not available
Revenue from new products [36]	91.759 Billion	7.867 Billions
Number of papers published [37]	3192	313
Number of papers presented [37]	Data not available	Data not available
Number of papers cited [37]	Data not available	Data not available
Market share of new products [38]	62.3 %	21.3 %

Table 15.3 The performance metrics of Intel and AMD

Sub-factors	Intel	AMD
New products new to the world as the percentage of total products	10 %	13 %
New products new to the company as the percentage of total products	79 %	58 %
The ratio of number of awards to total researchers	1 per 27	1 per 7
The ratio of number of honors to total researchers	Data not available	Data not available
The ratio of number of patents granted to total researchers	1 per 2	1 per 2
The ratio of number of patents filed to total researchers	1 per 2	>1
The ratio of number of patents cited to total researchers	Data not available	Data not available
Revenue from new products as percentage of total revenue	64 %	42 %
The ratio of number of papers published to total researchers	>1	>1
The ratio of number of papers presented to total researchers	Data not available	Data not available
The ratio of number of papers cited to total researchers	Data not available	Data not available
Market share of new products	62.3 %	21.3 %

Table 15.4 The innovativeness index of Intel and AMD

	Company	
Baseline	Intel	AMD
Innovativeness index	56.7	42.11

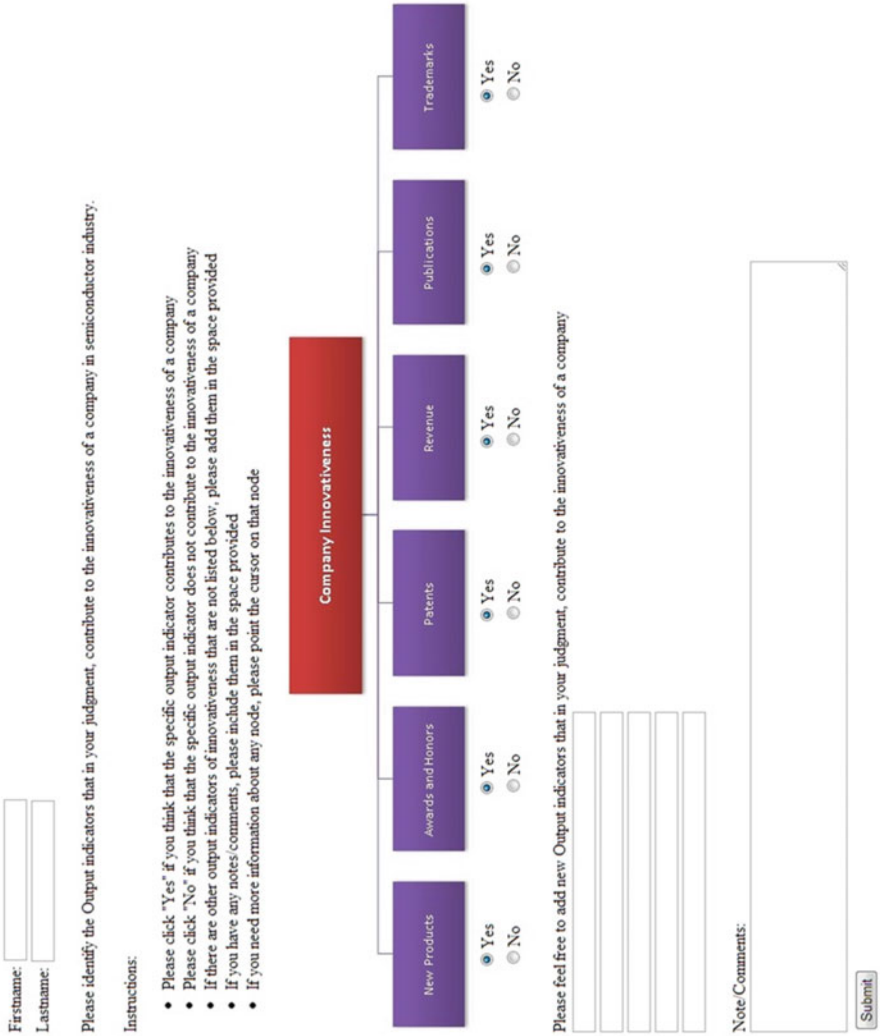
15.5 Conclusion

Innovation is crucial to sustain competitive advantage of a company. Because of its importance, a company needs to manage its innovation activities. A decision framework is needed to help company to measure its innovativeness. This development of such a framework with a decision model and metrics for measuring the innovativeness of a company in the semiconductor industry has been demonstrated in this chapter. Revenue of new products (0.28), market share of new products (0.21), and number of new products new to the world by a company (0.20) are perceived as the top three indicators to assess the innovativeness of a company in the semiconductor industry. Number of papers cited (0.01), number of papers presented (0.02), and number of patents cited (0.02) are the lowest three of all the indicators according to the experts.

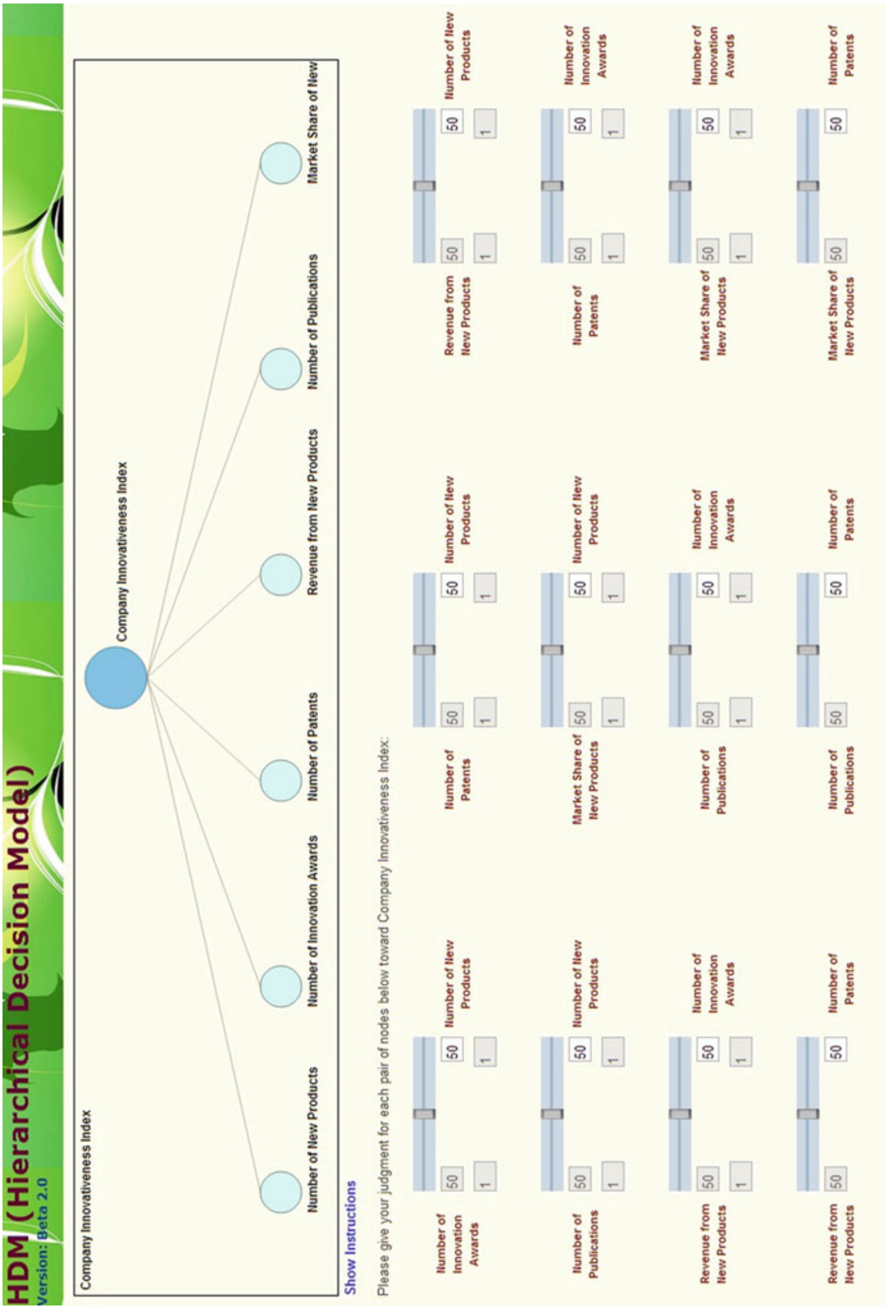
The simulated application of the model shows that focusing on the right indicators will help a company improve its innovativeness. Regardless of the size, companies that focus on the sub-factors with highest relative importance obtain a better innovativeness index. However, even though a company performs extremely well in some sub-factors, if those sub-factors do not have high importance values, the innovativeness index will not be affected significantly.

Appendix

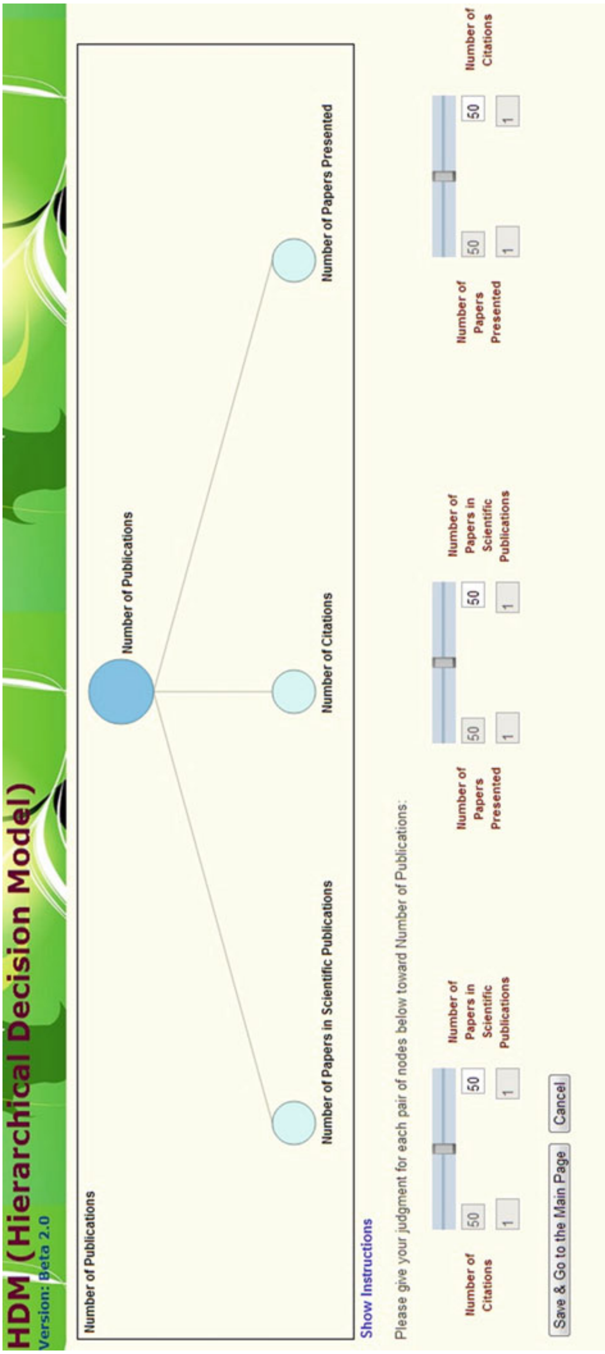
Research Instrument 1 (Example)



Research Instrument 2 (Example)



Research Instrument 3 (Example)

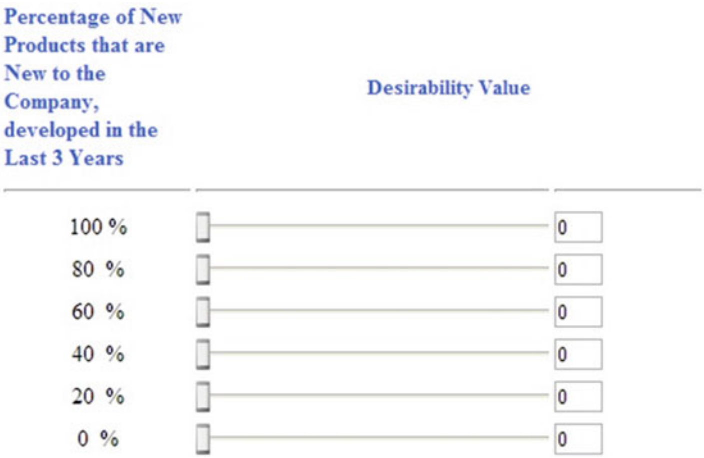


Research Instrument 4 (Example)

Please develop desirability curves for new products, below.

Number of new products that are new to the world in the last 3 years.

The metric for this variable is the number of new products that are new to the world developed by the company, as a percentage of the total number of products of the company in the last 3 years.



Percentage of New Products that are New to the Company, developed in the Last 3 Years	Desirability Value	
100 %		0
80 %		0
60 %		0
40 %		0
20 %		0
0 %		0

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