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Anna Burduk
Dariusz Mazurkiewicz *Editors*

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Editors

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Preface

The First International Conference on Intelligent Systems in Production Engineering and Maintenance ISPEM 2017 was organized by the Faculty of Mechanical Engineering, Wrocław University of Science and Technology and the Committee on Production Engineering of the Polish Academy of Sciences. The high prestige of the conference is confirmed by the honorary patronage of the Rector of the Wroclaw University of Science and Technology and the Dean of the Faculty of Mechanical Engineering. The conference was held in Wrocław (Poland) in September 2017. The ISPEM conference was established as an interdisciplinary forum in the areas of intelligent systems, methods and techniques, and there applications in production systems. The importance of these issues attracted both academic and industrial participants. The exchange of ideas and opinions on research efforts and industry needs related to intelligent systems in industrial applications was very fruitful. The primary concerns of the conference attendees were new solutions for innovative plants, research results, and case studies taking into account advances in production and maintenance from the point of view of Industry 4.0. Manuscripts submitted for ISPEM 2017 were accepted for publication in the Conference Proceedings on the basis of two independent reviews. At least one of the reviewers was affiliated at an institution from a country other than the author's. The reviewers were selected according to their competences and the principle of avoiding conflict of interest—a personal relationship between a reviewer and an author, occupational subordination, direct scientific cooperation over the last two years prior to the review. Each review was provided in a written form and concluded with an explicit recommendation to accept or reject the paper for publication. Minor or major revisions with additional review cycles were also possible—about 40% of the finally accepted manuscripts were subjected to a revision procedure. If a negative review was given, the submission was rejected. This situation happened in the case of 45% of the manuscripts submitted. The names of the referees for individual publications were not revealed. On receiving the required number of reviews and finishing the evaluation phase, the Conference Chairs passed them to authors. Before the final decision, the authors' replies to reviewers' comments were required. The entire evaluation and acceptance process

was carried out electronically with the use of Springer's Online Conference Service. We would like to thank all the authors for inspiring presentations and the representatives of both industry and academia for participating in lively discussions. Special thanks go to the members of the Program Committee for the reliable process of reviewing the papers. We are also grateful to the Organizing Committee for the hard work at the conference preparatory stage and a good organization of all events.

September 2017

Anna Burduk
Dariusz Mazurkiewicz

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Contents

Sesion Separator "Intelligent Systems in Maintenance"

A Concept of an IT Tool for Supporting Knowledge Transfer Among Facility Maintenance Employees as Part of Intelligent Organization 3
Bartosz Szczęśniak, Katarzyna Midor, and Michał Zasadzień

An Intelligent System Supporting a Forklifts Maintenance Process 13
Katarzyna Antosz and Dorota Stadnicka

An Intelligent System Supporting a Maintenance Process of Specialised Medical Equipment 23
Katarzyna Antosz and Dorota Stadnicka

Enabling Round-Trip Engineering Between P&I Diagrams and Augmented Reality Work Instructions in Maintenance Processes Utilizing Graph-Based Modelling 33
Matthias Neges, Mario Wolf, and Michael Abramovici

Incident Detection in Industrial Processes Utilizing Machine Learning Techniques 43
Giorgos Tziroglou, Thanasis Vafeiadis, Chrysovalantou Ziogou, Stelios Krinidis, Spyros Voutetakis, and Dimitrios Tzovaras

Intelligent Systems of Forecasting the Failure of Machinery Park and Supporting Fulfilment of Orders of Spare Parts 54
Ewelina Kosicka, Edward Kozłowski, and Dariusz Mazurkiewicz

SmartMaintenance - The Concept of Supporting the Exploitation Decision-Making Process in the Selected Technical Network System . . . 64
Andrzej Loska and Waldemar Paszkowski

Use of Intelligent Informatics Module for Registration and Assessment of Causes of Breaks in Selected Mining Machines 74
Kinga Stecuła, Jarosław Brodny, and Magdalena Tutak

Using a Simulation Method for Intelligent Maintenance Management 85
Sławomir Kłos and Justyna Patalas-Maliszewska

Sesion Separator "Intelligent Systems in Production Engineering"

A Heuristic and Simulation Hybrid Approach for Mixed and Multi Model Assembly Line Balancing 99
Damian Krenczyk, Bozena Skolud, and Anna Herok

A New Petri Nets Based Approach for Modeling of Discrete Manufacturing System 109
Reggie Davidrajuh

Algorithm of Autonomic Shaping of Workflow 121
Bożena Zwolińska

An Intelligent System for Core-Competence Identification for Industry 4.0 Based on Research Results from German and Polish Manufacturing Companies 131
Justyna Patalas-Maliszewska and Sławomir Kłos

An Optimization Approach for Scheduling and Lot Sizing Problems in Electromechanical Industry Using GA-Based Method 140
Joanna Oleśków-Szłapka, Grzegorz Pawłowski, and Marek Fertsch

Application of Neural-Fuzzy System in Prediction of Methane Hazard 151
Dariusz Felka and Jarosław Brodny

Application of Support Vector Machine for Determination of Impact of Traffic-Induced Vibrations on Buildings 161
Anna Jakubczyk-Gałczyńska, Adam Kristowski, and Robert Jankowski

Artificial Neural Networks as a Means for Making Process Control Charts User Friendly 168
Izabela Rojek, Agnieszka Kujawińska, Adam Hamrol, and Michał Rogalewicz

Assessment of the Feasibility of a Production Plan with the Use of an Artificial Neural Network Model 179
Anna Burduk, Tomasz Chlebus, and Robert Waszkowski

Autocorrelation Analysis of Cu Content in Ore Streams in One of KGHM Polska Miedź S.A. Mines 189
Leszek Jurdziak, Witold Kawalec, and Robert Król

Binary Linear Programming as a Decision-Making Aid for Water Intake Operators 199
Edward Kozłowski, Dariusz Mazurkiewicz, Beata Kowalska, and Dariusz Kowalski

Competence-Based Performance Analysis of U-Shaped Assembly Lines 209
Przemyslaw Korytkowski and Bartlomiej Malachowski

Decision Support System for Rapid Production Order Planning in Production Network 217
Sebastian Saniuk and Anna Saniuk

Durability of Supply Chains as Non-renewable Systems 227
Katarzyna Grzybowska and Patrycja Hoffa-Dąbrowska

Dynamic Spaghetti Diagrams. A Case Study of Pilot RTLS Implementation 238
Bartlomiej Gladysz, Krzysztof Santarek, and Cezary Lysiak

Information Management and Decision Making Supported by an Intelligence System in Kitchen Fronts Control Process 249
Dorota Stadnicka, Andrea Bonci, Massimiliano Pirani, and Sauro Longhi

Integer Linear Programming in Optimization of Waste After Cutting in the Furniture Manufacturing 260
Grzegorz Kłosowski, Edward Kozłowski, and Arkadiusz Gola

Kanban System in the Flow Control Subassemblies as a Component of Lean Manufacturing 271
Edward Michlowicz

Modeling and Analyzing Performance of a Production Unit Using Dynamic Bayesian Networks 284
Ayeley Tchangani and François Pérès

Modelling and Forecasting the Sludge Bulking in Biological Reactors of Wastewater Treatment Plants by Means of Data Mining Methods 296
Bartosz Szeląg and Jan Studziński

Modelling and Recycling-Oriented Assessment of Household Appliances 306
Jacek Diakun, Ewa Dostatni, Damian Grajewski, Radosław Wichniarek, Anna Karwasz, Wiktor Brzeziński, and Bartosz Ciechanowicz

Multi-agent Meta-model of a Non-cooperative Game in a Virtual Manufacturing Network 316
Aleksander Gwiazda, Małgorzata Olender, and Agnieszka Sękala

Multivariate Process Capability, Process Validation and Risk Analytics Based on Product Characteristic Sets: Case Study Piston Rod 324
Stefan Bracke and Bianca Backes

Optimization of Production Organization in a Packaging Company by Ant Colony Algorithm 336
Dagmara Górnicka, Marcin Markowski, and Anna Burduk

Optimization of the Supply of Components for Mass Production with the Use of the Ant Colony Algorithm 347
Joanna Kotowska, Marcin Markowski, and Anna Burduk

Predictive Scheduling as a Part of Intelligent Job Scheduling System 358
Łukasz Sobaszek, Arkadiusz Gola, and Antoni Świć

Process Assessment of Risks in the Production Company with the Use of Linguistic Variables and the FMEA Analysis 368
Agnieszka Tubis

Production Costs of Machine Elements Estimated in the Design Phase 380
Dorota Więcek and Dariusz Więcek

Reliability Assessment of Production Process – Markov Modelling Approach 392
Tomasz Nowakowski, Sylwia Werbińska-Wojciechowska, and Maciej Chlebus

Soft Modelling-Based Methodology of Raw Material Waste Estimation 407
Agnieszka Kujawińska, Magdalena Diering, Michał Rogalewicz, Krzysztof Żywicki, and Łukasz Hetman

Study on Tracking the Mined Ore Compound with the Use of Process Analytic Technology Tags 418
Leszek Jurdziak, Witold Kawalec, and Robert Król

The Use of Neural Network Model in the Assessment of Annoyance of the Industrial Noise Sources 428
Waldemar Paszkowski and Andrzej Loska

Transport Trolley Control in a Manufacturing System Using Simulation with the FSAW, FWASPAS and FTOPSIS Methods 440
Katarzyna Rudnik

Virtual Reality Production Training System in the Scope of Intelligent Factory 450
Krzysztof Żywicki, Przemysław Zawadzki, and Filip Górski

Water Consumption Prediction for City Pumping Station Using Neural Networks 459
Volodymyr Drevetskyi, Marko Kleapch, and Vitalii Kutia

Author Index 469

Sesion Separator “Intelligent Systems in Maintenance”

A Concept of an IT Tool for Supporting Knowledge Transfer Among Facility Maintenance Employees as Part of Intelligent Organization

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Abstract. The article presents a concept of an IT tool, supporting knowledge transfer among people working in a facility maintenance department. The developed assumptions of the tool are a continuation of the previously conducted investigations into the current status and expectations regarding the transfer of knowledge among the employees of such a department in an international enterprise producing pre–insulated steel pipes. The presented concept includes a description of the functionality and a data structure which enables ensuring this functionality. The tool's functionality has been presented by means of use case diagrams. Particular cases have been characterized in detail in scenarios presented in tables. To increase the clarity of the description in the study, also systems of windows used to present the scenarios have been shown. The data structure which allows obtaining the pre–defined functionality of the tool has been presented by means of a model compliant with IDEF1x.

Keywords: Maintenance · Organization · Knowledge · Management · Employer · Breakdown · Database · Transfer · Support

1 Introduction

One can say that contemporary economy is based on knowledge. Knowledge is one of the major factors that allow enterprises to develop and build a competitive advantage. Its acquisition and propagation in a right time and scope enables an organisation to effectively and intelligent manage the resources possessed [1]. The creation, learning and transfer of knowledge is considered one of the major problems related to the functioning of today's organisations – intelligent organizations; therefore, such issues should be dealt with by contemporary science [2, 3].

In literature devoted to knowledge management one can encounter various approaches to the perception and definition of the notion of knowledge. D. Paulin and K. Suneson [4] propose separating two major trends in this area. According to one of them, knowledge is considered as an object, whereas in the other one it is perceived more intangibly – as a subjective contextual construction. The approach proposed by D.J. Skyrne [5] places the notion of knowledge among the notions of data, information

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and wisdom. According to it, data includes facts and figures, information is data in an appropriate context, knowledge is information with understanding, whereas wisdom means knowledge combined with intuition and insightfulness. The definition of knowledge proposed by A. Brooking [6] is similar. Both approaches can be included in the first of the above mentioned trends. A different, less technical definition has been proposed by I. Nonak and H. Takeuchi [7]. According to it, knowledge refers to beliefs, activities, expectations as well as meanings and is equivalent to "confirmed beliefs". According to this definition, knowledge is an orderly reflection of reality in human mind. Irrespective of the adopted definition, one can see that knowledge is always inseparably linked with man. According to I. Nonak and H. Takeuchi [7], only an individual can have and process knowledge.

Major processes involving knowledge that are implemented in an organisation include: creation and transfer of knowledge. Transfer can concern processes implemented in the organisation itself as well as processes between the organisation and environment [8–10]. The very notion of knowledge transfer is frequently used in literature interchangeably with knowledge sharing. This phenomenon has been noticed by A. Jonsson [11]. Considering the problem of ambiguous differences between the two notions, D. Paulin and K. Suneson [4] suggest a greater correlation between the notion of knowledge sharing and knowledge perceived as subjective interpretation referring to a particular context as well as a stronger relationship between the notion of knowledge transfer and knowledge perceived as an object. G. Szulanski [12] uses the notions of knowledge transfer and good practices transfer interchangeably, defining them as replication of organisational operation algorithms. In particular, this applies to the methods of working which have been developed in a certain area of the organisation and are better than the previously used ones.

Knowledge, its generation and transfer are also very important for facility maintenance service teams. The quality of work and, in consequence, the quality of services provided in this scope, is inextricably linked with the employees' experience and skills. It is crucial that knowledge generated by particular individuals is shared with the remaining workers Practically, each facility maintenance employee carrying out their daily work deals with situations that involve generating new knowledge, which they can make available to the remaining co–workers [13, 14]. In such terms each employee of this section of the enterprise is considered as a knowledge worker. The term "knowledge worker" was first proposed by P. Drucker in 1960 [15]. One of the most popular current definitions has been proposed by T.H. Davenport [16]. According to it, a knowledge worker has reached a high level of specialist knowledge, education and experience, and the work he/she performs requires creation, distribution and usage of knowledge. In a similar way knowledge is perceived by M. Lotko and A. Lotko [17].

The phenomenon of knowledge transfer among facility maintenance employees was the subject of earlier research conducted by the authors of this article. These investigations were carried out in an enterprise producing pre–insulated pipes. The company in question is a part of an international concern, employing in Poland approximately 700 people in production departments and 40 facility maintenance workers. In the aforesaid research it was found that facility maintenance workers were aware of the meaning and need of knowledge transfer, and the process of its sharing was often effected on their

own initiative [18]. This awareness is visible in both basic workers and managerial staff. However, attention was drawn to the fact that there are no tools which could be used to support knowledge transfer processes. Moreover, the managerial staff signaled a need for greater formalisation of these processes.

2 General Outline of the Proposed Tool's Functionality

Based on the conclusions resulting from the previously conducted investigations, an appropriate IT tool was proposed to streamline the processes of knowledge transfer among facility maintenance workers. Apart from facilitating the transfer of knowledge, this tool would force specific methods of operation, which to a certain degree would formalize the processes implemented in this scope.

After repairing a device or subassembly, precise descriptions of such repair are created in the proposed tool. In the concept of the tool the devices or subassemblies are called elements and the repair is referred to as an operation. Detailed descriptions refer to procedures included in an operation. Each operation can consist of a few procedures. When creating a procedure, an employee verbally describes the actions performed, defines the time necessary for their performing and encloses indispensable documents in a form of attachments. From time to time the team responsible for verifying the procedures entered in the system has a meeting. Until verification all the procedures have the status of pending verification. After verification they can be accepted or rejected. If the procedures have been accepted, they can be recommended as a good practice. When a breakdown has been reported, a facility maintenance employee in charge of the repair can become acquainted with the existing methods of implementing relevant procedures by means of the proposed IT tool. In case of doubt concerning the operations to be undertaken in response to particular symptoms, the employee can check what operations are related to particular elements or symptoms in the system. The assumed scope of functionality for the proposed tool has been presented by means of use case diagrams. There are three main use cases, such as:

- "Adding methods of operation" – implemented after a facility maintenance employee finished the repair,
- "Becoming acquainted with a method of operation" – effected before undertaking the repair,
- "Verification of a method of operation" – effected periodically during a meeting of the team in charge of verification of the operating methods entered in the system.

In specific situations the "Adding methods of operation" case can be extended with "Adding an element", "Adding an operation", "Adding a symptom", "Adding a procedure", "Adding documents" and "Assigning a symptom to an operation". The case entitled "Becoming acquainted with methods of operation" can be extended with "Modification of the operation list". The use case diagram for the proposed tool has been presented in Fig. 1. For all the use cases detailed scenarios have been developed, which are presented in tables in the next part of the article. To describe the scenarios, elements of computer programme structures were used, such as a loop, presented by means of

[FOR EACH] [END FOR EACH] block and a conditional statement presented by means of [IF] [ELSE] [END IF] block.

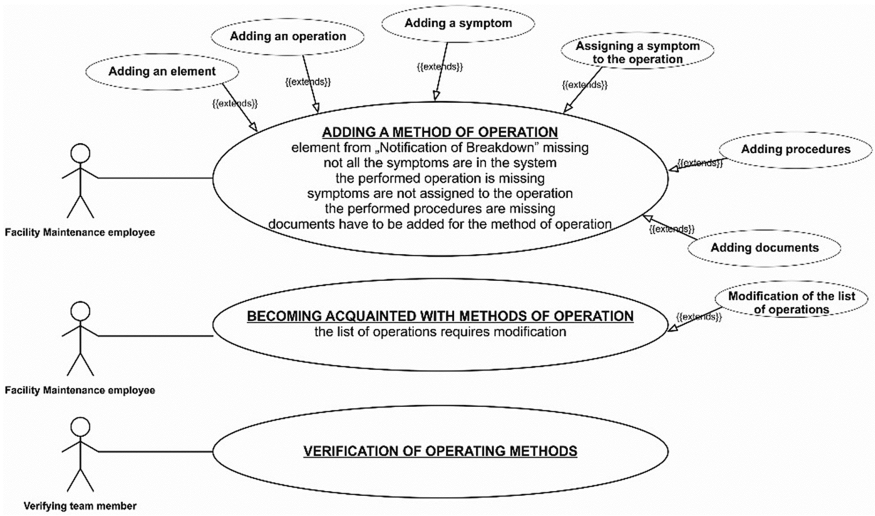


Fig. 1. Diagram of use cases for the proposed tool

Tool responses have been preceded with designation [SYSTEM] and the implementation of another use case has been presented by means of [PU] and the name of the case. In the first place, in Table 1, a scenario for the basic part of "Adding methods of operation" use case has been presented. In subsequent tables descriptions of extending cases have been contained. To increase the description transparency, in Fig. 2 visual drafts of application windows have been shown, such as symptoms edition window, element adding window, symptom adding window, operation edition window, procedure adding window, method of operation adding window, new documents assigning window and document adding window, used in the process of implementing particular scenarios.

Table 1. Use case scenario: adding methods of operation

Step	Description
1	Selecting the symptom edition window
2	[SYSTEM] Displays the symptom edition window – the list of available elements
3	[IF] The element for which symptoms have been described in „Notification of Breakdown" does not exist.
3.1	[PU] „Adding an element"
3.2	[FOR EACH] For a symptom described in „Notification of Breakdown"
3.2.1	[PU] „Adding a symptom"
3.2	[END FOR EACH]
3	[END IF]
4	Selecting an element
5	[SYSTEM] Displays the list of symptoms
6	[IF] Not all the symptoms described in „Notification of Breakdown" exist in the System
6.1	[FOR EACH] For a symptom not included on the list
6.1.1	[PU] "Adding a symptom"
6.1	[END FOR EACH]
6	[END IF]
7	Selecting the operation edition window
8	[SYSTEM] Closes the symptom edition window. Displays the operation edition window. Displays the list of elements
9	Selecting an element
10	[SYSTEM] Displays the list of operations assigned to a selected element and the list of symptoms assigned to the selected element as well as its master and slave elements
11	[IF] The performed operation is not included on the list
11.1	[PU] "Adding an operation"
11	[END IF]
12	Selecting an operation
13	[SYSTEM] Displays the list of symptoms assigned to a selected operation as well as the list of procedures of which the operation consists
14	[IF] There are symptoms described in Notification of Breakdown which have not been assigned to the operation
14.1	[FOR EACH] For the symptom which is described in the notification and has not been assigned to the operation
14.1.1	[PU] „Assigning a symptom to an operation"
14.1	[END FOR EACH]
14	[END IF]
15	[IF] There are procedures which have been performed as part of a selected operation but they are not included on the list
15.1	[FOR EACH] For a procedure not included on the list
15.1.1	[PU] "Adding a procedure"
15.1	[END FOR EACH]
15	[END IF]

16	[FOR EACH] For a procedure for which a new method of operation is to be added
16.1	Selecting a procedure
16.2	Selecting the „Add a method of operation” command
16.3	[SYSTEM] Displays the method of operation adding window
16.4	Supplementing the details of a method of operation. Introducing a description, duration of a procedure, employee’s code.
16.5	Approval
16.6	[SYSTEM] Creates a new method of operation. Adds an identification number for it. Introduces the status as “1 – pending verification”. Adds the date of creation. Assigns it to a selected procedure.
16.7	[IF] There are documents which should be linked to the added method of operation.
16.7.1	[PU] „Adding documents”
16.7	[END IF]
16.8	Selecting the “finish” command.
16.9	[SYSTEM] Closes the method of operation adding window.
16	[END FOR EACH]

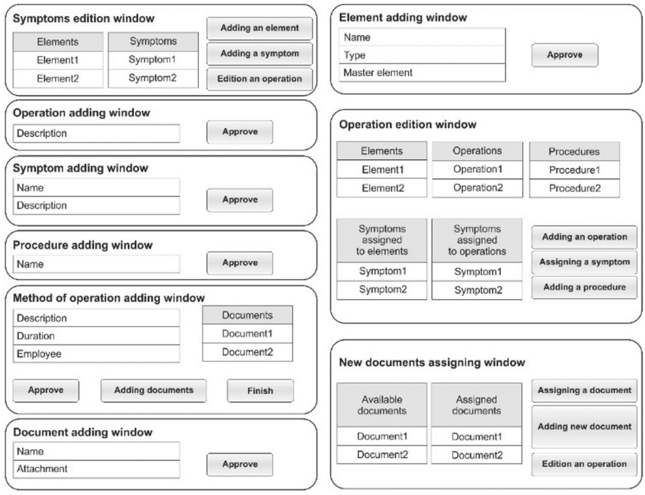


Fig. 2. Visual arrangement of windows for procedure scenarios

The first use case extending the case presented in Table 1 which can occur when employing the described tool is “Adding an element”. It is effected when the element for which a breakdown has been reported does not exist in the system. The course of this case has been described in Table 2.

Table 2. Use case scenario: adding an element

Step	Description
1	Selecting the „Add an element" command
2	[SYSTEM] Displays the element adding window
3	Entering a value for attributes „name", „type"
4	[IF] Type of element other than „Device"
4.1	Entering the id of a master element
4	[END IF]
5	Approval of data
6	[SYSTEM] Creates a new element, adds an identification number to it, closes the element adding window

Another extension of the basic course of the case presented in Table 1 is a situation in which the symptom described in the notification of breakdown was not entered in the system before. Another extending case for "Adding methods of operation" is "Adding an operation". It is effected in a situation when the performed repair was not entered in the system before. In a situation when not all the symptoms described in the notification of breakdown are displayed for a particular operation, it is necessary to implement another extending case entitled "Assigning a symptom to the operation". Another extending case for "Adding methods of operation" is "Adding a procedure". It is necessary in a situation when a particular operation involves procedures which have not been entered in the system before. The last extension of the use case described in Table 1 is "Adding documents". It is implemented when the description of a particular procedure requires enclosing additional documents. This case is effected when the enclosed documents already exist in the system as well as in a situation when they have to be added.

The remaining use cases, i.e.: becoming acquainted with a method of operation and operating method verification have not been included in this study due to its limited size.

3 Database Structure

As part of the IT tool concept, the following entities have been proposed to be separated for the issue in question: Elements, Operation, Types of elements, Symptoms, Procedures, Methods of Operation, Employees, Documents, Status, Operations–Procedures, Symptoms–Operations, Documents–Methods of Operation. Short characteristics of the entities are contained in Table 3.

The data structure which enables implementing the pre–defined functionality of the tool has been presented by means of a model compliant with IDEF1x. This model is shown in Fig. 3.

Table 3. Description of separated entities

Entity	Description
Elements	A device, assembly, subassembly, part – each device or its separated subsystem
Types of elements	A type assigned to an element. Currently there are two types of elements: device and other. The device does not have an assigned master element
Symptoms	A symptom of improper functioning of an element requiring corrective measures
Operations	A set of procedures performed on a given element due to corrective measures
Procedures	A basic activity involved in the operation.
Employees	Facility maintenance employee
Methods of operation	A method of conducting the procedure
Status	The status of the manner of performing a procedure. Currently 4 statuses are possible: pending verification, accepted – good practice, accepted, rejected
Documents	A document which can help to document the method of operation
Symptoms – operations	Defining the operations undertaken after particular symptoms have occurred. The operation assigned to an element can be undertaken in the case of various symptoms assigned to various elements
Operations – procedures	Defining the procedures that make up a particular operation. An operation can consist of a few procedures. A procedure can be included in a few operations
Documents – methods of operation	Assigning documents to particular methods of operation. A few documents can be assigned to a method of operation. A document can be related to a few methods of operation

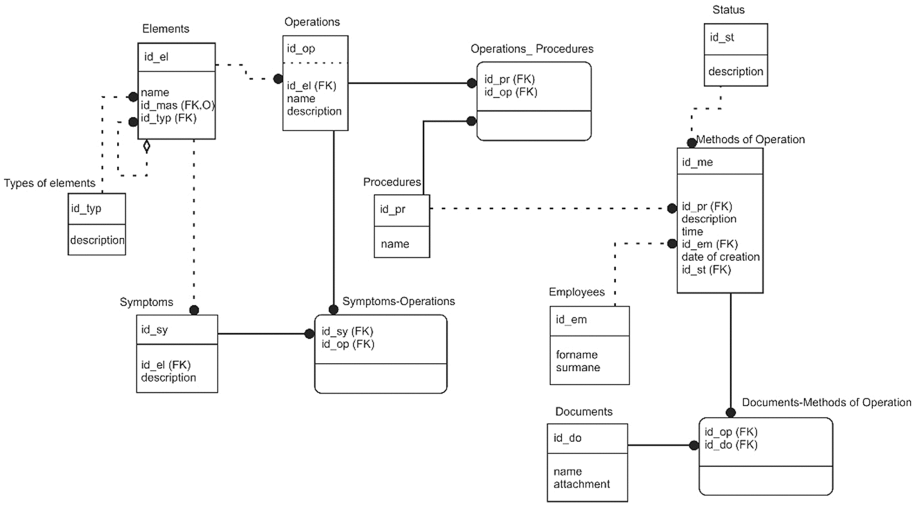


Fig. 3. Data relational model for the proposed tool

4 Summary

The tool whose concept has been presented in the article should enable improving the transfer of knowledge among facility maintenance employees. On the one hand, it should improve the employees' access to a particular piece of information when it is really needed, while, on the other hand, it should allow the development of knowledge collected at an organization by enabling the identification of operating methods that are considered recommendable and imitable. Further investigations should include the implementation of the solution in a real production environment so as to verify the concept and assumptions made.

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An Intelligent System Supporting a Forklifts Maintenance Process

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Abstract. A maintenance process of forklifts presented in this work is realized by a service organization which delivers services for several companies that use forklifts. In the work, the fuzzy logic was implemented to assess the risk of failures for different groups of forklifts. The results of the analysis are to be taken into consideration by the service company in the decision making process. The plan of maintenance activities for each client's forklifts can be developed and adequate maintenance activities can be indicated for each group on the basis of the risk of failures.

Keywords: Maintenance · Fuzzy logic · Intelligent system · Frequency of maintenance tasks

1 Introduction

A maintenance process made by a service organization on machines being used in different organizations is difficult. It is even more difficult because of different conditions that can be included in a service contract [1]. Additionally, when it comes to the servicing organizations, two different situations can appear. A servicing company can be a producer of a machine [2] or an organization only delivering maintenance services.

It is not only a matter of distance between a service organization and the locations of serviced machines, but there are also other factors which make the process difficult.

Undoubtedly, the most important is the proper planning of the maintenance activities, which should be made on the basis of a machine exploitation. Therefore, the right communication between machines owners and a service organization is very important in order to plan the maintenance process in a collaborative way. For example, in the work [3] the authors propose such a collaborative maintenance planning system.

Another factor is a company engagement in the autonomous maintenance. In some organizations the autonomous maintenance can be performed properly. Other organizations do not undertake any autonomous maintenance activities even to keep their own machines clean.

The next problem is connected to financial issues. Sometimes, even if a company knows that some maintenance activities should be undertaken, it is not willing to pay a service organization at a certain time, and it postpones the actions what in consequence

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may lead to failures. It can be related to the importance of machines for companies. Sometimes even the same machine can have different importance for different companies. Therefore, a maintenance service company should perform the machines categorization with the participation of the owner of the serviced machines. The results of the machines categorization will be the basis for the decision about maintenance activities which should be undertaken to keep the risk of failures on the established level. It will also help in the spare parts management [4, 5] as well as the management of maintenance employees and their workplace [6–8].

Therefore, the main issue is connected to the risk of failures assessment. The failures may interrupt the production process and generate costs connected not only with failures elimination, but also with production disruptions. In the work [9], the authors propose to use ontologies and multi-agent systems as an approach for disruptions and risks monitoring. The system was designed to support a decision making process.

Various situations may arise depending on a company, a branch, a product, a company financial situation, consequences of a machine failure, etc. In some cases the results of machines failures are connected only with financial losses, in other cases the consequences of failures may influence e.g. the environment or people's safety.

The author of the paper [10] proposes to use a multicriteria decision making approach to improve maintenance policies in a healthcare organization where the condition of healthcare equipment may influence human life.

In turn, in the work [11], the authors incorporated machine learning techniques together with the distributed learning and hierarchical analytical approaches to explore historical and real-time data concerning railway conditions and to predict failures. However, for example in the manuscript [12], a combined data mining-based methodology for the condition-based maintenance, which considers the condition monitoring data and historical maintenance management data, is presented. In the paper [13], the importance of predictive maintenance as well as its impact of machine operation and manufacturing equipment throughout the years was presented. The authors of the work [14] propose the policies for preventive replacement of machines components for complex process plants, where the tracking of each component is difficult. In the paper [15, 16], a novel degradation prediction approach based on the condition monitoring signals and evaluation of the risk in production systems with a parallel reliability structure is presented. However, such sophisticated analytical systems are not always justified.

Simply, the risk of failures can be calculated with the use of the data collected in a maintenance process, for example on the basis of the machine age and its working hours. Nevertheless, knowing that in different companies the autonomous maintenance and general utilization of machines can be on a different level, the risk can be also different even if the input data are similar. For that reason, in this work the authors propose to use the fuzzy logic to calculate the risk of failures for the machines used in different companies.

In the case study presented in this paper, the maintenance process of forklifts undertaken by a service organization is realized to keep the forklifts ready to work. The forklifts are used in different companies and the service organization undertakes maintenance activities in various locations. In order to plan the activities, it is appropriate to predict failures to prevent them by undertaking adequate actions. In the presented case study,

the risk of failures was calculated for forklifts on the basis of the data collected in a maintenance process. In order to calculate the risk, the data concerning the age of forklifts as well as the number of their working hours were taken into consideration. The risk was assessed with the use of a simple method which takes into account the collected data. Then, the fuzzy logic was incorporated into the calculations. Finally, the percentage of preventive and corrective maintenance activities for the forklifts with medium and high risk of failures was presented on the basis of the historical data.

2 A Case Study

2.1 Structure of Forklifts Classification

The forklifts which are the subject of the following analyses can be classified according to different criteria, such as: a type of a forklift (diesel, hydraulic, electric), a brand (b_1, b_2, …, b_n), a model (m_1, m_2, …, m_n), a year of production (age <10, 10–20, >20 years) and working hours (millage <10,000, 10,000–20,000, >20,000). The data obtained during the own study as well as the data from [17] were used for the analysis.

2.2 Analyses of the Frequency of Maintenance Activities

In order to identify the frequency of maintenance tasks (*MT*) the gathered data were analysed. With the purpose of analysing the frequency of *MT,* two criteria were examined. The first is the age of a forklift (*Ao*F) and the other is the number of working hours (*NoWH*). It was observed that the *AoF* is in the range of 5–31 years, and *NoWH* is in the range of 1,346–29,100 h. These criteria were divided into three categories – *Low (L), Medium (M)* and *High (H)* (Table 1).

Table 1. Criteria classification.

Range			
Category	L - Low	M - Medium	H - High
Age of forklift (AoF) [years]	<10	10–20	>20
Number of working hours (NoWH) [hours]	<10,000	10,000–20,000	>20,000

For the groups created with the use of these categories of the criteria, the frequency of maintenance tasks (*FoMT*) in the analysed group of forklifts was calculated by means of the formula (1). The results of the calculations are presented in Table 2.

$$FoMT = \frac{NoMT_C}{\sum NoMT} \tag{1}$$

where: *FoMT* – the frequency of maintenance tasks,

NoMTc – a number of maintenance tasks in each category (in relation to *AoF* and *NoWH*),

$\sum NoMT$ – the sum of all (number) maintenance tasks in the analysed period of time.

Table 2. Frequency of maintenance tasks of analysed forklifts.

Age of forklift (AoF) [years]		L	M	H
Number of working hours (NoWH) [hours]	L	0.24	0.42	0.02
	M	0.08	0.18	0.02
	H	0	0.04	0

Based on the experience of both the maintenance personnel and authors, it was assumed that if *FoMT* is less than 0.20 the frequency is Low, if *FoMT* ranges between 0.20–0.40 the frequency is Medium, and for more than 0.40 the frequency is High (Table 3). In Table 4 the risk level for each category is presented.

Table 3. The categories of FoMT.

The category	L	M	H
The values	<0.20	0.20–0.40	>0.40

Table 4. The level of FoMT.

Age of forklift (AoF) [years]		L	M	H
Number of working hours (NoWH) [hours]	L	M	H	L
	M	L	L	L
	H	L	L	L

There is no problem in estimating the level of *FoMT* if the values of both, the age of a forklift (*AoF*) and the number of working hours *(NoW*H) are in the middle of each range. However, if the value falls to the border of a particular range, then there is a high possibility of making suboptimal classification the level of *FoMT*. In addition, such uncertainty creates significant variability in the analysis depending on the available information, knowledge and experience. In order to cater these circumstances, it is vital to use a fuzzy logic-based approach for enhancing the level of *FoMT*.

2.3 Fuzzy Logic in Support of FoMT Determination

The illustrative case presented in this work uses a Mamdani-type fuzzy inference process.

This type of Fuzzy Interference System was used because it is based on the expertise and experience of an operator of the system. Mamdani systems are the most intuitive and easy to understand. The general scheme of the system of inference presented for the analysed example is shown in Fig. 1.

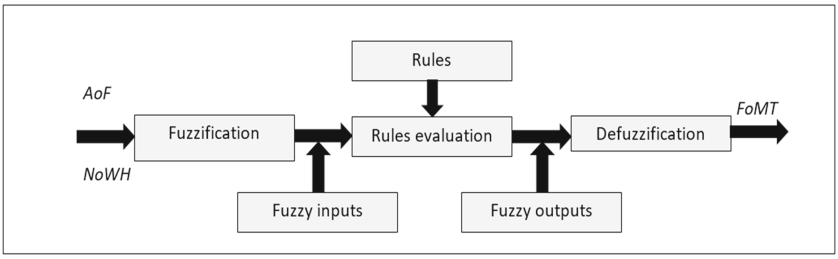


Fig. 1. Fuzzy Interference Process.

The operation of the fuzzy inference consists of the following steps:

1. **Fuzzification** of input values, and thus the calculation of the degree of the inputs membership to each of the terms.
2. **Rules evaluations.** Determination of the degree of fulfilment of each rule. On this stage the fuzzy input variables are entered. These values carry out a logical operation. As a result the changing shape of the membership function is obtained. To change the shape, the levels of the condition are determined. Besides, each of the rules has a declared weight between 0 and 1, which expresses its validity. As the output of this stage we get fuzzy.
3. **Defuzzification** is the combination of all individual collections created (by cutting or rescaling) in the previous step for each rule. These sets are combined into one fuzzy set. It is a determination of the values for each of the output of the fuzzy set [18].

In this case the membership functions are established with respect to the ranges of the *AoF* and *NoWH*, which were developed by engaging maintenance experts. The input data used for the analysis must be quantitative [19–21] or qualitative and judgmental (i.e. linguistic) [22]. Additionally, using the corresponding membership function, the user is more confident that the input parameter is located in the central part of the range than at the edges. In this article, the authors incorporated the functions of Gaussian membership, as in the works [19–21, 23], to minimize the difference between the practical application and mathematical modelling which is defined by the Eq. (2):

$$\text{Gaussian}\,(x;sigm,c) = e^{\frac{-(x-c)^2}{2\sigma^2}} \tag{2}$$

where c represents the centre and *sigm* determines the width of the membership functions. In order to determine the membership functions, the Gaussian combination membership (GCMF) (i.e. 'gauss2mf'), which is accessible in MATLAB (R2012a), was used [24]. The function "gauss2mf" is a combination of two parameters [i.e. (*c, sigm*)] indicated in the Eq. (3). It follows the syntax from Mathworks [25]:

$$y = gauss2mf\{x, [sigm_(1)\, c_(1)\, sigm_(2)\, c_2]\} \tag{3}$$

This function, 'gauss2mf', is a combination of the two of these parameters. The first function, defined by *sigm1* and *c1*, determines the profile of the left-most curve.

The other function defined by *sigm2* and *c2* determines the profile of the right-most curve. Whenever $c1 < c2$, the "gauss2mf" function reaches the maximum value of 1. Otherwise, the maximum value is less than one [25]. The parameters are listed in the order [*sigm1*, *c1*, *sigm2*, *c2*]. Additionally, other parameters were selected (Table 5).

Table 5. Parameters of the fuzzy logic system.

The parameter	AND	OR	Implication	Aggregation	1 Defuzzification
The values	Min	Max	Min	Max	Centroid

A fuzzy rule base was developed with a table-look-up approach (Table 4). The simulator tool of MATLAB Fuzzy Toolbar (R2012a) was used to execute the suggested fuzzy inference process in Matlab program [24].

2.4 Analysis, Results and Discussion

Figure 2 illustrates Matlab R2012a based fuzzy logic designer used for calculating frequency of MT in relation to *AoF* and *NoWH*.

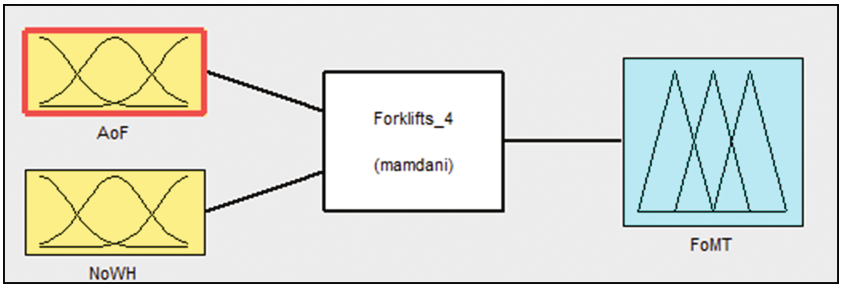


Fig. 2. Fuzzy logic designer

Using the level of frequency of MT (see Table 6), a rule base was developed (see Fig. 3). The Gaussian combination memberships for the *AoF, NoWH* are illustrated in Figs. 4 and 5 respectively.

Table 6. The percentage of maintenance tasks.

Type of maintenance		Preventive Maintenance (PM)	Corrective Maintenance (CM)
Level of FoMT	M	24%	76%
	H	18%	82%

Figure 6 illustrates a rule view and an example calculation of the frequency of maintenance tasks (*FoM*T) for forklifts. The calculation was carried out for the $AoF = 15$ and $NoWH = 19{,}500$ h. The frequency rank estimated by the fuzzy inference process is 0.183. The corresponding linguistic value is L (using the membership function in Fig. 5). This linguistic value shall be used for the organisation of the range and types of

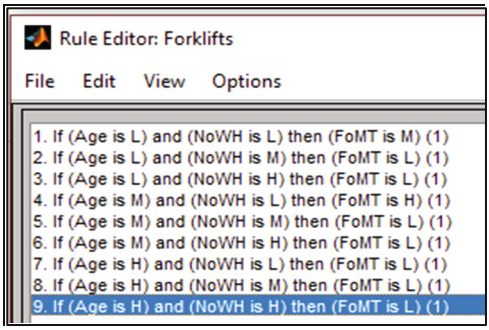


Fig. 3. A rule base.

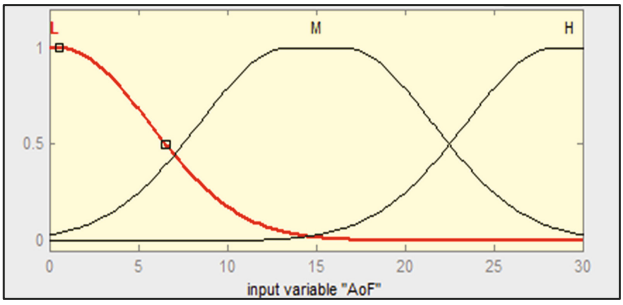


Fig. 4. Gaussian combination membership of *AoF*.

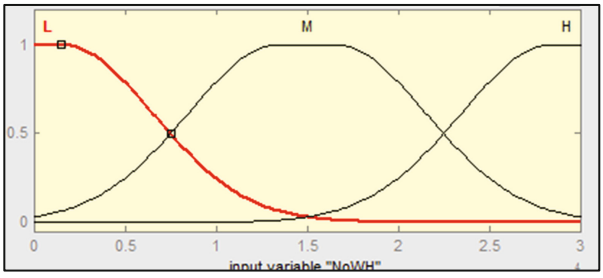


Fig. 5. Gaussian combination membership of *NoWH*

maintenance tasks for forklifts (i.e. forklifts with high frequency of MT will be given a main priority).

Figure 7 illustrates three dimensional (3D) risk (*FoMT*) profiles in relation to *Ao*F and *NoWH*.

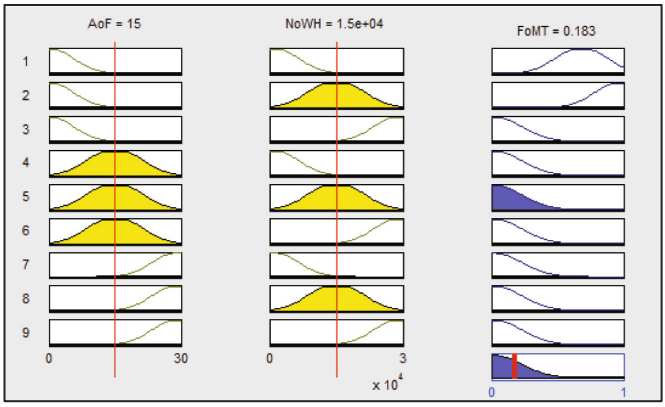


Fig. 6. Calculations [$FoMT = 0.183$ for $AoF = 15$ and $NoWH = 15{,}000$] and rule view.

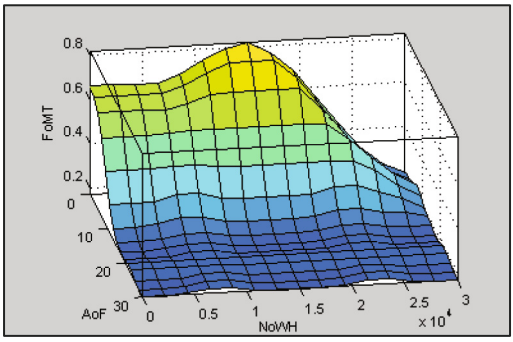


Fig. 7. 3D profile.

Based on the manufacturing company risk philosophy, it is possible to prioritize: 1. *AoF*, 2. *NoWH* or any other sequence.

Knowing the level of *FoMT* it would be good to know what kind/type of maintenance tasks the company will have to perform. That is why, the data collected of the maintenance of forklifts were analysed. The type of activities implemented was specified. Two types of maintenance tasks were defined: preventive and corrective maintenance. Table 6 shows the percentage of operations for these types of tasks for the levels of M and H of *FoMT*.

In this case study, a significant share of CM in relation to PM is noticed. The share of CM increases for a high level of *FoMT*. It may indicate the possibility of planning of more preventive actions to prevent failures. Unfortunately, the companies possessing forklifts are not willing to increase preventive activities, even if the risk of failures increases. However, a service company can be prepared for any additional maintenance tasks. On the basis of the machine categorization results, made together with an owner on a forklift, it may try to justify the necessity of undertaking preventive actions.

3 Conclusions

A maintenance process of forklifts presented in this work is characterized by a high share of corrective actions in comparison to preventive actions. The historical data can be used in the fuzzy logic programming, and then to present the risk of forklifts failures. The main reason why the fuzzy logic was implemented is that different forklifts owners treat forklifts in different ways. Therefore, even if there are two the same branches, the same models, at the same age, and forklifts used in a similar way (similar millage), the risk of failures can be different. The fuzzy logic implementation for the assessment of the risk of forklifts failures and for the maintenance tasks (preventive and corrective) prediction, as it is known to the authors, hasn't been done so far. The issue is interesting because, probably in many cases, it will be a service maintenance organization which will try to convince an owner of a forklift that it will be justified to undertake preventive actions, instead of corrective actions. It is worth emphasizing that many of the companies which cooperate with a case study service organization are SME with only one or two forklifts. Therefore, keeping their forklifts in a working order should lie in their interest. Using the presented concept, a service organization can calculate the risk of failure for each forklift and plan corrective and preventive actions. Obviously, it is impossible to predict exactly how many failures will happen on a particular forklift. However, the outputs of the analysis can be taken into account, for example in planning of human resources which are to be engaged in the maintenance tasks.

In the future work, the authors would like to integrate the presented concept with machines categorization.

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An Intelligent System Supporting a Maintenance Process of Specialised Medical Equipment

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Abstract. A maintenance process of medical equipment is very important because people's life or the quality of people's life depend on such equipment. The maintenance of some equipment can be only done by specialists. Nevertheless, some actions can be undertaken by the less specialized personnel. In this paper, on the basis of the data concerning complaints, the kind of failures and exchanged parts in equipment, preventive actions were proposed. However, the actions are recommended not to prevent failures but to avoid a long waiting time for the equipment to be repaired. The authors propose to use a fuzzy logic analysis to assess the risk of failures of a certain piece of equipment. The defects which can be eliminated by the less specialized personnel were indicated. The results of the analysis are taken into consideration in a decision making process identifying the situations in which a certain person, i.e. a dealer, should be trained to be able to make a repair without sending the equipment to a manufacturer.

Keywords: Maintenance process · Medical equipment · Skills improvement · Fuzzy logic

1 Introduction

The maintenance process of medical equipment may influence people's life or the quality of their life. Therefore, it is necessary to plan this process in a proper way.

In the literature, there are different concepts concerning the management of medical equipment in order to keep them safe and reliable. Besides, the methods to identify critical equipment are also presented. However, it mostly concerns hospital equipment. The authors haven't found works concerning a maintenance process of the equipment used by individuals. The literature review was made to identify the methods which can be possibly used in a maintenance process of the equipment used by individuals.

In the work [1], the authors emphasize the fundamental role of clinical engineers in the selection of medical equipment, equipment performance programs development, education programs, risk analysis, etc. In some cases the maintenance process can be realized only by specialists. However, it is also possible to undertake some actions by non-specialists who are trained how to perform some repairs. These can be hospital employees or dealers who sell medical equipment.

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In the work [2], the authors present how to identify and prioritize critical devices to mitigate functional failures. The authors used a multi-criteria decision-making model to prioritize devices and to propose appropriate maintenance strategies including 'preventive maintenance' and 'user training'. Moreover, in the works [3–6], the importance of preventive maintenance in the maintenance management process of equipment and the role of risk based maintenance was shown. In the work [7], user trainings are mentioned as an important part of preventive maintenance as well.

In the work [8], the authors propose to use the Analytical Hierarchy Process, the Technique for Order Preference by Similarity to Ideal Solution, and the mathematical optimization to determine the criticality of medical equipment, to rank the maintenance strategies and to select the optimal maintenance strategy taking into consideration the total maintenance cost. In the work [9], the authors used the Monte Carlo Simulation Tool to forecast the risks of medical equipment failures.

According to [10], in the medical equipment maintenance process the focus should be paid on the risks caused by equipment failure which influences larger groups of patients. In the paper [11], the authors discuss outsourcing of the medical device maintenance process.

In the work [12], the authors applied, among others, the fuzzy failure modes and effects analysis method to prioritize medical devices and to facilitate the classification of medical devices for maintenance activities based on their criticality scores. In the work [13], the authors proposed a risk assessment model based on the fuzzy logic to prioritize medical equipment maintenance. They emphasized that the risk for the same equipment type may be different, depending on the working conditions in a hospital, especially in developing countries.

This paper deals with medical equipment which is used by individuals. A case study of a company which manufactures specialised medical equipment is presented. The products, among others, include static and dynamic standing frames, positioning chairs, multifunctional devices or special strollers. The products of the company are designed to provide support for children, young people and adults with special needs. In case of a failure, a product is sent to the manufacturer, where condition based maintenance is realized in a complaints service area to repair the product. Sometimes, it even takes more than 2 weeks to return the equipment to a client. It causes discomfort for the client because during this time he or she is almost totally dependent on other people. Therefore, in order to decrease this inconvenience, the authors of this paper propose to identify the repairs which can be done by non-specialists, for example by medical equipment dealers. They deal with many kinds of equipment and it is impossible to train them how to eliminate failures in any kind of equipment. Hence, the authors propose to use a fuzzy logic analysis to identify trainings which should be done for these people to train them how to do the repairs. In the work, on the basis of the repairs done within 36 months on 11 kinds of products, the training process for dealers is proposed. Thus, the dealers may do some repairs without sending the equipment to the producer. Not only can it accelerate the repair process, but also decrease the cost of repairs, because it will not be necessary any more to send the equipment to the manufacturer.

In the work, the kind of failures which appeared and the product in which they appeared were analysed first. Then, the probability of failures was assessed with the use

of the fuzzy logic, on the basis of the data such as the **weight of a client** and **environment**, in which a product is used. The information about a client's weight is important because the products are selected on this basis. A certain model of a product is proposed to a client also on the basis of the environment in which the product will be used.

2 Analysis of the Data Concerning Medical Equipment Failures

On the basis of the data concerning 11 kinds of equipment and received clients' complaints [13], the equipment with the highest number of failures was identified. Table 1 presents the information about the percentage of the manufactured products which were complained about for each kind of equipment. Additionally, a maximum weight that is allowed for different types of certain models is presented.

Table 1. Data concerning equipment sold in 36 months [Source: [14] and catalogue of products]

Model of equipment	Max weight of the user (kg)	% of complained products
HI01	20, 30	23.86%
DA01	25, 45, 60	21.62%
LI01	120	21.43%
RA01	35, 50, 60, 90	11.11%
ZE01	25, 45, 60	10.45%
PA01	55, 95	6.15%
RE01	30,55, 95	5.00%
SL01	30, 45, 75	1.96%
SM01	35, 55, 75, 95	1.64%
KO01	25, 35, 45	1.63%
AC01	25, 40, 60, 80, 95	0.62%

One complain can be connected to the exchange of more than one part of a product. Where a complaint was done in a shop it took more than 2 weeks to get the equipment back by a client. Figure 1 presents the percentage of parts which were exchanged or repaired in the equipment in comparison to all exchanged parts. However, only parts which can be exchanged by a dealer were further analysed. Figure 2 presents the percentage of the damaged parts of the equipment which had to be exchanged.

The data concerning the exchanged parts were carefully analysed, and the levels of parts convertibility were assessed on the basis of Table 2. Three levels of convertibility are proposed: Low, Medium and High. They depend on a number of clients who made complains concerning a certain part of a product as well as on the cost of training per a product. When, for example, about a dozen clients made complains (historical data), and it was necessary to exchange a certain part of a product in many products, and additionally, when the cost of training per a product is low the convertibility will be high. The results of the analysis for the equipment and the chosen parts which can be possibly exchanged in the shop are presented in Table 3.

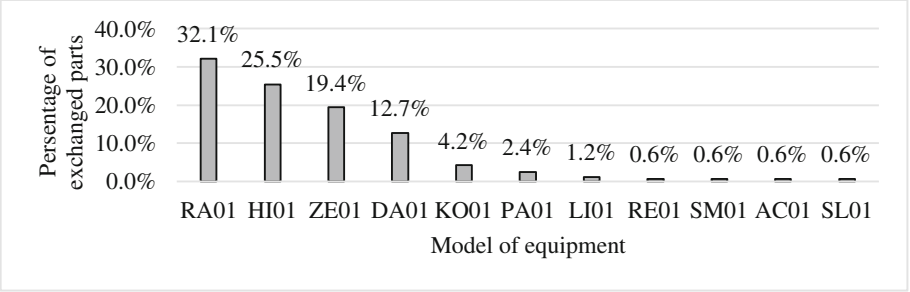


Fig. 1. Percentage of the parts exchanged in different models of equipment

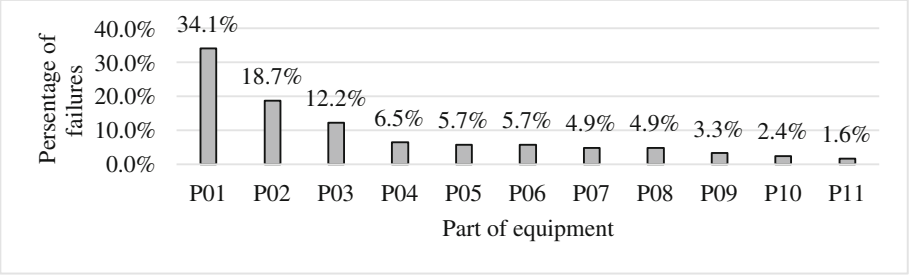


Fig. 2. Percentage of the parts exchanged in a total number of exchanged parts

Table 2. Possible levels of the parts exchanged in equipment

Number of clients	Cost of training per a product		
	High	Medium	Low
One to a few clients	L	L	M
A few to a dozen clients	L	M	H
A dozen clients and more	M	H	H

Table 3. Level of parts convertibility in the analysed equipment models

Model of equipment	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11
HI01	H	M			L	M	L	M		L	
DA01		M	L	M	L		L		L		L
LI01	L			L							
RA01	H	M			L	L		L			
ZE01	L	H	H		L				L	L	L
PA01	L	L					L				
SM01	L										
KO01			L				L				
AC01							L				

During a sales process equipment is ordered for a client by a dealer. The dealer asks a client, among others, about the weight of the client (*WoC*) and the environment in which the equipment will be used (*Env*). These pieces of information are important in order to select adequate equipment for the client. Additionally, these are important factors which can have influence on the equipment failures. Therefore, this information can be also transferred to the manufacturer. Then, the product is delivered to the shop. Hence, together with the products, a training for a dealer can be delivered jointly with the instructions how to do a repair. It may concern common failures.

In the further analysis, the authors propose the ways to identify the situations in which a training is recommended for the dealer.

3 Risk of Failures Assessment

3.1 Fuzzy Interference Process

The risk of failures will be an important factor for the decision concerning the training as well as to prepare a training program for dealers. It results from the fact that there are cases in which the training will not be undertaken. It will depend on the level of convertibility of the parts for the certain equipment and the risk of failures of the equipment. The probability of failures will be lower if the weight of a client is low, comparing to the maximum weight, and when the equipment is be used in good environment. In this situation, the training may be unnecessary. However, it is not easy to assess clearly the environment in which the equipment will be used. Similarly, the weight of a client can change in time. Therefore, in order to assess the risk of failures a fuzzy logic analysis was implemented.

In Fig. 3 a fuzzy interference system (FIS), used in the presented case study, is shown.

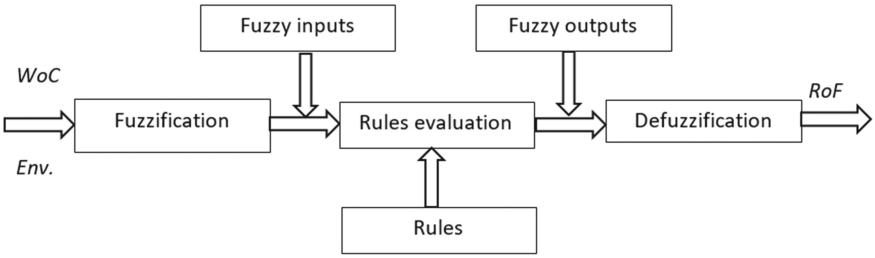


Fig. 3. Fuzzy interference system

In this Mamadami FIS two inputs were used. One is the Weight of Client (*WoC*), another one is Environment in which the equipment is used (*Env*). The output is the probability/risk of failure (*RoF*). This fuzzy inference process consists of the following stages: Fuzzification, Rules evaluations and Defuzzification. For the purpose of this analysis the Matlab R2012a program was used. In Fig. 4 the fuzzy logic designer (Matalab R2012a) is presented.

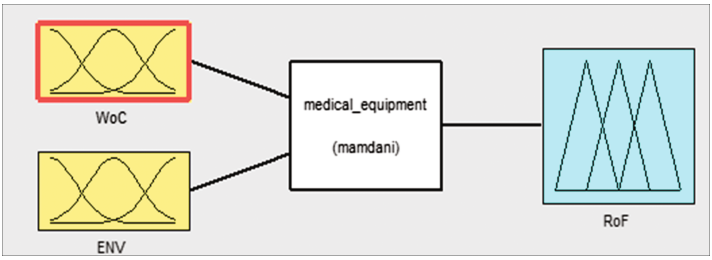


Fig. 4. Fuzzy logic designer (Matlab R2012a)

3.2 Parameters for the Proposed FIS

For the output (*RoF*) and inputs (*WoC*, *Env*), the membership functions were specified. Based on the authors' experience and the works [15, 16], in order to minimize the difference concerning the mathematical modelling and the practical application, the triangular membership functions were used (formula 1).

$$y = trimf(x, [a\ b\ c]) \tag{1}$$

The triangular curve membership function is a function of vector x, and it depends on three parameters a, b, and c. It follows the syntax from Mathworks [17]: (formula 2)

$$f(x; a, b, c) = \begin{Bmatrix} 0, & x \le a \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ \dfrac{c-x}{c-b}, & b \le x \le c \\ 0, & c \le x \end{Bmatrix} \tag{2}$$

or (formula 3)

$$f(x; a, b, c) = \max(min\left(\frac{x-a}{b-a}, \frac{c-x}{c-b}\right), o) \tag{3}$$

The parameter b is the peak of the triangle, the parameters a and c determine the "feet" [18]. In order to determine the membership functions for inputs (*WoC, Env*), the ranges presented in the Table 4 were used.

Table 4. The ranges for inputs.

	Category	L - Low	M - medium	H - High
Range	Weight of a client for the maximum weight (WoC) [%]	<80	80–90	>90
	Environment in which the equipment is used (Env)	Even surface	Averagely uneven surface	Uneven surface

Because the input 2 (*Env*) is a qualitative parameter, the range for the triangle membership functions (*TriMF*) were established as [0, 1] and the peaks for each category are as follows: (L – 0, M – 0.5, H – 1) (Fig. 5).

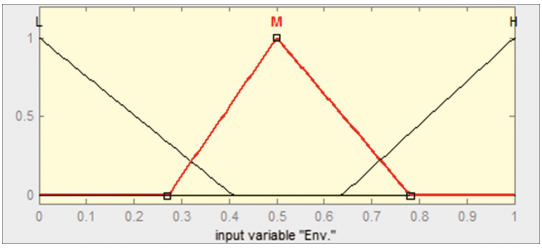


Fig. 5. TriMF for Env.

For output (*RoF*) the range for the triangle membership functions (*TriMF*) were also established as [0, 1] and the peaks, as in *Env* for each category, are as follows: (L – 0, M – 0.5, H – 1) (Fig. 6). Additionally, other parameters were selected (Table 5). In order to determine the fuzzification rules, based on the analysed date and experience of the authors, the risk matrix for failure (*RoF*) was developed (Table 6).

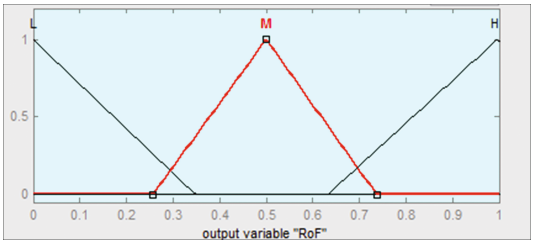


Fig. 6. *TriMF* for *RoF*

Table 5. Parameters of the fuzzy logic system.

The parameter	AND	OR	Implication	Aggregation	Defuzzification
The values	Min	Max	Min	Max	Centroid

Table 6. Risk matrix for failure (*RoF*)

Weight of a client to the maximum weight (WoC) [%]		L	M	H
Environment in which the equipment is used (Env)	*L*	L	L	M
	M	L	M	H
	H	M	M	H

Based on the risk matrix (*RoF*) (Table 6) the following fuzzification rules were established:

1. If (*WoC* is L) and (*Env* is L) then (*RoF* is L)
2. If (*WoC* is L) and (*Env* is M) then (*RoF* is L)
3. If (*WoC* is L) and (*Env* is H) then (*RoF* is M)
4. If (*WoC* is M) and (*Env* is L) then (*RoF* is L)
5. If (*WoC* is M) and (*Env* is M) then (*RoF* is M)
6. If (*WoC* is M) and (*Env* is H) then (*RoF* is H)
7. If (*WoC* is H) and (*Env* is L) then (*RoF* is M)
8. If (*WoC* is H) and (*Env* is M) then (*RoF* is M)
9. If (*WoC* is H) and (*Env* is H) then (*RoF* is H)

If the values of the analyzed parameters are in the middle of the estimated ranges, it isn't problematic to estimate the level of *RoF*. The problem arises especially when the values are near the border of the ranges. Additionally, in this case there is another impediment. *Env* is a qualitative parameter, what can have a huge influence on estimating a suboptimal classification of the level of *RoF*.

3.3 Analysis, Results and Discussion

The Matlab Fuzzy Toolbar (R2012a) simulator was used to implement the proposed Mamadami FIS [18]. In order to show how the proposed FIS works, the following example was analysed. During the sales process of medical equipment a client was asked about his/her weight and the environment in which the equipment will be used. *WoC* was assessed as 82 (M) and *Env* as Averagely uneven surface (M), therefore the value 0.6 can be adopted. Having these kinds of data, *RoF* (using proposed FIS) can be calculated. In this case, the value of *RoF* is 0.512 (M). Rule 5 mainly works (Fig. 7).

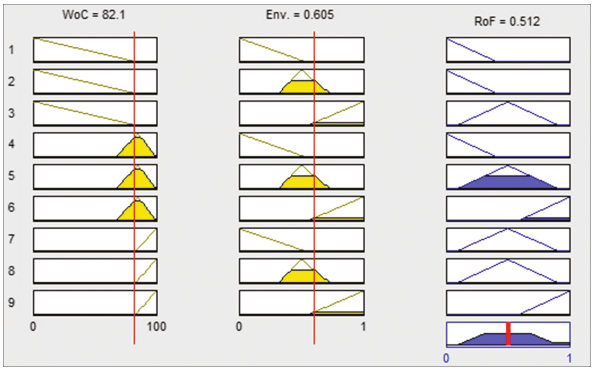


Fig. 7. Calculations of *RoF* [*WoC* = 82 for *Env* = 0.6 and *RoF* = 0.512] and rule view

Then, having the model of equipment (H101 in this case), the level of parts convertibility in equipment can be identified (Table 3). In this model, the level H is for parts P01, and M for P02, P06 and P08. Knowing the *RoF* level (Fig. 7) and the parts

convertibility (Table 3), the range and type of maintenance tasks can be initially predicted. Having this information the manufacturer can identify the range of preventive and corrective maintenance. In Table 7 preventive and corrective activities for each situation are presented.

Table 7. Proposed preventive and corrective maintenance

Level of parts convertibility	H	M	L
	RoF > 0.7	0.7 ≥ RoF ≥ 0.3	RoF < 0.3
H	Train the dealer and deliver a video instruction. Repair in the shop	Train the dealer and deliver a video instruction. Repair in the shop	Deliver a video instruction. Repair in the shop
M	Train the dealer and deliver a video instruction. Repair in the shop	Deliver a video instruction. Repair in the shop	Repair on the manufacturer's side
L	Repair on the manufacturer's side	Repair on the manufacturer's side	Repair on the manufacturer's side

The main goal of preventive activities is to avoid a long waiting time of a client for the equipment. It is not to prevent failures. Corrective actions concern the place where a repair will be done. On one side, we want to decrease a waiting time and, on the other side, we have to calculate the costs of dealers' trainings.

4 Conclusions

The maintenance process of medical equipment may concern not only the equipment used in hospitals but also the equipment used by individuals. At the same time, a maintenance process can concern not only preventive maintenance which exclude failures, but also preventive actions which do not allow for a long waiting time of a client who waits for repairing the equipment. The methodology presented in this paper allows the manufacturer to prepare better to make a service for the clients whose equipment was damaged during its exploitation. Based on the exploitation conditions (weight of a patient and environment), the risk of failures can be assessed. Additionally, based on the historical data, the parts of equipment which are most often exchanged were identified. The results of the analysis allow to prepare the training program for dealers in order to enable them to do simple repairs of equipment avoiding the necessity of sending equipment to the manufacturer. It will increase clients' satisfaction and, at the same time, it will decrease the costs of dealing with the damaged equipment. The presented methodology can also be applied for other types of equipment, not only for the medical one.

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Enabling Round-Trip Engineering Between P&I Diagrams and Augmented Reality Work Instructions in Maintenance Processes Utilizing Graph-Based Modelling

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Abstract. Round-trip engineering usually describes the synchronization between formalized documents and realizations in software engineering. Piping and Instrumentation Diagrams are commonly used in process engineering and play a major role in planning and documentation of maintenance processes. The authors propose a method for the synchronization of engineering data via a dynamic graph-based model, which offers context-sensitive work instructions utilizing smart devices and feedback from maintenance processes back into the engineering documents, thus facilitating manual consolidation afterwards. This paper elaborates the concept of graph-based modeling for hydraulic systems, the transfer of P&I Diagrams into the proposed model, utilization of the model for Augmented Reality support in maintenance processes and the feedback for added assistance in keeping engineering documents up-to-date. The authors implemented and validated the concept under laboratory conditions.

Keywords: Smart maintenance · Mobile devices · Process engineering · Augmented reality · Graph database

1 Introduction

"Industry 4.0" aims to achieve high flexibility and short lead times to face the growing competitive pressure between companies. Throughout all industrial branches the increasing automated production processes result in a rising complexity of machinery [1]. In this context maintaining one's machinery becomes ever more important to guarantee reliability and thereby ensure the company's supply capability [2].

A major part of life cycle costs sums up during maintenance, repair and overhaul (MRO) processes. It is essential to consider them in the life cycle engineering, especially when planning products that are even more complex. "Industry 4.0", "Internet of Things" or "Brilliant Factory" become more of a standard in both academia and industry and it becomes clear that the increasing amount and complexity of data will continue to challenge engineers. The "early adopters" of industry 4.0 were mostly found in automotive and mechanical engineering, but the process industry starts adapting to the new technologies, too [3].

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A major element in keeping machinery running correctly through MRO processes is the accuracy and appropriateness of documentation and engineering data in relation to the physical condition of the concerning machine [4]. The networking capability of smart products in the Internet of Things (IoT) and the accompanying availability of data enables these products not only to operate, react and start actions autonomously but even to use additional services [5].

The term "Smart Maintenance" [6] in context of "Industry 4.0" is used to address new structures and platforms for maintenance services. It resembles the overall idea of connecting asset management, sensor data and intelligent on-site maintenance support. The technological advancements offer enormous potential in maintenance processes, like the improvement of service documentation by combining it with operating data from the concerning machines [7, 8].

Schlick et al. [9] found that graphical instructions in maintenance are superior to textual ones whenever the repetition rate is low. Augmented reality is defined [10] as overlaying reality with additional virtual content and offering a higher degree of intuitional use compared to conventional documentation. Furthermore, studies show that context sensitive maintenance support with Augmented Reality (AR) reduces worktime [11] and reduces error rates [11, 12].

The authors already proposed methods for the modelling of hydraulic systems in context of maintenance processes in [13, 14]. In these publications the authors showed that graph based models can be used for an automated analysis of hydraulic systems and the generation of according Augmented Reality work instructions.

Round-trip engineering usually describes the synchronization between formalized documents and realizations in software engineering to achieve a single source of truth [15]. The goal of this approach is to eliminate inconsistencies between different representations of the same "thing". Generally, synchronization (which means data interchange) can be either unidirectional or bidirectional. In software engineering, code generator tools typically work unidirectional. This means a graphical system model is translated to more or less executable code. More advanced systems enable a bidirectional association, which translates to the ability to generate code from a graphic model and modifying the model after changes being made in the code. The latter is the ideal solution, more often the changes in the code are otherwise made known to the user to support the manual editing of the graphical model.

Piping and Instrumentation Diagrams are commonly used in process engineering and play a major role in planning and documentation of maintenance processes.

Systems Engineering is, by contrast, an interdisciplinary field, in which the modelling of product behavior and structure is but a part of the complexity management [16]. The graphical markup language SysML [15] is one of the standards for formalized modelling of complex products in Systems Engineering.

As this paper is aimed at users of common tools in the process industry, SysML documents are only conceptually acknowledged. This paper elaborates the concept of graph-based modeling for hydraulic systems, the transfer of P&I Diagrams into the proposed model, utilization of the model for Augmented Reality support in maintenance processes and the feedback for added assistance in keeping engineering documents up-to-date.

2 Aims and Requirements

The use case is inspired by one of the hydraulic systems currently in use in the laboratories of the Institute of Thermo and Fluid Dynamics of the Ruhr University. The pilot or prototype machines are often planned in a "traditional" way, meaning by 2D sketches and/or by Piping and Instrumentation Diagrams (P&ID). Furthermore, there are no 3D models available for components or machines, or they are not maintained over time after changes to the physical structure. As the approach is part of the movement towards the Internet of Things (IoT, cf. [17]) it will not contain the error-prone (cf. [18]) manual gathering of the operational data but real-time sensor data directly from the machine.

One main aspect for improving the viability of the overall concept proposed by the authors is to find an automated way for the creation of the graph-based model. As smart products are reconfigured throughout their lifecycle [19], it is essential that the engineering documents and models are kept up-to-date. So ensure that, feedback data from maintenance, repair and overhaul processes (MRO) must be used to either change the documents automatically or offer information to engineers about the changes made to the physical machine.

The mentioned aims include defining requirements for the concept. Furthermore, general requirements regarding the real-world usability are to be met.

As the graph-based model approach from the author's previous work is optimized for continuous processes in process engineering, the starting point for the automatic creation of the model has to be a widely used format for data exchange.

According to [20] Piping and Instrumentation Diagrams are widely used in the planning and maintenance in process industry. Common tools for the creation of these graphical plans for hydraulic systems are (amongst others) Autodesk AutoCAD, Microsoft Visio and Lucidchart. Consequently, the first requirement is to one of the mentioned tools as a basis to create the graph-based model. As the implementation of the proposed concept will be prototypical only and cannot include multiple different authoring tools, it is sensible to create a generic interchange format to process in the self-developed components. The second requirement is therefore the creation of a data scheme from proprietary authoring tool files to extract data into. Importing the generic data format into the graph-based model is the crucial step for the extension of the proven concept and by that, the third requirement.

To further adapt to the ever-changing configuration state of smart products, requirement four includes the feedback-loop after a MRO process, in case the physical process influenced the associated engineering documents.

3 Concept

The goal of the graph-based approach is to create a dynamic model as a single-source-of-truth for maintenance processes. In order to achieve that, it allows manipulation from either the planning side or the operational side by means of integration into the regular workflows of the involved stakeholders, such as engineers and technicians.

According to Haberfellner and Daenzer [21] models as a depiction of reality must be convincing enough in regards to the situation and problem position. When looking at hydraulic systems and possible ways to depict them in a formalized model, it becomes clear that one has to look for certain things and their interconnections. In both cases not only the thing or connection itself is relevant, but also their context and type. It is thereby possible to build classes and hierarchies. The first assertion is that hydraulic systems in general and their representation in P&I Diagrams in particular can be interpreted as a graph, whereas the afore mentioned "things" are represented through vertices and their logical or physical connections are represented through edges.

Figure 1 shows a simple example for the "facts" that can be modelled in a graph. The hydraulic connection between the components to the left are obvious for human technicians. To let algorithms perform analysis on the structure of machines, the graph-based model approach translates the engineering document to a formalized and structured representation.

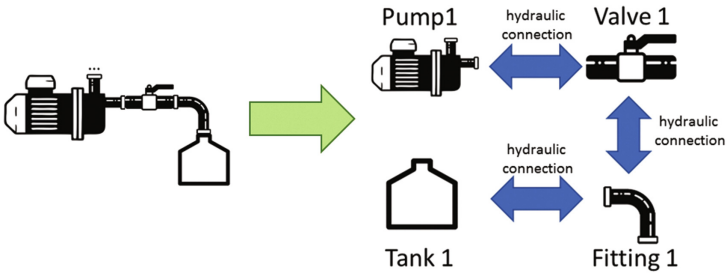


Fig. 1 Semantics of P&I diagrams

The new approach for the round-trip engineering enabled graph-based model for the provisioning of context-sensitive Augmented Reality work instructions consists of several components and steps. As the maintenance technician is not only the recipient of information for the assisted maintenance process, but also the author of data through his manual labor, the concept allows feedback data to flow back into the graph-based model and from there to the designated engineering documents.

To illustrate the approach Fig. 2 shows the idea and its interconnected components, actions and stakeholders.

The entry point to this concept is step 1.a, the creation of a P&I diagram by an engineer. At this stage, the incorporation of the diagram into the feedback cycle concept does not affect the engineer. Step 1.b is optional, as the Maintenance Manager may authorize an Action Request or Engineering Change Request (ECR) to physically change the machinery. Such a change may the addition of a sensor or component or the replacement of such.

The second step (Fig. 2) consists of the creation of an intermediate file with the necessary data for the import into the graph-based model from the P&I Diagram. To achieve this, step two consists of several phases to realize the interfacing between graphical representation and usable data in a graph database. To realize the export from the graphical representation, the proprietary authoring software needs either interfaces,

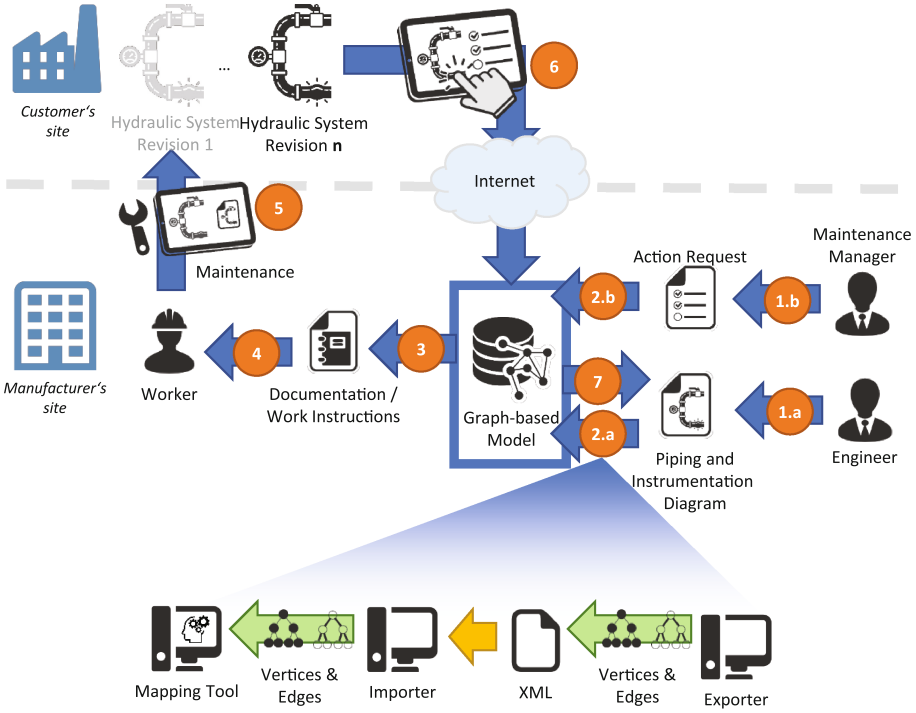


Fig. 2 Concept overview

add-on-capability or an inbuilt programming module. Either of these possibilities enable the parsing of the data behind the graphical representation for the extraction of edge and vertice classes and instances of edges and vertices. In the context of P&I diagrams this means the registration of edge classes for i.e. pipes or control wire and the according registration of the individual pipes with their respective start- and end-points and further meta data. The same principle applies to vertice classes and vertices. All components in the P&I diagram are analyzed to extract the used classes of components like valves, flow meters, tanks etc. Subsequently the exporter catalogues the individual components with their specific data.

Figure 3 shows the XML scheme that the exporter uses to save the gathered data.

On the side of the graph-based model, the according importer for the xml scheme loads the data and compares it to the already present data. Using the mapping tool, the engineer either can map classes for vertices and edges to existing classes in the graph-based model or mark them as new to create a new cluster of elements.

The third step (Fig. 2) includes the usage of the author's algorithms to conduct an analysis of the machine at hand with the graph-based model. The exact workings are described in previous work [13].

The fourth step (Fig. 2) consists of the analysis through the graph-based model that can trigger warnings and give guidance to reestablish a desired operation state.

```
<?xml version="1.0" encoding="UTF-8"?>
<pandidiagram>
   <verticeClasses>
      <verticeClass name=""
                safeName="" />
   </verticeClasses>
   <edgeClasses>
      <edgeClass name=""
                safeName="" />
   </edgeClasses>
   <vertices>
      <vertice name=""
                safeName=""
                verticeClass="" />
   </vertices>
   <edges>
      <edge name=""
                safeName="„
                edgeClass=""
                edgeFrom="„
                edgeTo="" />
   </edges>
</pandidiagram>
```

Fig. 3 XML scheme for the data export/import

The fifth step (Fig. 2) is the physical maintenance process in itself with added support through the mentioned assistant system using augmented reality visualization. The proven approach offers service technicians an interactive, intuitive and documentable way to maintain machinery. To realize context awareness, a smart device application uses graph-based algorithms to guide the technician in achieving the machine's desired operating condition after evaluating the current state of the machine.

The sixth step (Fig. 2) is the checkout process in which the technician confirms his actions, again by using the smart device application. By triggering the prepared actions through the graph-based model, the assistant application uploads the feedback data.

As the mapping between model and engineering documents is bidirectional, the seventh step (Fig. 2) then uses the freshly uploaded data to detect the inconsistencies between the engineering document and the graph-based model. The feedback assistant then uses the delta between the outdated representation in the engineering document and the more current data in the model to visualize which changes the engineer has to make.

4 Prototype Implementation and Validation

In reference to the line of action in the concept (Fig. 2), the validation follows a similar path. Harrison [22] cites the strength of graph databases lie especially in the use cases in which the correlation of elements is more important than the elements themselves. While company-wide systems like PLM specialize on administration of inventory data, the graph-based model is used as external storage for the maintenance data and information extracted and aggregated from existent systems, to be dynamically evaluable for service technicians.

For the validation of the presented approach, the author's laboratory environment was used. The realization makes use of OrientDB as the graph database storing the graph-based model, Apache Webserver for PHP scripting of the importer and Microsoft Visio 2016 for both the modelling of the P&I diagram and the scripting of the exporter in Visual Basic for Applications.

The authors used a P&I diagram from one of the prototype machines in the universities laboratories to fulfill step 1.a (Fig. 4). Step 1.b is the Action Request to install a flow meter between the tank and the mixing valve. The second step (Fig. 4) consists of two actions. First the export of the XML file is triggered via a button click in the Visio file, executing a function in the prepared VBA module. The file is then created in a directory that the Apache Server can access and by calling the web-based importer the mapping-process can be conducted. In case of this validation, the graph-database is cleared after every iteration.

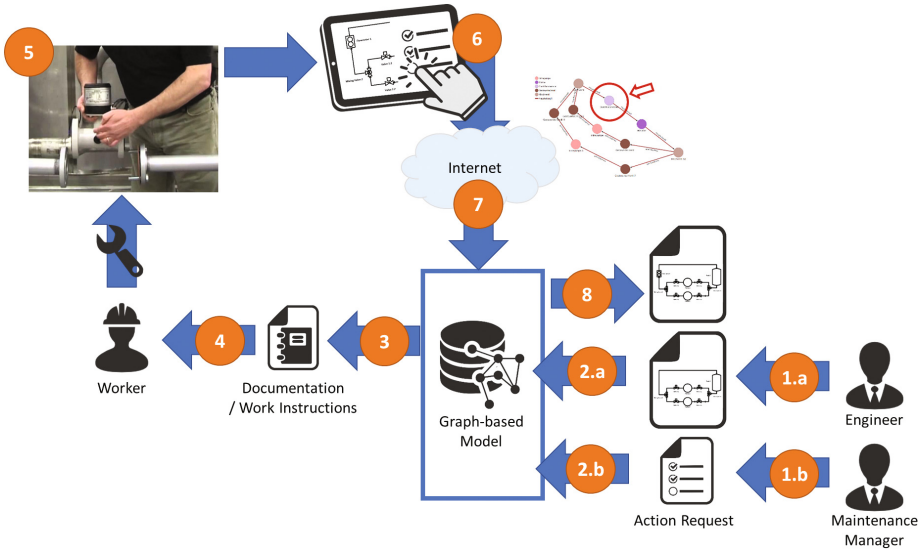


Fig. 4 Implementation overview

The third step (Fig. 4) includes the usage of the author's algorithms to extract a report of the current status of the machine from the graph-based model as described in previous papers [13]. The fourth step (Fig. 4) is played out as the work instruction from the maintenance manager to install the flowmeter. The fifth step (Fig. 4) is the physical installation process in itself with added support through the afore mentioned assistant system with the pre-generated documentation. The sixth step (Fig. 4) is the confirmation that the correct piece (the flowmeter) has been installed in the correct position. Note that all hydraulic components are non-smart, so the technician has to identify the correctness.

The seventh step (Fig. 4) is the automated process of the feedback upload. Once updated via the PHP implemented web service, the last step is triggered.

Step eight (Fig. 4) then involves another button-click in the Microsoft Visio file to compare the structure within the graph-based model with the P&I diagram.

Figure 5 shows the results after finishing the last step. On the left hand side, the graph representation of the hydraulic system is visualized in OrientDB's graph viewer. On the right hand side of Fig. 5, the GUI of Visio can be seen after the feedback data has generated the changelog. The chart under the P&I diagram shows which parts have to

be removed (also colored red in the diagram) and which parts have to be added to complete the synchronization between the graph-based model and the P&I diagram.

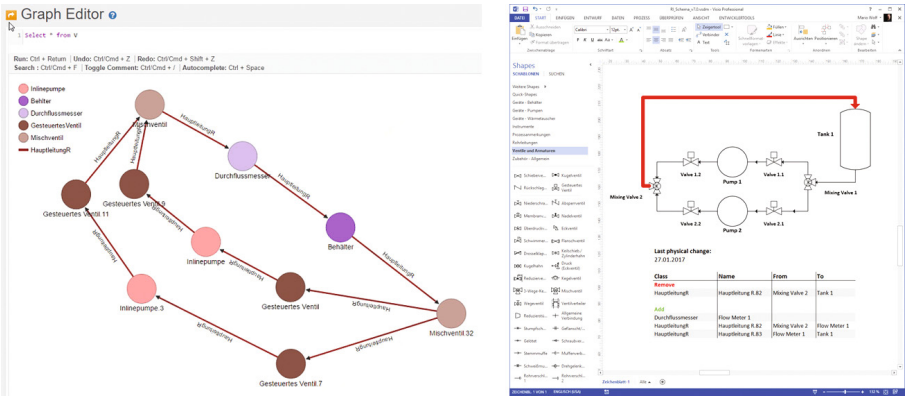


Fig. 5 Graph database visualization (left) and MS Visio assistance script (right)

5 Conclusion

We have shown that the approach at hand enables round-trip engineering between P&I Diagrams and physical machines by mapping the changes made in maintenance processes to the associated engineering documents. This enables an easier way to keep documentation up-to-date and furthermore automatically updates the analytic structure of the graph-based model. Future work will improve upon the implementation of P&I Diagrams in product lifecycle management (PLM) software such as PTC Windchill or Siemens Teamcenter. The authors seek to implement the tracking of feedback data induced changes in the PLM meta-data model and to trigger an automated synchronization between P&I Diagrams and the graph-based model on check-in and check-out of respective files in the PLM system. Furthermore, the focus for the near future is the implementation of the concept in an industrial case study.

The medium-term vision of the authors will implement a way of gathering feedback information without the need of either P&I diagram or 3D-models of the whole assembly. Through on-site smart device based 3D-scanning and geometry matching with catalogued, parametric 3D models, physical changes in the product structure will be recorded automatically.

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Incident Detection in Industrial Processes Utilizing Machine Learning Techniques

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Abstract. This work provides a comparative analysis of the most popular and widely used classification algorithms applied in industrial processes, in order to tackle the issue of incident detection of abnormal situations. The proposed analysis is based on actual datasets from derived by the operation of a chemical process system situated at the premises of CERTH/CPERI. The evaluation of the tested methods is based on cross-validation using a series of Monte-Carlo simulations among several free parameters of tested classifiers and finally the application of the Adaptive Boosting technique. The experimental results are highly reliable as the accuracy reaches 98% and the F-measure metric achieves a score over 97%. Therefore, the detection of potential malfunctions is achieved using the proposed machine learning techniques.

Keywords: Machine learning techniques · Incident detection · AdaBoost

1 Introduction

In last decades, the evolution of industrial sector and the increasing use of automated processes that are equipped with numerous data acquisition systems, result to an increasing expectation for high quality performance under varying operating conditions. Thus, the minimization of potential errors and unexpected failures of the process equipment is of great importance and need. Extensive research has being made on the creation of predictive models for anomaly and fault detection in industrial equipment and processes. In literature, one can find many approaches that deal with anomaly detection problem, such as classification [11, 18], clustering approach [16] and statistical approach [8, 17]. In recent years, machine learning, as an evolving subfield of computer science, is widely used on the challenging problem of incident and anomaly detection problem. While continuous progress has been made on the development of new

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algorithms and on the optimization and modification of those that already exist, new challenges arise continuously due to human interaction and complex process developments. Machine learning techniques and feature extraction methods for the improvement of overall accuracy have already applied in a variety of problems, due to their simplicity and efficiency. In literature, one can find extensive research and application of machine learning and feature extraction methods, specifically for the fault detection and diagnosis problem, on batch and semibatch reactors [5], tank reactors [6], in processes of semiconductor manufacturing [4, 9], in chemical plants [13], gearboxes [12], wind turbines [14] and others.

In this work the fault detection problem is addressed using time series that correspond to the behavior of heating zones at a chemical reactor of a Pilot Plant which is situated at the Chemical Process & Energy Resources Institute (CPERI) of CERTH. The tested time series are related to the internal thermocouples situated on several heating zones of the reactor. During a chemical experiment, where its evolution is normal, tested time series have nonlinear trend. We define as incident the time point that the stability of the time series changes and is followed by a continuous and significant decrease of temperature, meaning that linear trend is changed.

This work implements some of the most popular classification algorithms and techniques on the problem of detection of abnormal behavior in thermocouples of the chemical reactor. In particular, we compare the performance between Support Vector Machines and Decision Trees, Naive-Bayes and Logistic Regression. Moreover, we apply Adaptive Boosting (AdaBoost) algorithm only on supervised learning algorithms (Support Vector Machines and Decision Trees) because Naive-Bayes and Logistic Regression have lack of free parameters, a fact that implies that the application of them as the main classifier on the same dataset a number of times will always provide the same outcome. These classifiers are evaluated using Monte-Carlo simulations for different values of their internal parameters and simulation results are assessed with precision, recall, accuracy and f-measure. The dataset is experimental and has been obtained from the aforementioned chemical reactor.

The remainder of this paper is organized as follows. In Sect. 2, we give a short presentation of machine learning techniques that used in this work, the AdaBoost algorithm and the evaluation measures are given in Sect. 3, the simulation setup and simulation results are given in Sects. 4 and 5 are the conclusions.

2 Classification Methods – Machine Learning Algorithms

In this section, we briefly describe the aforementioned machine learning techniques and AdaBoost algorithm.

2.1 Support Vector Machines (SVM)

Support Vector Machines (SVMs) classifier is one of the most convenient and widespread classification and regression algorithm and it is first proposed by Boser, Guyon and Vapnik in 1992 [1]. SVM is a machine learning technique based on risk minimization. The main objective of SVM is to construct a hyperplane as a decision

boundary as the maximum margin between classified classes based on Kernel functions. Several kernel functions have been deployed so as to improve the predictive performance of the SVM. In our work, we apply two Kernel functions: Polynomial and Radial Basis Function, denoted hereafter as SVM-POLY and SVM-RBF, respectively.

2.1.1 Radial Basis Function (RBF) Kernel

The SVM-RBF case relies on the Gaussian Radial Basis function kernel with its form given by: $K(x, y) = \exp(-\gamma\|x - y\|^2)$, where $\left\|x - y^2\right\|$ is the Euclidean distance between the feature vectors x and y and $\gamma = \frac{1}{2\sigma^2}$ is a positive constant with σ to be a free parameter. Along with σ, RBF kernel has another free parameter, constant C.

2.1.2 Polynomial Function (POLY) Kernel

The SVM-POLY case relies on the Polynomial function kernel. Its form is given by: $K(x, y) = [x^T y + \theta]^p$, where p is the degree of the polynomial and θ is a free parameter that usually takes its values form integer space, although $\theta = 1$ is preferable as it avoids Hessian matrix to become zero. As in RBF, a free parameter C is defined.

2.2 Naive-Bayes (NB)

Naive-Bayes, denoted hereafter as NB, is a supervised learning algorithms and it's a very simple probabilistic model, which assigns conditional probabilities based on Bayes' theorem with the naive assumption of strong independence between the features. This assumption, reduce significantly the number of parameters to be estimated. However its simplicity and effectiveness in many problems, makes it a very competitive method.

2.3 Logistic Regression (LR)

Logistic Regression (or Logit Regression), denoted hereafter as LR, is type of regression where a response variable is related to a set of explanatory independent variables, which can be discrete and/or continuous. Generally, in one-class classification the response variable is binary or dichotomous (Binary Logistic Regression) i.e. it only contains data coded as 1 (True) or 0 (False). This algorithm can achieve good results, which in our case are comparable to the ones of Naive-Bayes.

2.4 Decision Trees (DT)

Decision Tree learning, denoted hereafter as DT, is a technique for approximating discrete-valued functions, in which the learned function is represented by a decision tree (or Classification Tree or Learning Tree). Decision trees can also be re-represented as sets of if-then rules so as to improve human readability. This tree-shaped structure is capable of generate classification rules for the tested dataset [7].

2.5 Random Forest (RF)

Random Forest, denoted hereafter as RF, also known as random decision forest, is an ensemble of decision trees and each decision tree is constructed by using a random subset of the training data, while the output class is the mode of the classes decided by each decision tree [2].

2.6 Adaptive Boosting (AdaBoost)

Adaptive Boosting or AdaBoost, denoted hereafter as AB, is a kind of ensemble learning technique where multiple learners, also called weak learners, are employed to build a center and stronger learning algorithm. The main goal of AdaBoost is to improve the performance of classification. AdaBoost works by choosing a weak learner and iteratively improving it by re-calculating its weights for the incorrectly classified cases in the training set. There are a lot of forms of the boosting algorithms [10, 15], but the most popular is AdaBoost, where the weak learners are decision trees [3]. In this work, we use the AdaBoost. *SAMME* with Decision Trees as weak learners.

3 Evaluation Measures – Boosting Algorithm

In order to assess our models, we use the measures of *precision*, *recall*, *accuracy* and *F-measure*, which are computed from the contents of a classic confusion matrix of the classification predictions. True positive and false positive cases are denoted as TP and FP, while true negative and false negative are denoted as TN and FN respectively. In order to fit the classification evaluation in incident detection problem, we will assign the classes *no-fault* and *fault*.

Precision measure, denoted hereafter in tables as P, is the ratio of predicted true positive cases to the sum of true positives and false positives. *Recall* measure, denoted hereafter in tables as R, is the proportion of the true positive cases to the sum of true positives and false negatives. *Accuracy* measure, denoted hereafter in tables as A, is the fraction of the total number of predictions that were correct. Precision or recall alone cannot describe a classifier's efficiency. That's why *F-measure,* denoted hereafter in tables as F-M, is introduced as a combination of these two metrics. It is defined as twice the harmonic mean of precision and recall and is the metric we will be most referring to.

A value closer to one, means better combined precision and recall of the classifier, whereas lower values imply worst accuracy or precision or both.

Following, a brief presentation of AdaBoost. *SAMME* algorithm is given. For a training set $TS_n = [(x_1, y_1), \ldots, (x_n, y_n)]$ where $y_i, i = 1, \ldots, n$ the classification labels, the observation weights $w_{learner}(i)$ for the weak learners are initialized as $w_{learner}(i) = \frac{1}{n}$. These weights are recomputed according to classifiers achievements. Iteratively, for $learner = 1, \ldots, k$, a weak learner $T^{(learner)}(x)$ is training of the initial training set in order to minimize the error:

$$err^{(learner)} = \frac{E_{learner}}{\sum_{i=1}^{n} w_{learner}(i)}, \tag{1}$$

$$E_{learner} = \sum_{i=1}^{n} w_{learner}(i) I(T^{(learner)}(x_i) \neq y_i), \tag{2}$$

where I is the indicator function, equal to one when the argument is true and zero otherwise. After *learner* iterations the weights are initial updated by the following function:

$$w_{learner+1}(i) = w_{learner}(i) \exp(a_{learner} I(T^{(learner)}(x_i) \neq y_i), \tag{3}$$

where $a_{learner} = log\left(\frac{1-err^{(learner)}}{err^{(learner)}}\right) + \log(K-1)$, where K denotes the number of classes (in our case $K = 2$). After the initial updates the weights are re-normalized. The final strong classifier is

$$T^{(final)}(x) = \underset{j \in y_i}{argmax} \sum_{learner=1}^{k} a_{learner} I(T^{(learner)}(x_i) = j), \tag{4}$$

4 Setup of the Fault Detection Analysis Method

In order to select the classifier with the best predictive performance on fault detection for the industrial process into consideration, some preliminary steps were applied such as data pre-processing, class labeling (*no-fault*, *fault*) and a decision about the simulation parameters will be used for each classifier. This is an initial approach relying on analysis of acceptable value deviations that signify potential faults in the field of process systems.

4.1 Data Pre-processing

The aim of the proposed technique is to detect, as early as possible, the starting point of a decrease on temperature time series. In this work, we evaluate the predictive performance of a tested classifier in three time series, denoted here after as TS1, TS2 and TS3 (see Figs. 1, 2 and 3, respectively). The initial time series are transformed based on the classification scenario we face, as described below.

In the case of TS1, Fig. 1a presents the sequence of values of a thermocouple before an upcoming fault. In the beginning of the process, the temperature of the particle ranges between the mean working temperature. After some time, the temperature drastically drops below 700°, which indicates a severe malfunction. Thus, from the initial time series, i.e. TS1 (see Fig. 1a), only the time intervals that fit to the incident definition (stability of the time series changes and is followed by a continuous and significant decrease) are used as input for training (see Fig. 1b). Thus, all the time intervals of the initial time series that do not fit to the incident detection scenario have not taken into account for the training process.

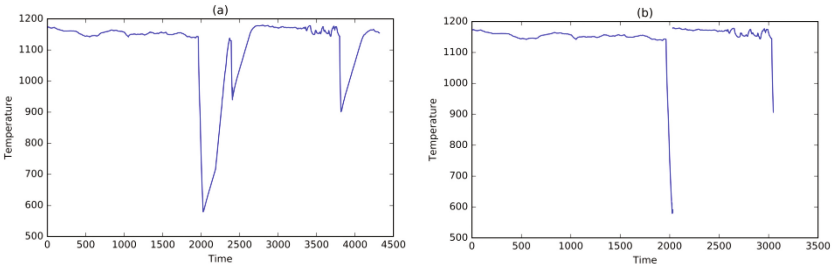


Fig. 1. (a) The initial time series TS1 and (b) transformed time series T-TS1 used as input the custom labeling and the training of predictive models.

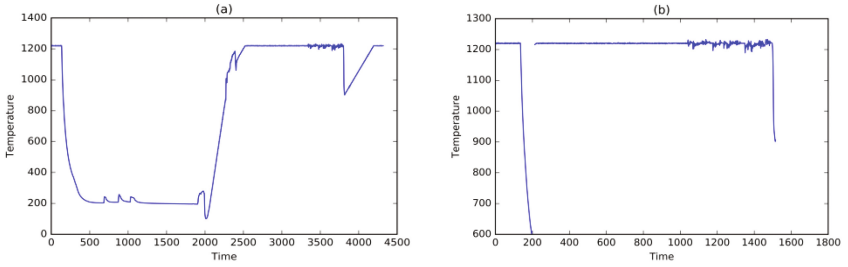


Fig. 2. (a) The initial time series TS2 and (b) transformed time series T-TS2 used as input the custom labeling and the training of predictive models.

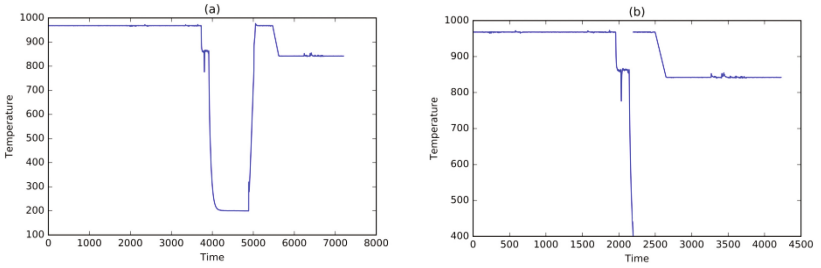


Fig. 3. (a) The initial time series TS3 and (b) transformed time series T-TS3 used as input the custom labeling and the training of predictive models.

As a result, the transformed TS1, denoted hereafter as T-TS1, matches closely the problem we face, namely the detection of the abnormal behaviour of a heating zone during nominal operating conditions. Subsequently, the values of the transformed time series T-TS1 are used for the decision of classes (*no-fault*, *fault*) due to the lack of ground truth and as input for the training and the testing procedure. The custom labelling method used for the decision of classes is described in Sect. 4.2.

4.2 Labeling

The rule we propose for labeling the classes (*no-fault*, *fault*) of the transformed time series is the following:

$$|AT_i - DT_i|_{thermocouple} = \begin{cases} no{-}fault\ if \leq threshold \\ fault\ \ if\ > threshold \end{cases}, \tag{5}$$

where AT_i is the *actual temperature* and DT_i is the *desired temperature* acquired by experiment configuration. The threshold varies as: $threshold = (20, 50, 100)$ so as to examine and evaluate classifiers predictive performance in different and more stressed conditions. Although this is a straightforward way of defining thresholds, the main benefit of using machine-learning techniques, is that they can adapt to the online changes of these thresholds without changing the rest of the structure of the problem. There is a multitude of heating zones, that produce the respective data, in a process system and the threshold is adjusted in relation to the operating conditions. The limits are defined at the automation system of the process and subsequently the labeling occurs accordingly. Also when a typical case of a pilot scale process system contains more than 300 thermocouples, the respective update to the "fault-no fault" case is performed is relation to the maximum span of operating error. The aforementioned cases are only an indicative case to test the validity and response of the proposed methods.

4.3 Monte Carlo Simulation – Cross-Validation

We generate 100 Monte-Carlo iterations (realizations) for different parameter scenarios of every classifier. For a every iterations we use cross-validation where the training and the testing datasets are chosen randomly in a percent of 70% and 30%, respectively. The 100-fold cross validation used here aims to eliminate the bias. Below we give a brief presentation of the parameters used in each classifier.

4.3.1 Support Vector Machines

For the RBF kernel (see Sect. 2.1.1), γ varies as $\gamma = 0.01, 0.1, 1, 10$ for TS1, TS2 and TS3. Constant C varies as $C = 1, 10, 100, 1000, 10000$ for TS1 and $C = 100, 1000, 10000, 100000, 1000000$ for TS2 and TS3. For the polynomial kernel (see Sect. 2.1.2), constant $\theta = 0$, the polynomial degree varies as $p = 2, 3, 4, 5$ and constant C varies as $C = 0.5, 1, 1.5, 2, 2.5, 10$ for TS1 and $C = 0.5, 1, 1.5, 2, 2.5$ for TS2 and TS3.

4.3.2 Decision Trees - Random Forests

The Decision Trees and Random Forest techniques are implemented in *Python* with *scikit-learn* library, thus for Decision Trees we use the default optimized version of the CART algorithm. As for Random Forest we use the default 100 estimators, which refers to 100 decision trees.

4.3.3 Naive Bayes - Logistic Regression

Naive Bayes and Logistic Regression models are implemented in Python with *scikit-learn* library, thus for Naïve Bayes we use the Gaussian algorithm for classification and for Logistic Regression we use the default configuration.

4.3.4 Adaptive Boosting Algorithm

AdaBoost algorithm is implemented in Python with *scikit-learn* library and utilizes the AdaBoost.*SAMME* algorithm. As week classifier we have chosen Decision Trees.

4.4 Simulation Results

Tables 1 and 2 present the simulation results of SVM-RBF and SVM-POLY classifiers, respectively, for TS1. For the RBF case of SVM, the classifier achieved its highest values on all evaluation measurers when $C = 10000$ and for all γ (see highlighted values in Table 1). Specifically, when the threshold is set at 50, precision reaches 100.00%, recall 92.99%, accuracy 98.81% and F-measure 96.35% on average. For the POLY case of SVM, recall achieves highest performance when $p = 5$. For the case where the threshold is set at 100, recall, accuracy and F-measure have greater values compared to other thresholds (see highlighted values in Table 2). More specifically, accuracy reaches 98.66% and F-measure 95.91% on average, when $p = 5$ and $\gamma = 1$.

Simulation results of Naive Bayes, Logistic regression, Decision Trees, Random Forest and AdaBoost for threshold 50 and 100 are given in Table 3. Among them, the highest performance on F-measure has the AdaBoost approach when the threshold is 100 (95.86% on average) (see Table 3). Overall, for TS1, SVM (RBF and POLY) and AB achieves accuracy over 98.5% and F-measure over 95.5%.

The simulation results for TS2 (not shown here) showed that the SVM-RBF classifier achieved its highest values on all evaluation measurers when $C = 1000000$ and for $\gamma = 10$. More specifically, when the threshold is set at 20, precision, accuracy and F-measure are greater than 99% on average. For the SVM-POLY case, when the threshold is set at 20, $p = 3$ and $\gamma = 2$, the classifier achieves its highest performance (F-measure is 92.29% on average). The simulation results of Naive Bayes, Logistic regression, Decision Trees, Random Forest and AdaBoost, show that the AdaBoost approach has the highest performance on F-measure when threshold is set at 20 (98.98% on average). Overall, for TS2, SVM-RBF and AB achieve accuracy over 98.5% and F-measure over 98%.

The simulation results for TS3 (not shown here) showed that the SVM-RBF classifier achieved its highest values on all evaluation measurers when $C = 1000000$ and for $\gamma = 10$. More specifically, when the threshold is set at 100, recall, accuracy and F-measure are all greater than 96% on average (precision is 96.70%, recall is 98.81%, accuracy is 99.22% and F-measure is 97.74% on average). For SVM-POLY, besides precision, all other evaluation measures are significantly low compared to other classifiers and time series cases. Simulation results of Naive Bayes, Logistic regression, Decision Trees, Random Forest and AdaBoost show that the highest performance on recall, accuracy and F-measure has the AdaBoost approach when threshold is set at 100 (recall is 98.44%, accuracy is 99.31% and F-measure is 97.97% on average). Overall, for TS3, SVM-RBF has grater predictive performance compared to the other classifiers.

Table 1. Simulation results of SVM-RBF for P, R, A and F-M (estimated averages) for 100 Monte Carlo iterations (highest values in bold). Tested time series: TS1.

		20				50				100			
C	γ	P	R	A	F-M	P	R	A	F-M	P	R	A	F-M
100	0.01	**100.00**	85.37	97.42	92.08	**100.00**	87.48	97.87	93.30	**100.00**	89.06	98.17	94.19
100	0.1	**100.00**	85.70	97.48	92.27	**100.00**	88.64	98.07	93.96	**100.00**	90.37	98.39	94.92
100	1	**100.00**	86.84	97.67	92.93	**100.00**	89.09	98.15	94.21	**100.00**	90.62	98.43	95.06
100	10	**100.00**	90.41	98.31	94.94	**100.00**	90.96	98.47	95.24	**100.00**	91.62	98.60	95.61
1000	0.01	**100.00**	86.10	97.55	92.51	**100.00**	88.73	98.09	94.01	**100.00**	90.42	98.40	94.95
1000	0.1	**100.00**	86.03	97.53	92.46	**100.00**	88.31	98.02	93.77	**100.00**	90.44	98.40	94.96
1000	1	**100.00**	86.99	97.70	93.02	**100.00**	89.15	98.16	94.24	**100.00**	90.80	98.46	95.16
1000	10	**100.00**	90.95	98.40	95.24	**100.00**	**92.99**	**98.81**	**96.35**	99.91	91.93	98.64	95.74
10000	0.01	**100.00**	85.81	97.50	92.34	**100.00**	88.90	98.12	94.10	**100.00**	90.71	98.45	95.11
10000	0.1	**100.00**	86.90	97.68	92.97	**100.00**	89.16	98.16	94.25	**100.00**	90.74	98.45	95.13
10000	1	**100.00**	87.72	97.83	93.44	**100.00**	89.77	98.27	94.59	**100.00**	91.05	98.50	95.30
10000	10	**100.00**	**92.73**	**98.72**	**96.21**	**100.00**	92.93	98.80	96.32	99.63	**92.24**	**98.64**	**95.78**

Table 2. Simulation results (in %) of SVM-POLY for P,R, A and F-M (estimated averages) for 100 Monte Carlo iterations (highest values in bold). Tested time series: TS1.

		20				50				100			
p	γ	P	R	A	F-M	P	R	A	F-M	P	R	A	F-M
3	0.5	90.94	90.16	96.47	90.19	99.03	90.47	98.19	94.48	99.95	91.50	98.54	95.53
3	1	**100.00**	86.50	97.60	92.74	**100.00**	88.84	98.10	94.07	**100.00**	90.17	98.32	94.81
3	1.5	**100.00**	86.44	97.59	92.70	**100.00**	88.99	98.12	94.15	**100.00**	90.40	98.36	94.94
3	2	**100.00**	86.46	97.59	92.71	**100.00**	89.08	98.14	94.20	**100.00**	90.57	98.38	95.03
3	2.5	**100.00**	86.52	97.60	92.75	**100.00**	89.14	98.15	94.24	**100.00**	90.69	98.40	95.10
3	10	**100.00**	86.51	97.60	92.74	**100.00**	89.28	98.17	94.32	**100.00**	90.81	98.43	95.17
4	0.5	68.10	94.78	91.17	79.20	67.35	97.21	91.49	79.52	67.26	98.47	91.55	79.88
4	1	**100.00**	87.55	97.79	93.34	**100.00**	89.83	98.27	94.62	**100.00**	91.07	98.47	95.31
4	1.5	**100.00**	87.26	97.74	93.17	**100.00**	89.59	98.22	94.49	**100.00**	90.89	98.44	95.21
4	2	**100.00**	87.20	97.73	93.14	**100.00**	89.63	98.23	94.51	**100.00**	90.95	98.45	95.24
4	2.5	**100.00**	87.19	97.72	93.13	**100.00**	89.64	98.23	94.51	**100.00**	91.01	98.46	95.28
4	10	**100.00**	87.15	97.72	93.11	**100.00**	89.62	98.23	94.51	**100.00**	91.06	98.47	95.31
5	0.5	68.21	**95.26**	91.25	79.45	67.48	**97.79**	91.59	79.81	67.43	**99.23**	91.67	80.25
5	1	96.89	89.05	97.54	92.75	99.89	90.83	**98.42**	**95.12**	**100.00**	92.17	**98.66**	**95.91**
5	1.5	**100.00**	87.94	**97.86**	**93.56**	**100.00**	90.11	98.31	94.78	**100.00**	91.29	98.51	95.43
5	2	**100.00**	87.88	97.85	93.53	**100.00**	90.04	98.30	94.74	**100.00**	91.30	98.51	95.44
5	2.5	**100.00**	87.86	97.84	93.51	**100.00**	90.04	98.30	94.74	**100.00**	91.32	98.51	95.45
5	10	**100.00**	87.85	97.84	93.51	**100.00**	90.03	98.30	94.73	**100.00**	91.33	98.51	95.45

Table 3. Simulation results (in %) of NB, LR, DT, RF and AB for P, R, A and F-M (estimated averages) for 100 Monte Carlo iterations (highest values in bold). Tested time series: TS1.

Threshold	Metric	NB	LR	DT	RF	AB
50	P	83.24	100.00	94.09	93.92	98.12
	R	94.53	86.04	93.62	94.12	93.64
	A	95.81	97.60	97.88	97.96	98.57
	F-M	88.47	92.47	93.82	93.97	95.81
100	P	84.57	100.00	93.85	93.57	98.27
	R	**95.68**	87.04	93.90	93.84	93.61
	A	96.28	97.80	97.92	97.89	**98.63**
	F-M	89.71	93.05	93.83	93.66	**95.86**

5 Conclusions

In this work, seven of the most powerful and state of the art machine learning algorithms were tested using a set of industrial time series from a chemical reactor of CERTH/CPERI. The objective is to be able to detect potential faults and abnormalities which are caused during the nominal operation of the pilot plant. A custom labeling rule was applied using available data in order to acquire the ground truth, which is fed into the classifications techniques. It is observed that when the labeling rule threshold is set at 20, an overall significant predictive performance is achieved. The evaluation of the performed experimental dataset analysis concluded that SVM-RBF and AdaBoost techniques (F-measure is over 97% and 96% on average, respectively) provide better results for several tested thresholds, compared to the other algorithms for tested cases. Therefore, they can be used for the accurate detection of abnormal incidents, such as heating zone failures, occurring at chemical reactors.

With our approach, we manage to bypass the human decision of the proper threshold selection in order to distinguish between *no-fault* and *fault* condition on the tested time series, by training predictive models to decide for fault condition, accurately and effectively. The proposed work will be used as the basis for further analysis of the identification of the abnormal behavior of measured variables at process systems in order to further exploit the capabilities that machine learning to the problem of early detection and notification of unplanned events.

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Intelligent Systems of Forecasting the Failure of Machinery Park and Supporting Fulfilment of Orders of Spare Parts

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Abstract. The article presents the possibility of forecasting failures of machinery park using IIOT (Industrial Internet of Things) that supports the range of activities concerning the collection of data using solutions that, by means of time series analysis and dynamic adjustment of the individual models, will allow to generate prognosis for failures of machinery park. Moreover, the use of the generated prognosis to control the storage of replacement parts and to support the area of orders fulfilment was proposed.

Keywords: Predictive modelling · Expert systems · Predictive maintenance

1 Among the Source Development Factors Contributing to the Definition of the Currently Developing Concept of the Industry 4.0 One May Note

Continuous pursuit of the world of technology to create newer and newer solutions to improve the actions that take place in the industry [1], to achieve increased operational efficiency but, above all, to relieve human from his work, has become the cause of ground breaking changes known as industrial revolution. Thus, over the past two centuries, evolution of industrial solutions has taken place, of which the most advanced elements once were water and steam drives, while today, as part of the fourth industrial revolution, cyber-physical systems or the Internet of Things and Services are used.

The target solution formed by the concept of Industry 4.0 is to create smart factories, in which cyber-physical systems for monitoring physical processes will provide relevant information thus enabling decentralized decision-making.

One of the areas that are rapidly developed and supported in the smart factories through the use of modern technology is the Maintenance Department. Among the assumptions about its mode of action, the use of tools containing algorithms predicting failures, remote support systems and integration with machines are indicated. It will be possible for obtaining by [3]:

– implementation of modern manufacturing systems (through visualization and monitoring of the production),

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– the use of cloud computing (through storage and processing of data in the clouds, the use of analytical systems and spreadsheets in the cloud data storage),
– analysis of data coming from production (the use of advanced decision-making algorithms for real-time analysis),
– the use of smart sensors (for obtaining wireless transmission of data),
– the use of cyber-physical systems (ones that link the machines together to form a team with a global reach, as well as those being autonomous decision-making systems).

Despite the risks associated with improper operation of the monitoring systems for machine operation or for the analytical and decision-making systems, as well as the issue of information security, the introduction of automation to the analysis and interpretation of data becomes an unavoidable reality. The entry into realities of the functioning of IIoT enterprises, as well as easier access to the systems for monitoring operation of the machines has significant influence on it. Moreover, management staff becomes aware that the issue of automatic data collection may constitute the historical documentation of the status of the machinery park [4], but having huge data sets at disposal, the excess of which does not allow one to perform the analysis, requires implementation of the solutions for decision-making support.

2 Internet of Things and Cyber-Physical Systems in the Industrial Plants

The Internet of Things (IoT) is a concept according to which every object in the real world can automatically connect to the network and communicate with any other module connected to it [5]. The term was first used in 1999 by Kevin Ashton in his presentation on the transmission of data via the Internet with the use of radio-frequency identification (RFID) to control the supply chain in the enterprise Procter and Gamble [6]. According to the Cisco Internet Business Solutions Group, as the beginning of the Internet of Things one should consider the point at which the number of devices connected to the network exceeded the number of inhabitants of the Earth, which dates back to the turn of 2008 and 2009 [7]. The dynamic development of the IoT associated with increasing technological capabilities contributed to the increase of the range of application of this concept.

According to the classification adopted by O. Vermesan and P. Friess IoT can be used in the areas of smart environment, water management, transport, energy, cities, housing, life, health and industry [8]. Of course, these areas do not limit the potential of the IoT for wider use in other areas, especially taking into account the dynamics of its development.

Although the Internet of Things is a concept which was already discussed in the previous century, the year 2016 can be regarded as the moment of its implementation into industrial solutions. The interconnection of the machines in the production plants gave birth to IIoT (Industry Internet of Things), which is based on the same principles

as IoT. Improving communication between the machines, as well as conducting autonomous action based on the exchange of information in real time has become an opportunity to exceed, by the company, the so far achieved level of efficiency and process flexibility.

Hand in hand with the enthusiasm about the opportunities created by the implementation of IoT to the industrial plants, goes the prospect of risks associated with the operation of the industry network, among which one may indicate connection failure, failure of devices, improper configuration, breach of security [9].

As a result, enterprises can suffer the consequences arising from the loss of security or from production losses. Thus the prospect of dynamic market development of IIoT creates the need for protection against cybercrime.

Referring to the Internet of Things in the context of Industry 4.0 it is scarcely possible not to mention cyber-physical systems which, together with IoT, forms two essential components of its generation [10]. Cyber-physical systems (CPS) are systems in which by means of sensors and actuators the physical world connects with the virtual one where the information processing, based on a mathematical representation of physical objects known as Digital Twin, takes place [2]. The implemented mathematical model uses data from the sensors installed on the device. CPS, like IoT, has a wide range of usage the example of which may be its use in, among others, medicine (e.g. to monitor patient's vital signs), energy sector (e.g. to control the state of power grids), transport (air, car or rail), the industry (e.g. to monitor the state of the machinery park).

In the case of usage of the CPS solutions in the industry, the name cyber-physical production systems (CPPS) is used. They are defined as extensive production systems, whose purpose is to collect, analyse and store information on processes and technical infrastructure of a company. Information can be exchanged via communication interfaces, and may also be transmitted globally to those responsible for the operation or service. Easier access to data should be guaranteed by BYOD program (Bring Your Own Device), which involves the performance of duties on employees' own devices. As a result there will be a popularization of e-maintenance and m-maintenance class solutions.

3 Algorithm of Prediction of Failure with the Use of CPPS and IIoT

Futuristic technologies, which more and more easily enter the reality of the operation of production plants, [11] encourage the creation of new solutions that can support the human factor in the analytical and decision-making area. The Maintenance Department is the department in which the correct definition and implementation of IIoT and CPPS will increase the effectiveness of these actions.

Disposing of the noted technologies by MD personnel is related to the necessity of a change of realized maintenance strategy into predictive one. Adequately adjusted predictive model or models so that the moment in which failure may occur was indicated as precisely as possible constitutes a challenge. Thanks to this, it will be possible to avoid certain types of failures, as well as incorporating the forecasted failures within the schedule of works of Maintenance Department and adequate management of storage of spare parts. So far, the literature has described predicting failures during the use of

various predicting methods, however, none of them was based on intelligent selection of adequate model, depending on the change of character of the monitored parameters.

Carrying out activities in accordance with the Predictive Maintenance requires the application of appropriate mathematical models, which will allow to gain knowledge about the occurring development phenomena or mode of action of objects under study. Analysis of literature allowed to identify mathematical models applied so far, used for predicting failures both of machines and their components.

Huang, Xi, Li, Liu, Qiu and Lee undertook the research on the use of self-organizing map and neural network using an algorithm of back propagation (back propagation neural network methods) to predict failure of ball bearings. The obtained results were significantly better than those obtained so far on the rating life [12]. Also Zhao, Chen and Li were interested in the bearings failure rate and suggested the use of neuro-fuzzy model to predict damage [13]. On the other hand, Lahyani, Venet, Grellet and Viverge focused on predicting the failure of electrolytic capacitors during the operation of switched-mode power supplies [14]. Salfner and Malek in their publications presented the possibility of using hidden semi-Markov models for effective online failure prediction for the telecommunications system [15]. Whereas Tabaszewski and Cempel proposed method of Deng's grey systems for predicting the state of machines using vibration symptoms [16]. Srivastava and Mondal focused on the possibility to use modified failure mode effect and criticality analysis technique (Mod-FMECA) to predict the failure of the coal mill, and the positive predicting results that were achieved encouraged the authors to expand the possibilities of using the developed methods of prediction to other industrial equipment. Legat, Mosna, Ales and Jurca in their work described a method of determining an optimal break time for periodic preventive maintenance, and optimal diagnostic parameter for predictive maintenance. In the study they used the three-parameter Weibull distribution, proposing the use of the method for typical engineered facilities [18]. Sobaszek on the other hand introduced the concept of predicting the failure of the machinery park based on the survival analysis [19].

The indicated examples present only a small part of the conducted research on the use of prediction methods in forecasting the failure and intend to show the comprehensive use of various prediction models. Research results obtained by the authors confirm the benefits of the application of prediction to infer about further development of phenomena and dispose to continue research on the use of other mathematical models for forecasting in accordance with the predictive maintenance strategy [20] according to technical status which will be able to intelligently adjust to the values of monitored residual processes changing in real time. Such an approach is designated to reflect changes taking placed by mathematical modelling and generating the forecast of date of failure which will most likely cover the real-time date. Furthermore, including predicting of failures of both IIoT and CPPS gives a chance of effective elaboration of solutions which might form the basis of intelligent tools as expert systems constituting human support at decision-making level.

The authors of this article propose application of an algorithm that forecasts failure frequency of machinery park and uses time series models, which, due to the possibility of real time processing of residual process values, as well as implemented stationarity tests and forecast errors, will generate information on the date of failure. Additionally,

an intelligent algorithm will facilitate inventory controls of replacement parts, and, in case of their absence, it will make an inquiry about the possible delivery time and costs incurred. Such type of solution has not so far been proposed and it fulfils the expectations placed in the context of a strive for obtaining an intelligent company, ensuring dynamic support of predicting and decision-,making process in the scope of ordering spare parts.

Figure 1 presents the concept of the proposed algorithm of decision support in the maintenance system, which is to represent a new approach to forecasting failures, a system of setting the terms of repairs, as well as ordering replacement parts.

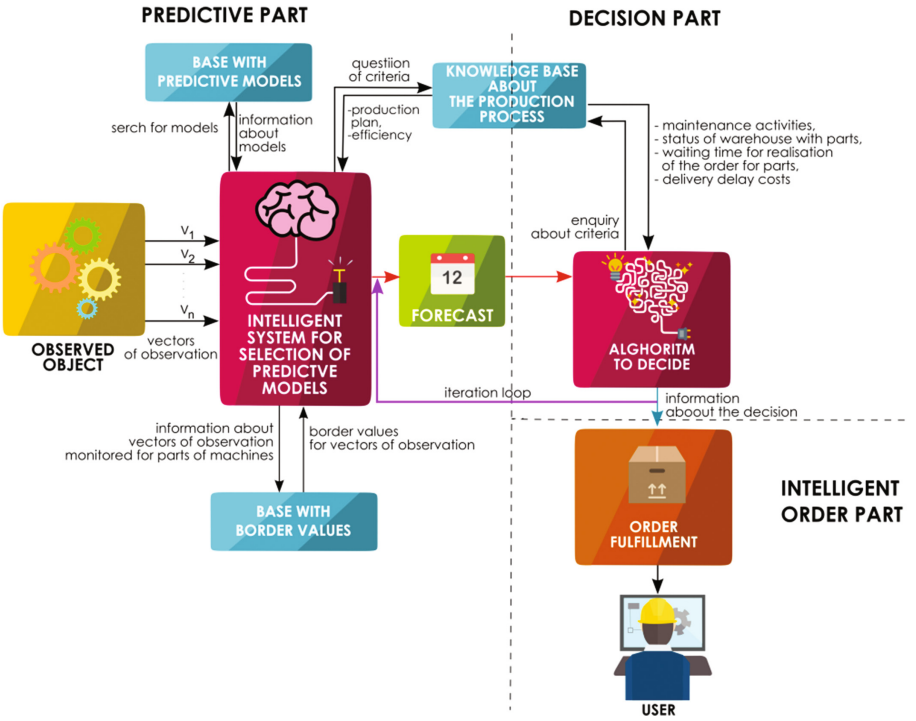


Fig. 1. Concept of the prediction and decision model supporting actions taken by maintenance services [21]

Information from the system that monitors working of the observed object (such as readings of temperature, vibrations, or noise intensity), marked in the drawing as the observation vectors, are received by the *intelligent system of prediction method selection.* On the basis of a set of values for the studied phenomenon (factor) the intelligent system, by using the appropriate information criteria, would select the appropriate mathematical model (Linear Regression, ARMA, ARIMA, ARCH, HARCH, TARCH, GARCH, EGARCH, or RGARCH).

The optimal model is projected in this way, understood as model that enables receiving the most accurate forecast. It is selected with the use of a ranking method as model that receives most of the indications of information and predictive criteria.

Moreover, it is important to link the system with the base of limit values for observation vectors, due to which the safe size level of the observation vectors for the monitored machine parts will be determined, exceeding of which carries the risk of failure. For the conduct of the forecast, in addition to the measurement of key residual processes, information from the database of the production process relating to the plan, schedule, and productivity will be used. This type of approach will help to clarify the forecast by making it dependent on the operating conditions of the machinery. Production stops, as well as planned productivity losses, contribute to delaying the possibility of potential failure, which in turn translates into the extension of the time between maintenance works carried out by Maintenance Service.

The result of the working of the cyber-physical system reflecting the work of the machine park will be a time interval in which there is a risk of failure. This information will be passed to decisive part, that consists of the decision-making algorithm and database of production process providing information about the activities carried out by MS (i.e. scheduling maintenance and repair works). In this way, on the basis on indications of cyber-physical system and taking additionally into account non-technical aspects, the narrowed optimal time period will be generated, in which it becomes necessary to perform maintenance works. The attained forecast will be used at a later stage to support the decision-making process from the scope of the ordering machine parts. The role that is played by the decision-making system implementing orders of spare parts was described more extensively by Wang, Zhao, Cheng, and Yang [22].

Information about the forecast date of failure is passed on to the order processing system. If the number of days to failure is equal to the number of days exceeding of which makes it necessary to collect offers for the purchase of replacement parts, then in the first instance the inquiry about the availability of a particular part is directed to the storehouse. In case it is not available there, a demand for it is sent automatically to companies that provide parts, information of which is collected in the system. Within a specified period of time offers containing information about prices, discounts, delivery time of a part, or the proposed warranty period are gathered. On the basis of specific criteria the optimal offer is selected, the selection is authorized by the operator of the system, who is entitled to make decisions about purchasing. After the acceptance, a part is ordered.

4 Example Application of an Algorithm

In fashioning trends occurring in physical, technical, and economic phenomena, the class of the examined time series Trend Stationary or Difference Stationary must be first designated. Using the ADF test (Augmented Dickey-Fuller test [23]) it is possible to designate the degree of integration of time series $\{x_t\}_{1\le t\le N}$ or the polynomial degree that approximates the deterministic part of this series. When the elements of the series are integrated in degree $r \ge 0$, then the time series $\{\Delta^r x_t\}_{r+1\le t\le N}$ is identified with models of the ARMA class $ARMA(p, q)$,where Δ is the difference operator $\Delta^{k+1}x_t = \Delta^k x_t - \Delta^k x_{t-1}$

for $k \in \mathrm{N}$. The elements of the series $\{x_t\}_{1 \le t \le N}$ are modelled by *ARIMA*(p, r, q) model, $p, r, q \in \mathrm{N}$ and fulfil the equation

$$\Delta^r x_t = \alpha_0 + \alpha_1 \Delta^r x_{t-1} + \ldots + \alpha_p \Delta^r x_{t-p} + \omega_t - \theta_1 \omega_{t-1} - \ldots \theta_q \omega_{t-q}, \tag{1}$$

where $\{\omega_t\}_{t \in \mathrm{N}}$ is a sequence of independent identically random variables with normal distribution $N(0, \sigma^2)$, where $\alpha_0, \alpha_1, \ldots, \alpha_p, \theta_1, \ldots, \theta_q$ are the model parameters. The identification of a sequence with model *ARIMA*(p, r, q), $p, r, q \in \mathrm{N}$ is based both on the choice of autoregressive order $0 \le p \le p_{\max}$ and moving average order $0 \le q \le q_{\max}$ further to being based on the estimation of parameters of model (1). The highest values of the autoregressive orders $p_{\max}$ and of moving average $q_{\max}$ are determined by analysing the behaviour of PACF (Partial Auto Correlation Function) and ACF (Auto Correlation Function). For the final selection of the model Akaike information criterion (AIC) or Schwarz's Bayesian information criterion (BIC) are used most often.

The example of a DS series was presented below. The results come from a research station that implements accelerated process of pitting of steel rollers. Tests were conducted on a cylindrical sample of ŁH15 (PN) heat-treated steel. The roller was compressed by two discs – one of them was driven by electric motor and transmission belt. The speed of the sample was 27,000 RPM. The vibration acceleration was recorded on the body in which the roller was mounted [24].

In Fig. 2a the black curve represents realization of series $\{x_t\}_{1 \le t \le 30}$. The red straight line presents the value of critical level peak acceleration. Below, critical value was accepted $v_{crit} = 6.5$ m/s^2. Using the ADF test the integration degree $r = 1$ was determined.

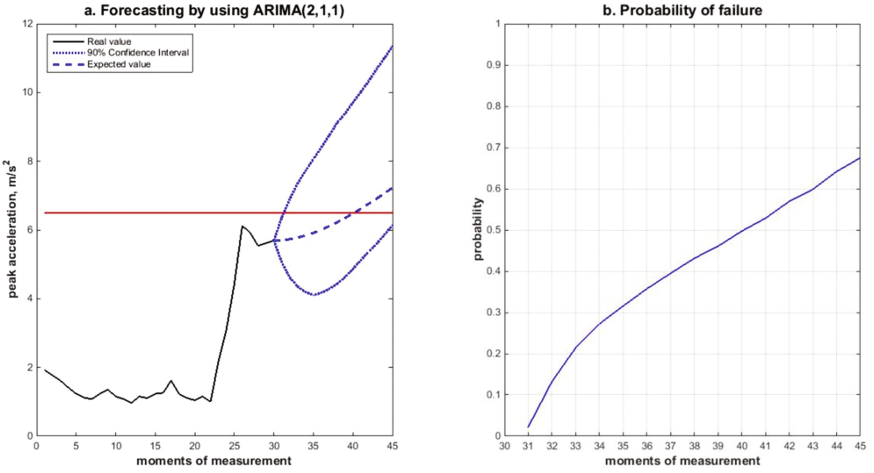


Fig. 2. Forecasting values of vibration acceleration in the band of approx. 16 kHz using (a) ARIMA model, (b) probability of reaching critical level.

As the series $\{x_t\}_{1 \le t \le 30}$ belongs to the DS class, models *ARIMA*(p, 1, q) were identified. While analysing AIC indicator, the elements of series $\{x_t\}_{1 \le t \le 30}$ should be shown by the model *ARIMA*(2, 1, 1) (AIC = 39.5478), i.e. the elements satisfy the equation

$$\Delta x_t = 0.0115 + 1.4027\Delta x_{t-1} - 0.4647\Delta x_{t-2} + \omega_t - 0.96\omega_{t-1}, \quad (2)$$

where $\{\omega_t\}_{t\in\mathrm{N}}$ is a sequence of independent identically random variables with normal distribution $N(0, 0.1602)$. In Fig. 2a the blue dashed curve represents the expected value the elements of this series by formula (2) for 15 consecutive periods. Using the Monte Carlo method also 90% confidence interval which on Fig. 2a is indicated by the blue dotted curves. Figure 2b presents probability of exceeding critical level $P(x_t > v_{crit})$ for moments $t = 31, 32,\ldots, 45$. Figure 2a shows that for moment $t = 40$ expected values of peak acceleration will exceed critical level, that is. $Ex_{40} > v_{crit}$. Also Fig. 2b shows that $P(x_{40} > v_{crit}) > 0.5$, thus with probability of at least 50% critical value will be exceeded in the moment $t = 40$. Combining prognostic part with supportive part of realization of orders for spare parts requires establishing values of probability of exceeding critical value, after reaching of which having a spare part by storehouse is required. Assuming that it amounts to 50% and falls on the 40th day of observation, then it would be advisable until then with adequate advance to start an algorithm supporting the order of spare parts. Date of launching of the algorithm ought to be set based on the so far deliveries of parts and estimated time for formalities related to gathering offers and realization of purchase. Assuming that normally waiting time for a given part amounts to approx. 7 days, then launching of algorithm would occur on the 33rd day of observation when this probability of occurrence of failure amounted to only 22%.

5 Summary and Conclusions

Due to the development of cyber-physical systems, as well as IIoT and deploying them to the enterprise it becomes necessary to consider improving the decision-making process through the development of expert systems. They are designed to support human decision-making based on information generated on the basis of the monitored parameters. Their functioning, in conjunction with the use of intelligent tools that respond dynamically to changes in the reliability of machinery, may become a guarantee of increased operational efficiency. It should however be emphasized that it should not be a stand-alone tool that excludes man from the final stage of decision-making. Instead, it should be a part of a developed CMMS system, the design of which should take into account the possibility of remote access of system end-users of laptops, tablets, fablets or smartphones (in line with e-maintenance [25] and m-maintenance concept [20]). The pursuit of Industry 4.0 to implement predictive maintenance solutions places additional requirements of appropriate selection of a mathematical model. The analysis of the literature has not shown previously developed solutions for the dynamic selection of the model, depending on the changing nature of the collected and processed data. Innovative recognition is therefore a failure prediction based on econometric models selected and determined based on the information criteria, as well as the forecast errors and error rates forecasts. Combining the predictive part with the part responsible for carrying out the orders of replacement parts of machines can replace men at the investigative stage in the case of the determination of stock in connection with the forecasted failure and at the stage of collecting information about the availability of parts from suppliers, as well as the proposed conditions of their purchase. Eliminating the risks of implementing

such a solution could be made by carrying out a risk analysis to determine the degree of impact of individual risk factors.

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SmartMaintenance - The Concept of Supporting the Exploitation Decision-Making Process in the Selected Technical Network System

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Abstract. The article presents the SmartMaintenance concept, as a basis for the development of intelligent solutions that support exploitation activities. On the background of the main guidelines of the SmartMaintenance concept, as well as taking the principle of an open architecture, there was described the main components of a computer system supporting exploitation decision-making process. The last part of the article is the SMOPE module, which has been developed by the author. SMOPE complying with the requirements of the SmartMaintenance concept, supports the realization of the exploitation decision-making process of the selected technical network system.

Keywords: SmartMaintenance · Exploitation decision-making process · Technical network system

1 Introduction

Enterprises that manage network technical systems, distribute media from the source to the recipients ensuring the required quantitative parameters (diverse needs of the recipients, in space and in time, for assumed perspective period of predicted operation of the network), as well as the required qualitative parameters (a need to adapt and maintain qualities of supplied media at a level exceeding the criterial) [5, 19].

Due to the specificity of the activity, network companies are often natural monopolists on the local markets, that might suggest that they are not interested in making changes and increasing their competitiveness [9]. The companies are subject of public control, and the price of supplied media is regulated. In order to satisfy the expectations of the recipients, network companies are obliged to activities aimed at ensuring a reliable supply of media, with high quality and at an acceptable. With a limited income, these companies manage huge resources, which include networks, buildings and engineering equipment. In conjunction with the limited funds, it causes a need for rationalization exploitation activities.

Therefore, core activities of network companies should be rationalization of the exploitation, which is considered in the sense of operate and maintenance. The operate

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activity is intended to ensure the organizational and economic possibilities of effective use of all components of the technical network system, for the delivery of media to end users with the assumed parameters of quantitative and qualitative. The maintenance activity is intended to ensure technical possibilities for an efficient functioning and an effective use of all components of the technical network system.

Network enterprises often take advantage of modern IT systems, which allow for gathering the data about objects, events, and exploitation processes. The main objective of the use of IT systems in the exploitation activities of the network companies should be supporting the exploitation decision-making process. It requires a look at the needs of the maintenance organization and possibilities of a computer software (including intelligent solutions), not only in terms of the procedural realization of typical routine work orders, but especially in the context of the analytical and decision-making requirements, in the short and long term.

Therefore, later in the article, results of the research on the development of the SmartMaintenance concept are presented. They are considered in the context of the specificity of enterprises managing technical network systems.

2 The Assumptions of the SmartMaintenance Concept

Technical network systems are the subject of dynamic development and implementation of innovative solutions, that also generate problems resulting from aging and the wear processes of components of the technical network systems, and hence, there appear exploitation events. Therefore, developed and implemented innovative and technologically advanced solutions must take into account the exploitation activities.

The proposed concept, named by the author SmartMaintenance, includes the development of models, methods and tools adapted to requirements of exploiting of technical network systems and supporting the maintenance activities. In particular, SmartMaintenance is going to shape and support the realization of technical, organizational and economic tasks, to ensure rationality of the exploitation policy, and to achieve the intended functionality of smart technical solutions at the assumed level.

The developed concept represents a model consisting of the three task modules, differing in the scope of the collected data and the role and share of the particular components in the overall project. Schematic diagram of the SmartMaintenance concept is illustrated in Fig. 1. In this regard, it should be distinguished:

1. The module of identification and description of exploitation events, which is implemented in the operate field, and includes collecting and processing data and information about functional features of various parts of the technical network system, for the purpose of forming model sets of exploitation events.
2. The module of realization of maintenance tasks, which includes collecting and processing data and information about features of maintenance works, for the purpose of forming model sets of factors for assessment of the exploitation policy.
3. The module of realization of exploitation decision-making process, which includes collecting and processing data and information about factors of the exploitation

policy in the context of the defined environment features, for the purpose of selection and assessment of the decision path.

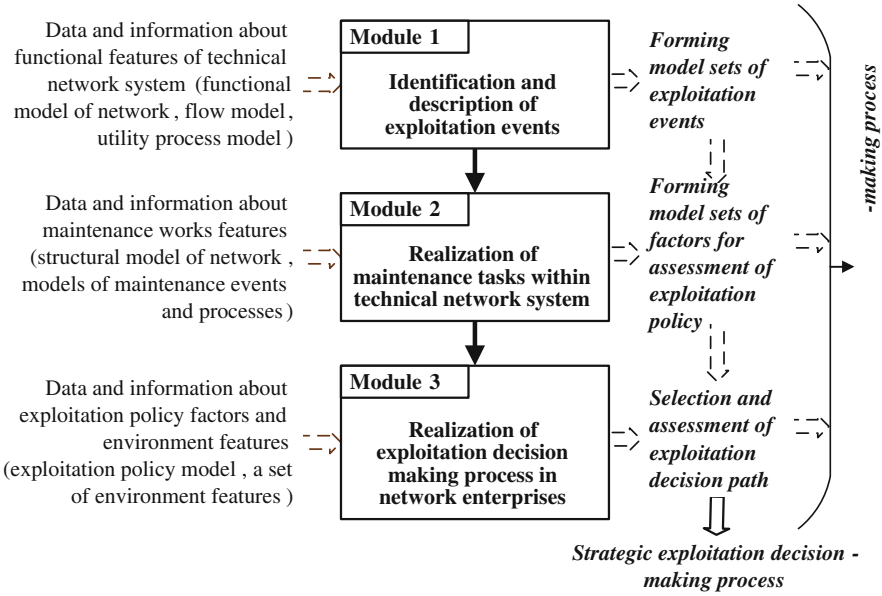


Fig. 1. The scheme of the developed SmartMaintenance concept

In this approach, each of the modules is a separate solution, represented in Fig. 1 by horizontal paths. These solutions are based on the individual arrangements of models and data structures, as well as on the ways of using them. Thus, the horizontal paths reflect supporting selected (individual) aspects of the exploitation processes, e.g. failure identification, workload analysis of maintenance works, assessment of the results of enhance preventive maintenance works. The comprehensive implementation of the exploitation decision-making process is represented, in Fig. 1, by the vertical path. This is result of cumulative use of all modules, e.g. the assessment of the exploitation policy, the scenario shaping the exploitation decision-making process [12].

3 Computer-Aided Under the SmartMaintenance Concept

Development of a computer supporting system, according to the proposed SmartMaintenance concept, involves the use of partial solutions and their adaptation to the requirements of exploitation decision-making process. This allows for carrying out tasks under horizontal linkages (partial exploitation procedures of the decision-making process) and the tasks carried out in a vertical linkages (procedures of the strategic exploitation decision-making process).

The supporting way, shown schematically in Fig. 2, is logically divided into three layers, with proposed models, methods and tools, in an orderly manner. It includes:

1. The data layer, in this case being the data warehouse, based on the assumption of deliberate use of existing data resources of the enterprise without any interference and modification of IT solutions applied in the enterprise. This layer, in addition to the functions of defining and storing structure models, makes it possible disposal of space or data and information, to perform calculations, to store intermediate and final results, and visualizing the effects of the analyzes and interpretations.
2. The analytical layer, including a set of algorithms for determining exploitation measures, in order to assess the exploitation policy by the assumed model.
3. The interpretation layer, which allows for expert processing the measures, identified in the analytics layer, with the use of environmental exploitation factors. The effect of these is interpretation of the functioning of the technical network system in the context of the exploitation decision-making process.

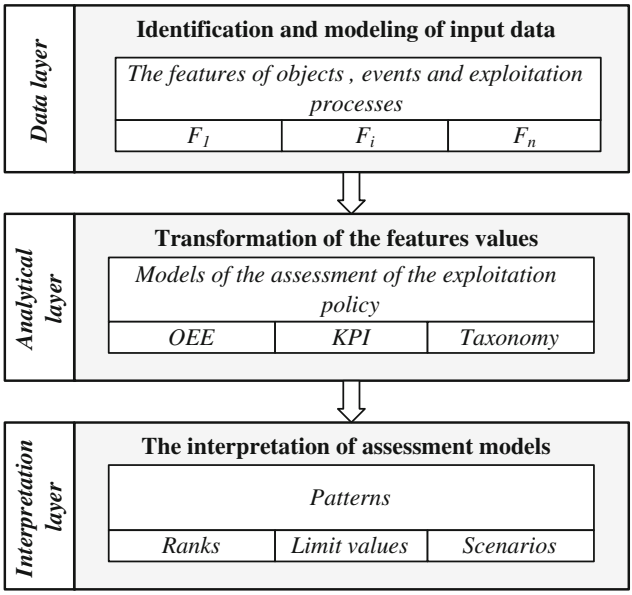


Fig. 2. The scheme of a computer system supporting the SmartMaintenance concept

The developed way of computer-aided of the SmartMaintenance concept is conceived as an universal platform for the realization of the exploitation decision-making process in a flexible manner - adapted to the opportunities and requirements of the maintenance organizations managing technical networked systems. This platform has an open character, what is meant by:

- the lack of restrictions on the implementation of the model of data collection,
- the lack of restrictions on the implementation of analytical methods for assessing the exploitation policy (e.g. OEE, KPI, taxonomic methods) [1, 3, 7],

- the lack of restrictions on the implementation of intelligent interpretation solutions (rank methods, reference methods, variants methods, scenario methods, expert systems, neural networks) [4, 8, 18].

4 Computer-Aided Under the SmartMaintenance Concept - Case Study

Research on the SmartMaintenance concept led to the development of computer module named SMOPE. In the structural context, SMOPE was built in web technology, with the use of relational database management system MySQL, PHP, as well as jQuery and CSS libraries. In the functional context, SMOPE, launched within a web browser. It allows for the assessment of procedural support of the exploitation decision-making process in the scenario technique.

SMOPE is based on the assumptions of the SmartMaintenance concept (Fig. 1), including the guidelines of the proposed computer-aided way (Fig. 2). Within the particulars layers, there have been prepared partial solutions, which on the one hand, allow for supporting the exploitation decision-making process, and on the other, constitute its dedication. The further points belong to these solutions:

- the data layer: the multi-model of the technical network system,
- the analytical layer: the taxonomic model of the assessment of the exploitation policy [11, 15, 16],
- the interpretation layer: the scenario model of the exploitation decision-making process [12, 13].

4.1 The Multi-model of the Technical Network System

Application of the multi-model within the SMOPE module, is intended to unambiguous identification and location of the components of the network technical system. For this purpose, there was developed the structure of the multi-model system, based on the concept of three subsystems, formally described by graph theory and matrix algebra.

The functional subsystem, reflects the time and spatial conditions (or their lack) of the possibilities of achieving the final parameters (output) at known and preset input values. This subsystem is formally represented by a set of relationships between engineering objects ob_j, including the linear objects ol_i, and it can therefore be described by the incidence matrix:

$$SY = [sy_{ij}] \tag{1}$$

where: sy_{ij} is 1, if j-th ob_j edge is incident with the i-th ol_i node, is 0, otherwise.

The structural subsystem, reflects the relationship type of parent–child, in relation to a particular section of the system or within a specific class of similar objects - groups of objects. This subsystem can be described by the neighborhood matrix:

$$ST = [st_{ij}] \tag{2}$$

where: stij is 1, if there is an edge between i-th node $ob_i(ol_i)$, and j-th node $ob_j(ol_j)$, is 0 otherwise.

The topological subsystem reflects the arrangement of the components (technical objects) integrated with places their physical occurrence in the area. This subsystem can be described by the arrays of the point and linear coordinates representing the engineering and line objects:

$$TP = \left[ol_i(ob_i), xp_i, yp_i, xk_i, yk_i, w_j\right] \tag{3}$$

where: ol_i (ob_i) - identifier of a linear or engineering object, xp_i, yp_i - initial coordinates of a linear or engineering object, xk_i, yk_i - end coordinates of a linear or engineering object (for engineering objects $xk_i = yk_i = 0$), w_j - identifier of map layer, to which is assigned an object.

Developed multi-model allows for the fragmentation of the technical network system within the analysis and interpretation implemented in the SMOPE. Figure 3 shows an excerpt of the analyzed technical network system, while Table 1 summarizes features of the topological subsystem.

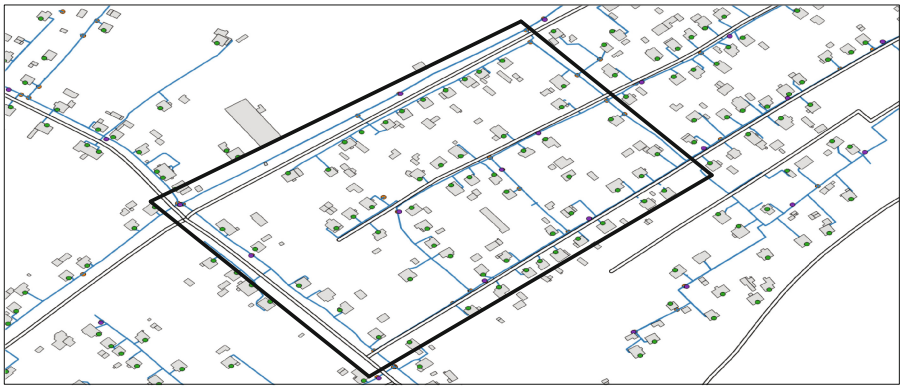


Fig. 3. An excerpt of the analyzed technical network system

Table 1. The arrays of the coordinates representing the engineering and line objects of the exemplary technical network system

Object ident.	Initial xp_i coordinate	Initial yp_i coordinate	End xk_i coordinate	End yk_i coordinate	Layer	Description
02	212576,49	857153,83	0,0000	0,0000	01	Node
03	212726,78	857258,05	0,0000	0,0000	01	Node
721	212615,54	857179,66	0,0000	0,0000	02	Water hose
43157	212727,38	857257,19	0,0000	0,0000	03	Valve
43051	212576,94	857153,36	0,0000	0,0000	03	Valve
45024	212576,49	857153,83	212587,71	857142,11	05	Pipe
41322	212576,49	857153,83	212726,78	857258,05	05	Pipe

4.2 The Taxonomic Model of the Assessment of the Exploitation Policy

The taxonomic model applied within the analytical layer of the SMOPE module includes determination of synthetic measures and geometric distances from the pattern (the Euclidean measure), based on a set of key features of the exploitation policy (cost, time, quantity of maintenance works) for selected categories of the maintenance works (inspections, maintenances, repairs, overhauls). The taxonomic model can be described using the formulas [15, 16]:

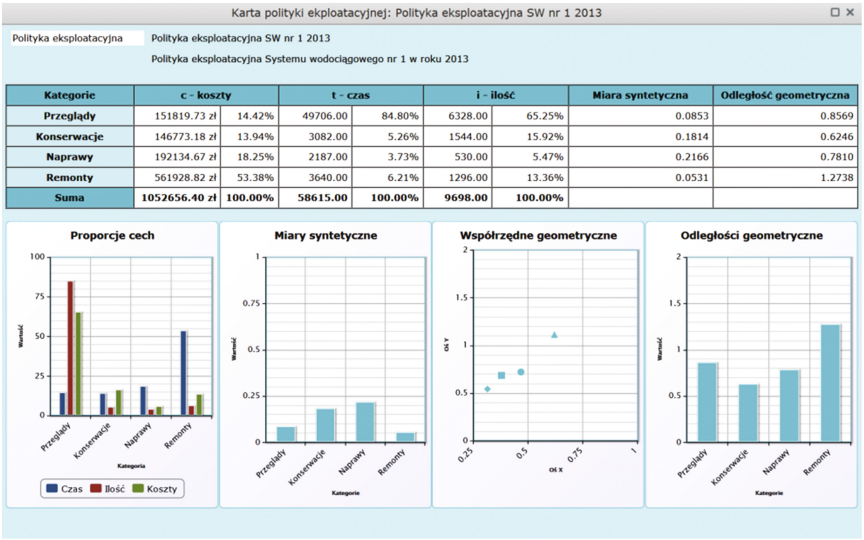
$$d_{i0} = \sqrt{\sum_{j=1}^{m} \left(z_{ij} - z_{0j}\right)^2} \tag{4}$$

$$s_i = 1 - \frac{d_{i0}}{\sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} \left(d_{i0} - \overline{d_0}\right)^2}} \tag{5}$$

where: d_{i0} - the measure of the geometric distances from the pattern, s_i - the synthetic measure, z_{ij} - the normalized feature.

The taxonomic way of modeling has been described in detail [13]. It constitutes the subject of assessing the contribution of the works of specified categories within the exploitation policy, and it is the basis for the interpretation of the exploitation decision-making process.

Figure 4 shows the screen of the SMOPE module with numerical and graphical visualization of the calculation results of the taxonomic measures for the exploitation policy of the analyzed network technical system, realized in 2013.



Kategorie	c - koszty		t - czas		i - ilość		Miara syntetyczna	Odległość geometryczna
Przeglądy	151819.73 zł	14.42%	49706.00	84.80%	6328.00	65.25%	0.0853	0.8569
Konserwacje	146773.18 zł	13.94%	3082.00	5.26%	1544.00	15.92%	0.1814	0.6246
Naprawy	192134.67 zł	18.25%	2187.00	3.73%	530.00	5.47%	0.2166	0.7810
Remonty	561928.82 zł	53.38%	3640.00	6.21%	1296.00	13.36%	0.0531	1.2738
Suma	**1052656.40 zł**	**100.00%**	**58615.00**	**100.00%**	**9698.00**	**100.00%**		

Fig. 4. Sample screen of the SMOPE module with visualization of the taxonomic assessment of the exploitation policy of the analyzed technical network system

4.3 The Scenario Model of the Exploitation Decision-Making Process

Interpretation of the exploitation policy should be carried out into consideration of the environment circumstances of the exploited technical network system [2, 17]. Therefore, a key aspect of the SmartMaintenance concept is a collection of pattern models, which can represent a specific reference level. For this purpose, within the SMOPE module, there are applied scenario models, according to the La Prospective methodology [6]. This allows for the interpretation of the exploitation decision-making process, in the environment of future variants, represented by different scenarios.

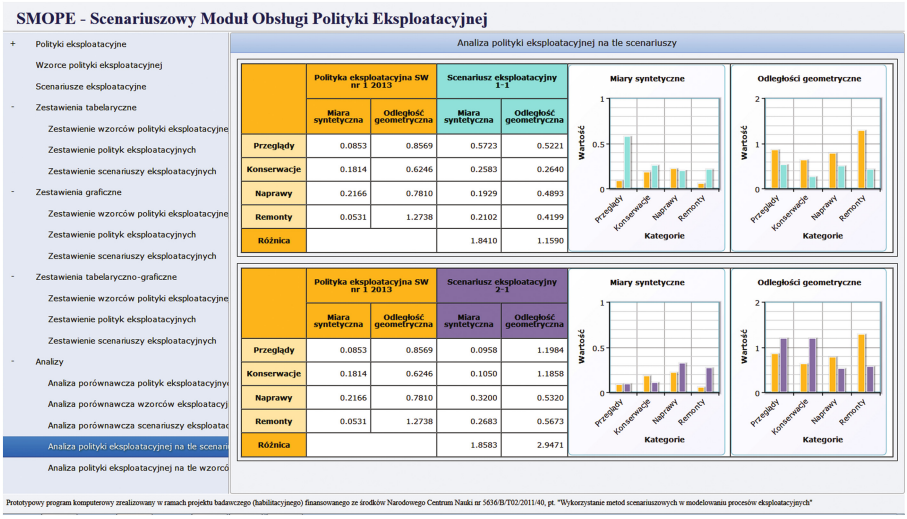


Fig. 5. Sample screen of the SMOPE module with scenario interpretation of the exploitation policy of the analyzed technical network system

Figure 5 shows the screen of the SMOPE module with numerical and graphical visualization of the comparison of the exploitation policy and the scenarios for the development of the exploitation policy of the analyzed technical network system. The exploitation policy as well as the scenarios are described by the taxonomic measures. Scenario shaping the exploitation decision-making process, with the use of the SMOPE module, enables:

1. The analytical taxonomic comparative procedure of the exploitation policy with the scenario models.
2. The assessment of the similarity (convergence) of the exploitation policy with the particular scenarios,
3. The assessment of the implementation of the exploitation decision-making process, in the context of potential different future variants, represented by the scenarios.
4. Monitoring of the exploitation policy, consisting of cyclic assessment of the exploitation policy based on the developed taxonomic models, and then interpreting the statement in successive, predefined, time points [10] (this allows for continuous

assessment of the direction and level of changes in the degree of similarity (convergence) exploitation policies to individual scenarios. This, in turn, can correct the assumptions and guidelines for exploitation decision-making process.
5. Simulation assessment of changes in the exploitation decision-making process, consisting in the analysis and interpretation of the impact of the modification of the features in change of the level of similarity (convergence) of the exploitation policy with individual scenarios.

5 Conclusions

Presented in this paper, key aspects of exploitation of technical network systems, justify the need to optimize exploitation processes in the context of rational decisions. The solution proposed by the author, methodologically housed within the SmartMaintenance concept. This enabled the development of computer system, supporting rational exploitation decisions. The methodology of scenario development of the exploitation decision-making process, as the basis for the implementation of the SmartMaintenance and supporting with the SMOPE was presented in detail in [14].

The test results of the SMOPE module, based on exploitation data of the analyzed technical network systems, confirmed the possibility, desirability and reasonableness of applying the tools of the analytical and expert class, for the needs of supporting exploitation decision-making process in the long term, according to the developed methodology. The SmartMaintenance concept, having an open specificity, can form the basis for the development and implementation of innovative and intelligent support solutions. Further author's research focus on the development and adaptation solutions, in the SMOPE environment, based on knowledge engineering, including:

- rule-based expert systems, for the needs of interpretation of exploitation decision-making in the short term,
- artificial neural networks, for the needs of quantitative interpretation of development scenarios for exploitation decision-making process in the long term.

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Use of Intelligent Informatics Module for Registration and Assessment of Causes of Breaks in Selected Mining Machines

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Abstract. Growing competition and an unstable energy market force mining enterprises to take actions aimed at decreasing production costs. The area in which there are great reserves linked with costs is a use of mining machines that are owned by mining companies. In practice, it has been observed that underutilization of mining machines at present is one of the main problems in mines. The paper presents the results of research whose aim was to determine availability and performance of the studied machines and quality of the excavated material which was the product of the machines' work. Based on the results, the effectiveness of the machines was determined. In the area of availability a large number of the unidentified breaks during the machines' work was registered. To find the causes of the breaks, many interviews with expert workers from maintenance departments were made. Using their knowledge, the special and intelligent module for the reasons for the breaks registration were developed and implemented. This module has been permanently linked with the integrated management and maintenance system that had been used in the mine. The application of the developed solution made it possible to indentify more than 72% of the breaks in the studied machines' work and it was an increase by 90% in relation to the level before its installation. It appeared that the main cause of the low efficiency of the reasons identification was the lack of dispatchers' knowledge and motivation. The obtained results make it possible to take activities in order to reduce the breaks in the studied machines' work and subsequently improve their effectiveness.

Keywords: Machines' effectiveness · Tacit knowledge · Intelligent system · Identification of the breaks in machines' work

1 Introduction

The Polish mining industry that is engaged in the coal exploitation uses more and more machines that are highly reliable and characterized by very good technical parameters. In particular, it refers to the machines that are included in the mechanized longwall system. They are dedicated to directly excavating the coal and transporting the excavated material from the zone of the longwall face. These machines are the first as well as the most important link in the technological line which includes coal cutting,

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underground horizontal and vertical transport and transport on the surface. It can be assumed that the effectiveness of the whole exploitation process depends on the level of a use of the mining machines. Figure 1 shows the sample view of the longwall system [9].



Fig. 1. The sample view of the longwall system [9].

The cost of these machines is very high due to their high parameters and advanced technologies which are used for these machines' production. For this reason, the mining companies seek to make the best use of the machines. Moreover, it also is connected with a great competition in the energy resources market. In addition, the companies, including mines, have to pay attention to the use of ecological technologies and measure a level of eco-innovation [1, 7]. The reason for the growing competition is a globalization of this market as well as the competition from renewable energy sources. With so many unfavorable factors, the mining companies have to take activities and actions aimed at reducing the unit costs of the production to maintain their position in the market [4, 5]. One of the areas, where the efficient actions can be made, is a use of the machines. The experts' opinions and audit firms' applications have shown for a long time that at present underutilization of mining machines and devices is one of the mining enterprises' main problems. This kind of comparison of the use of machines mostly refers to closed plants. However, the comparison between open and closed plants should not be made due to the specific nature of exploitation of the first type of plants. The open plants are very often exposed to different kinds of dangers that have random nature. Despite these facts, levels of the use of the machines in the mining industry are unsatisfactory. In addition, it is very hard to find direct and rational causes of this state.

For this reason, the authors of the paper conducted research whose purpose was to determine the real effectiveness of selected machines. The study included a longwall shearer and, to a lesser extent, an armored face conveyor. In the first stage of the research, availability and performance of the studied machines and quality of the excavated material, which was the product of their work, was determined.

Subsequently, based on the results using the Overall Equipment Effectiveness model the effectiveness of the use of machines was determined.

While analyzing the availability of the studied machines, a very big number of unidentified breaks was observed. To find the causes of these breaks many expert interviews with workers from maintenance department were made. Using their opinions the special and intelligent module for the registration of the causes of the breaks was developed and implemented. This module has been permanently linked with the integrated management and maintenance system that had been used in the mine.

The paper presents and discusses the developed module and shows the results of its work. What is more, the article presents the results of the analysis of the effectiveness of the studied machines.

2 Determination of the Effectiveness of the Studied Set of Machines

In many experts' and audit firms' opinions the level of the use of the mining machines despite their high reliability and great technical parameters is low and unsatisfactory. At the same time, the costs of purchasing or leasing these machines are very high. In this context, it is justified to objectively determine the effectiveness of the use of the machines. The basis of the effectiveness determination and credible results obtaining is the selection of the appropriate study method and the tools that will make it possible to efficiently assess this chosen method. In the presented case, the Overall Equipment Effectiveness (OEE) model, which is a quantitative tool as a part of the Total Productive Maintenance (TPM) strategy [3, 6], has been used to analyze the level of the use of the studied mining machines. It was assumed that this model is able to objectively evaluate the effectiveness of the machines. Its greatest advantage is taking into account three areas of the studied machines to make an assessment. These areas include availability, performance and quality of the product. It was assumed that an examination of the effectiveness of the machines in the mentioned three areas guarantees taking into account all of the important factors. Moreover, a big advantage of this model is the fact that it is widely used in other industries. Thanks to this, the obtained results can be compared with the results from other industries.

The partial indicators of the effectiveness have been determined on the basis of the Overall Effectiveness Equipment model. The availability and the performance of two studied machines were independently determined. However, the quality was calculated for the whole exploitation system, not for the particular machines. This kind of method of determining the partial indicators was chosen because of the specifics of the mining exploitation, in particular the mining machines, in which the final product is the amount of excavated material transported away from the zone of a longwall face. In the area of performance and quality, the analyzed set of machines has been treated as a single machine [2, 8].

The basic source of information to calculate the availability of the studied machines was the data obtained from the industrial information system. The use of this data guarantees the high credibility of obtained information registered in real time. The parameters, which were recorded during the machines' work, were currents consumed

by the particular motors of both of the machines and the feed speed of the longwall shearer. This data clearly makes it possible to determine the level of the use of these machines and to register all kinds of downtimes.

Figure 2 shows the temporal speed waveforms of the longwall shearer and its position in the longwall for one work shift.

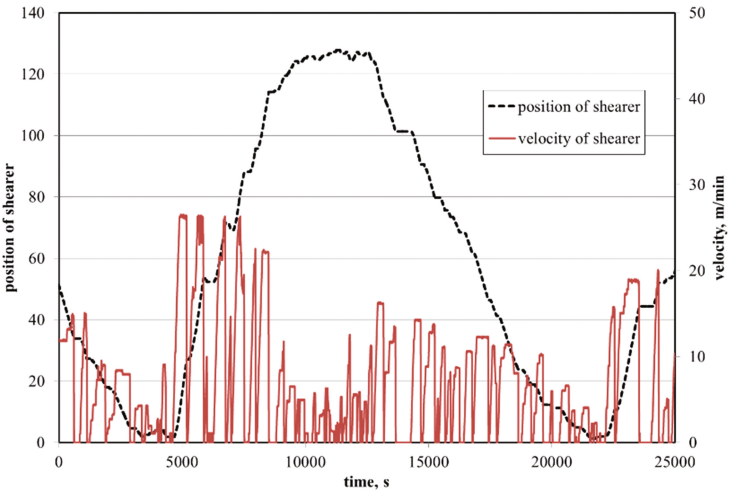


Fig. 2. The temporal velocity waveforms and the position of the longwall shearer.

By analyzing the obtained waveforms it can be claimed that there were many breaks during the longwall shearer's work shift. The availability indicator for this work shift was only 65%. Based on the registered waveforms, the availability values of the two studied machines were determined for 30 work shifts (Fig. 3).

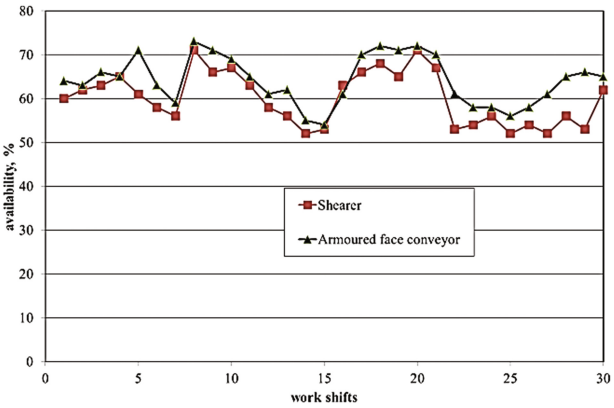


Fig. 3. The availability values of the studied machines for the particular work shifts.

The performance indicators were determined based on the amount of planned daily coal extraction, which is written in the technical and economic plan, and the real daily extraction that is determined for every mining work shift. These values were the same for both of the studied machines. The quality indicators were calculated based on information obtained from the processing plant in relation to the assortment of coal as well as gangue content in the useful mineral. This data was averaged for ten consecutive days and the values of this data were the same for the studied set of machines.

It is very difficult to determine the excavated material parameters for each work shift. What is more, the determination is subject to some errors. Therefore, the values of this indicator for the whole set of machines were averaged for decades.

Based on the mentioned way of determining the particular partial indicators, the Overall Equipment Effectiveness indicator has been calculated for the two studied machines during the studied period (Fig. 4).

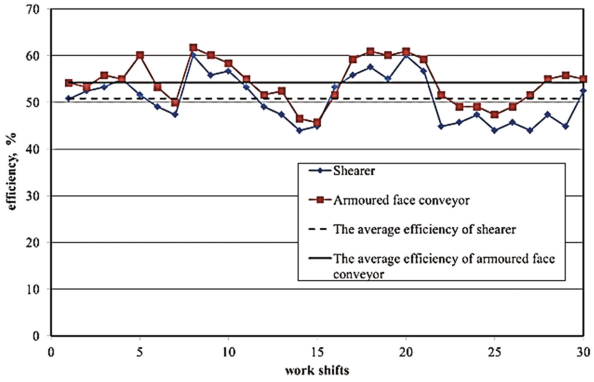


Fig. 4. The effectiveness indicator values for the studied machines.

Based on the results, it can be claimed that the determined values of the effectiveness indicator are low and they are dependable mostly on the studied machines' availability. Therefore, it can be assumed that the availability of the machines has a very big influence on this indicator. It justifies more detailed analysis on the causes of such a low value of the availability indicator in the studied machines' case.

The next natural stage of the analysis of the effectiveness of the studied longwall shearer has been the identification of the causes of such a high number of breaks in its work. In order to clarify the causes of the breaks, the analysis of dispatchers' notes for one work shift was conducted. It turned out that the notes can explain only the two longest breaks. The sum of these breaks was 47 min. The reasons for the remaining 112 min of breaks were not explained. To clarify such great differences in the identification of the reasons for the breaks in longwall shearer's work, interviews with experts were made. Based on the results, it can be claimed that the main reasons for this state are not a perfect system for the registration of the breaks and their causes and workers' solidarity in this industry. According to the respondents, because of this solidarity, workers do not want to reveal all information. They are simply afraid of the

negative activities which would be taken due to the revealed knowledge. The service workers in most cases have knowledge about the reasons for the registered breaks but they are not interested in revealing it. These facts prompted the authors to take actions to create an informatics tool that will make it possible to establish the real causes of the registered breaks in the most objective way.

3 The Characteristics of the Intelligent Module for the Registration of the Causes of the Breaks in the Studied Machines' Work

When developing the module for the registration of the causes of the breaks in the work of mining machinery, it was assumed that the basic source of information about the number of these breaks will be the results obtained from the industrial automation system. This system, which obtains data directly from the studied machines, guarantees full credibility of the data. Information from this system is the input data of a warehouse in which this data is archived, synchronized in time and analytically processed. The analysis of this data makes it possible to identify the downtimes in the machines' work. In order to identify the causes of the breaks, an intelligent module, which has been connected to the integrated management system used in the mine, was developed. Figure 5 shows the structure of this module.

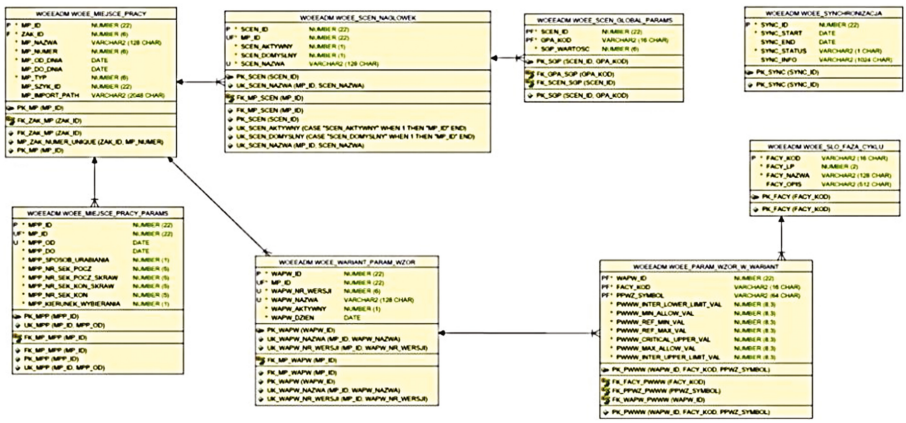


Fig. 5. The structure of the intelligent module for the registration and identification of the causes of the breaks in the machines' work.

Its main task was to make it possible for the dispatcher to simply and intuitively register the specific break in the machine's work (in this case, a longwall shearer) and give as many as possible pieces of information about the cause of this very break. Figure 6 shows the view of the panel's module for registration of the break and description of the reason for this break.

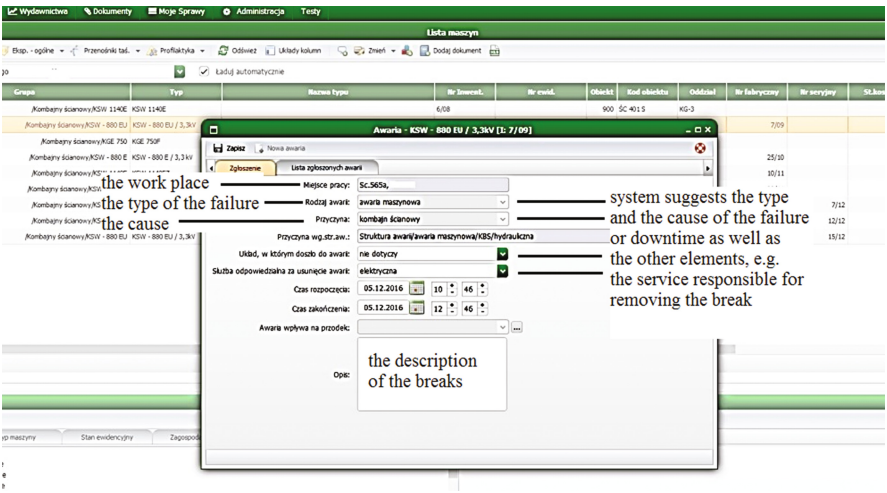


Fig. 6. The view of a part of the module for the registration of the machines' failures.

The registration of the break in the shearer's work has worked as follows: the module indicates every situation in which the longwall shearer does not move (the speed of the feed is zero) and the currents consumed by its cutting heads have not greater values than the currents during idling. It was assumed that this case is understood as a break in the work. In the case of the armored face conveyor, this mentioned criterion refers only to zero values of a current consumed by the motors.

When this situation takes place, information about the necessity of choosing the reasons for the failure giving the beginning and ending time of the break and providing additional information about the event in the dialog box is shown in the system (Fig. 7). This dialog box, named "downtime" or "failure", is active until the dispatcher writes down the information about the ending time and chooses at least one cause for the break. The dispatcher providing this information uses the communication panel (ultimately touch panel). To provide detailed information about the cause of the breaks, the system suggests to the dispatcher some answers. It is because the designed module has a database containing all of the already registered failures and other causes of downtimes in the machine's work. When a thus far unidentified event occurs, the base is automatically updated with information about this very event. Figure 7 shows the view of a part of the module for the registration of the failure's structure which means description of a failure's type.

In addition, in the module, an anonymous way of the dispatchers' registration has been developed. Each of the dispatchers received a unique identifier that prevented the dispatcher, who made a break registration, from being identified by the other workers. This solution has allowed obtaining a large amount of information on the breaks and their causes.

The developed application presents a quantitative status of the studied machines and to fully analyze the failure and their causes. Such overviews are dedicated to the specific types of equipment, for example longwall shearers, conveyors, etc.

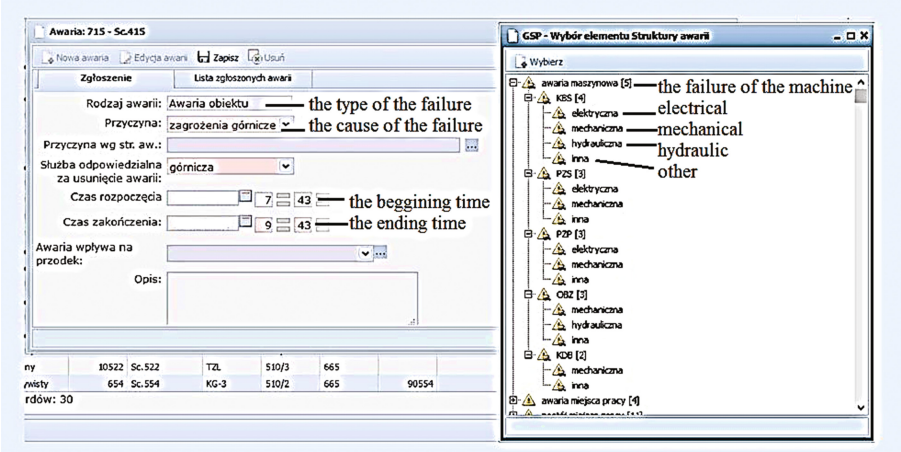


Fig. 7. The view of a part of the module for the registration of a failure's structure.

The application of the developed module led to know the reasons for most of the breaks in machines' work that were recorded by the automation system, and at the same time increasing discretion of the workers who recorded this data.

4 Analysis of the Causes of the Breaks in the Studied Machines' Work

Thanks to the practical application of the developed module, the causes of most of the breaks have been identified. The causes are automatically referred to the particular machines and their components. Moreover, the initial classification of the type of the failure is made. This classification can be verified based on the description of the causes in case of any doubts. The time of the breaks and the place of their occurrence is automatically registered. The place of the longwall shearer's failure is determined in relation to the shearer's position to the section of the roof support. The shearer moves along the longwall whose average length is about 200 m.

In the present case, the registration of the breaks was made for 30 work shifts (10 work days). Figure 8 shows the number and the length of the recorded breaks in the shearer's work by the industrial automation system. This figure also indicates the number of the breaks whose causes were identified. The identification was possible thanks to the application of the developed module.

Analyzing the results, it can be claimed that the duration of most of amounts of the breaks did not exceed 2 min. What is more, more than 93% of all breaks in the longwall shearer's work were the ones whose duration was no longer than 30 min.

The number of the identified causes of downtimes means that the longer the break is, the higher efficiency of the causes of the break identification. The identification of the breaks lasting more than 10 min was more than 90%. This result should be perceived as very good.

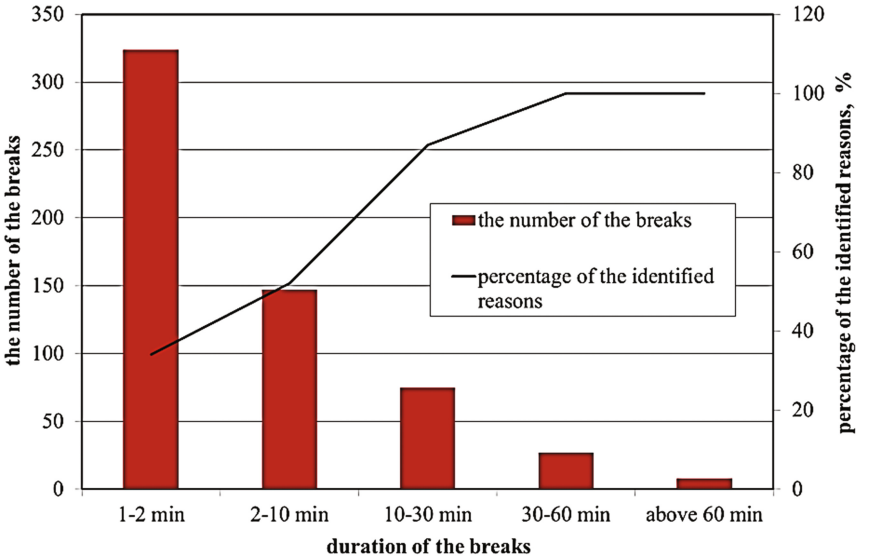


Fig. 8. The number of the breaks based on the duration and percentage of the identified reasons.

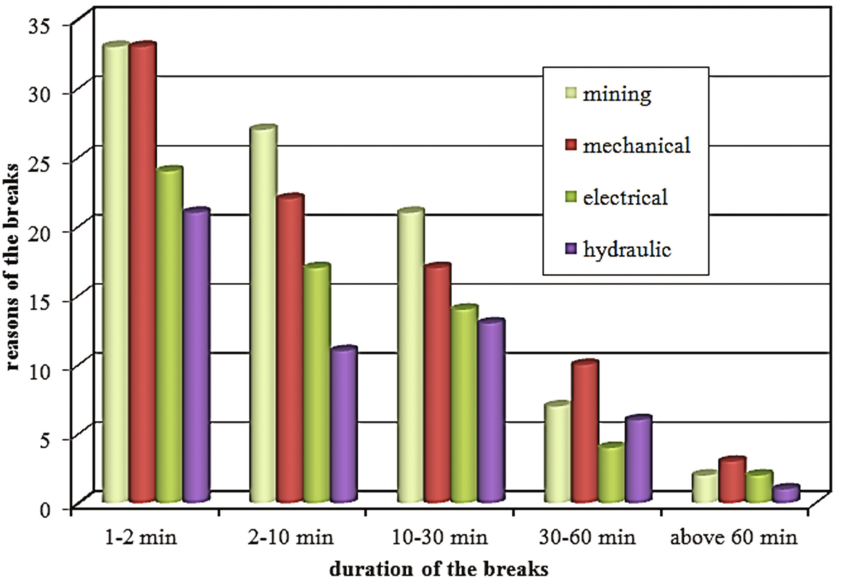


Fig. 9. The comparison of the types of the causes of the breaks in the longwall shearer's work, and the duration of these breaks.

However, there are differences and problems with the shorter breaks. The reason for this is that these kinds of downtimes occur very often in short intervals. Because of this, the dispatcher is often not able to register them. Despite this fact, the obtained results clearly indicate that the applied solution has significantly improved the identification of the causes of the downtimes in the studied longwall shearer's work.

The developed module also made it possible to determine the structure of the registered breaks by describing their nature. It was assumed that these causes are divided into mining, mechanical, electrical and hydraulic. Figure 9 shows the comparison of the reasons for the breaks occurring in the tested shearer. The division also was referred to the duration of the downtimes. The application of the developed module and the data and information, which has been obtained thanks to this module, make it possible to conduct many analyses depending on the need.

5 Conclusions

The main task of the developed intelligent informatics module was to enable quick and reliable registration and identification of the causes of the downtimes in the studied machines' work. By using this solution, the mentioned breaks have been recorded by two independent systems which allow the controlling in the correctness of the registration. The solution enables the dispatchers to friendly and easily register the breaks of the machines, as well as the causes of these breaks. The results confirm the usefulness and effectiveness of the implemented solution. In particular, there was a very significant improvement in the identification of the cause of the medium-lasting breaks (from 5 to 30 min). What is more, 100% of the causes of the 30 minutes-long breaks were identified.

The most intelligent part of the developed system is located in the dispatcher supporting system. It suggests the identification of the cause of the registered break based on the historical data on the causes. It makes identifying the reasons for the breaks easier than the previously used systems. It is also easier to describe the break as well as find the source of it, which is undoubtedly a great advantage of the developed system.

The developed application also opens up wide opportunities for the analysis of the obtained data and the preparation of the various types of reports depending on needs. All of the mining machines can be the subject of such research. Moreover, the system fully archives all obtained data.

The developed and implemented informatics solution is another step in the process of the effectiveness improvement of the machinery's use in the mining industry. This process mainly refers to an increase in the availability of the machines. It turns out that in practice, it is the availability that has the biggest influence on the effectiveness of the mining machines' use.

Therefore, actions were taken related to this area. In the next stage, more detailed analysis of the causes of the registered breaks will be carried out. Its aim will be to develop recommendations for the maintenance service and the managers in order to improve the effectiveness of the exploitation process. However, it is the complete and

reliable information regarding the mentioned process that is crucial for exploitation. It should be highlighted that this is the main goal of the implemented solution.

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Using a Simulation Method for Intelligent Maintenance Management

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Abstract. Effective maintenance management determines the competitiveness of manufacturing enterprises. Breakdowns and inspections of manufacturing resources affect the total throughput of manufacturing systems and the requirements for maintenance staff. In this paper a model of an intelligent maintenance-management system based on a computer-simulation method is proposed. On the basis of the simulation model and conducted experiments, the impact of the availability of manufacturing resources on the throughput and average lifespan of products is analysed. The simulation model of the manufacturing system is used for the intelligent allocation of the manufacturing resources to derive assumed values for the throughput and average lifespan of products. The model takes into account the number of maintenance staff and processing times. An illustrative example of the maintenance management of a flexible manufacturing system is given.

Keywords: Computer simulation · Maintenance-management system · Resources availability · Throughput · Lifespan of products

1 Introduction

Computer simulation is a commonly used method in manufacturing to analyse the efficiency of production processes and maintenance. Most often the simulation method is used to analyse the behaviour of manufacturing systems, manufacturing-system design, manufacturing-operation planning and scheduling, or performance analysis. Computer simulation can be used to build complex manufacturing systems, analyse the effectiveness of preventive or corrective maintenance, and improve overall operational reliability, the utilisation of manufacturing resources, and the productivity of manufacturing systems [1].

In the literature there have been proposed many decision-support tools based on the computer-simulation method for effective maintenance operations. For example, Ni and Jin propose mathematical algorithms and simulation tools for data-driven short-term-throughput bottleneck identification, the prediction of windows of opportunity for maintenance, the prioritisation of maintenance tasks, joint production- and maintenance-scheduling systems, and maintenance-staff management [2]. Roux et al. recommend

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tools be combined to collaborate in order to optimise multi-component preventive-maintenance problems. The structure of the maintenance-production system is modelled by a combination of timed petri-nets and Parallel Discrete-Event System-Specification models, and implemented in a virtual-laboratory environment [3]. P. Renna is engaged in the evaluation of manufacturing-system performance in dynamic conditions, when various maintenance policies are being implemented in a multi-machine manufacturing system controlled by multi-agent-architecture. A discrete simulation environment has been developed in order to investigate the performance measures and the indices of the costs of maintenance policies [4]. Mokhtari et al. suggest joint production and maintenance scheduling (JPMS), with multiple preventive maintenance services, in which the reliability/availability approach is employed to model the maintenance aspects of a problem. They propose the development of a mixed-integer nonlinear-programming model, and a population-based variable-neighbourhood-search algorithm as a solution method [5]. Intelligent maintenance systems (IMS) include methods and tools that support decisions which minimise the breakdown times of manufacturing resources, reduce the total cost of maintenance, and improve the efficiency of manufacturing systems. Frazzon et al. propose a simulation model to evaluate the performance improvements provided by integrated intelligent-maintenance systems and spare-parts-supply chains [6]. Maintenance projects can be evaluated in the long-term perspective by the analysis of costs or time reduction [7]. Hellingrath et al. argues that the only way to minimise breakdown times with no high-stock strategies is by combining efficient spare-parts-supply-chain coordination with better system-failure forecasting [8].

In this paper a model for an intelligent maintenance-management system (IMMS), based on a computer simulation method, is proposed. The following assumptions and limitations are taken into account:

- the intelligent maintenance-management system is dedicated to fully automated manufacturing systems,
- the simulation model of the manufacturing system is created using Tecnomatix plant-simulation software,
- both machining and assembly operations are taken into account,
- the processing times are defined using *uniform distribution*,
- the different variants of availability of the manufacturing resources are analysed,
- the different variants of number of maintenance staff are analysed,
- simulation time for one experiment is 10 days,
- 1 observation per experiment is assigned,
- the initial processing times are given in the Table 1,
- the input values for experiments are presented in the Table 1 and operation times in the Table 2,
- the setup times are 0,
- the number of maintenance staff is 1, 3 or 5 person.
- for different allocations of manufacturing-resources availability the throughput and average lifespan of products can be determined.

The model for the IMMS will be devised on the basis of an analysis of the results of a computer simulation of discrete manufacturing systems [9]. The results of the research

facilitated the establishment of correlations between the availability of manufacturing resources and the throughput of the manufacturing system. The input and output variables are defined. The simulation model of the manufacturing system was prepared on the basis of an actual manufacturing enterprise which produces details for equipment for automotive branch. The equipment is consist with different parts of varying complexity. The processing and assembly times range from 1 to 5 min (more than 500 different CNC programs for manufacturing individual parts is used). In the next section the model for the IMMS is presented. The IMMS includes a simulation model of the manufacturing system, decision rules, and a description of the knowledge repository.

2 The Model for the Intelligent Maintenance-Management System (IMMS)

The model for the IMMS is presented in Fig. 1. On the basis of the specification of manufacturing processes (manufacturing resources, transportation, operation times, setups, production batches, intermediate buffers, etc.) and maintenance-process specifications (the number of maintenance workers, OEE - Overall Equipment Effectiveness, OCE - Overall Craft Effectiveness, MTTR - Mean Time to Repair, MTTF - Mean Time

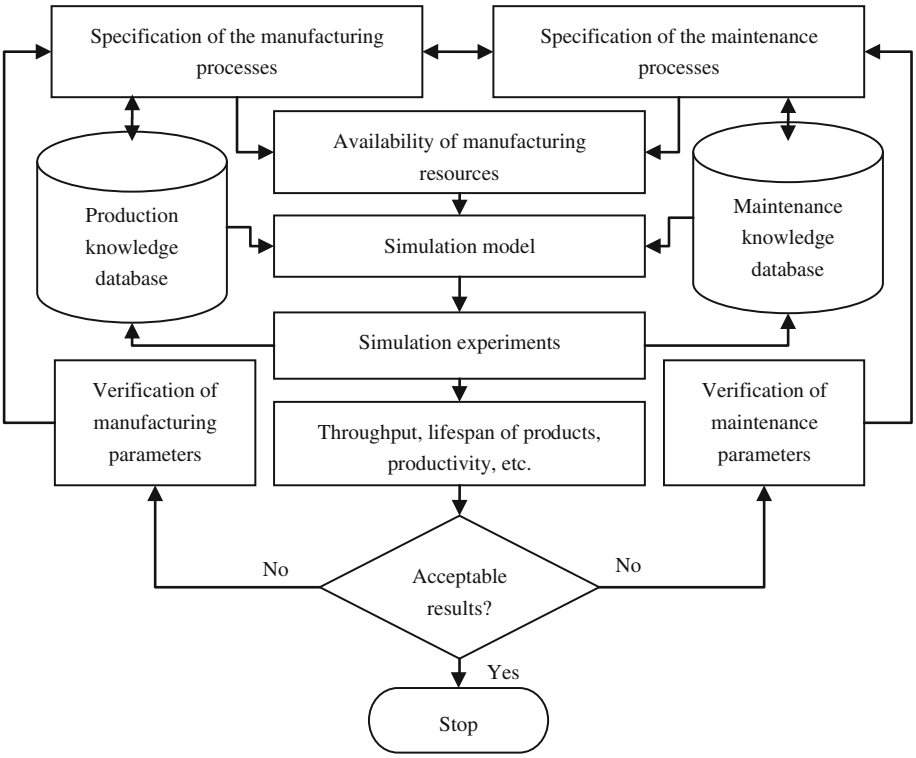


Fig. 1. The model for the intelligent maintenance management system (IMMS)

to Failure, MTBR - Mean Time Between Repair., etc.), a simulation model of the manufacturing system can be created.

The simulation model should include information on manufacturing-resources availability (defined on the basis of maintenance parameters and eventual variants of resources availability). For the simulation model of the manufacturing system, a set of simulation experiments will be proposed. The results of the simulation experiments are recorded in the production and maintenance knowledge database (it can be one database) and facilitate the verification of manufacturing and maintenance parameters for the obtained results of the effectiveness of the manufacturing system. The proposed IMMS includes mechanisms for the collection of data on the manufacturing and maintenance processes. The selection of input parameters is made on the basis of decision rules which determine, for example, acceptable values for the throughput and the average lifespan of products (work in progress). If the results are not acceptable, the decision rules allow the verification of maintenance and manufacturing parameters using the information collected in the knowledge database. The database will be the repository of knowledge which reflect correlations between manufacturing and maintenance parameters.

The simulation model of the manufacturing system is prepared using Tecnomatix Plant-Simulation software (Fig. 2) [10]. The system includes 8 CNC machines and 3 assembly stations. Each manufacturing resource has an assigned service workplace (S1–S10). The material flow is achieved using automated conveyers (lines L1-L10), and the maintenance staff use the footpath (FP1-FP7) to reach the manufacturing resources. The conveyers play the role of intermediate buffers. The footpaths allow the mapping of the actual routes allocated to the service staff. The structure of the manufacturing system is symmetrical (CNC1-CNC4, A1; and CNC5-CNC8, A2 are two symmetrical parts of the

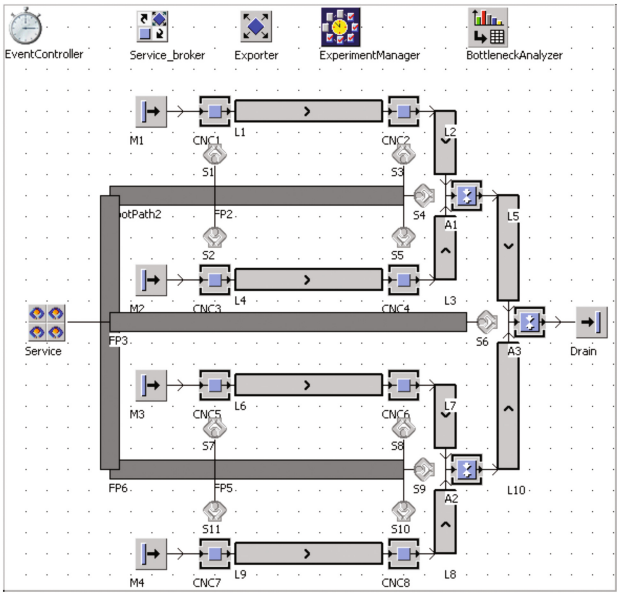


Fig. 2. The simulation model of the manufacturing system

system). The operation times are determined using *uniform distribution* (standard distribution in Technomatix Plant Simulation). *Uniform distribution* can be used for the modelling of random numbers which are located between the '*start and stop'* interval limits. This is useful when little is known about the distribution of the random numbers.

The function of the density of the probability of distribution for values between $start < x < stop$ has the following formula:

$$f(x) = \frac{1}{stop - start} \tag{1}$$

where the average value of the distribution is

$$\mu = \frac{start + stop}{2} \tag{2}$$

and the variance takes on the value of

$$\sigma^2 = \frac{(stop - start)^2}{2} \tag{3}$$

An example of a uniform distribution is presented in Fig. 3. The processing times for CNC machines are defined as *start = 1:00* and *stop = 5:00,* and for assembly stations *start = 1:00* and *stop = 3:00.*

Besides *uniform distribution,* the operation times of the manufacturing resources are defined as increasing and decreasing. First, the simulation experiments were prepared for different variants of resources availability (Table 1), and the output-variables throughput of the system and the average lifespan of the product were analysed. The experiments were prepared for different numbers of maintenance workers (1, 3 and 5). The availability of manufacturing resources was changed from 80% to 100%. The results of the simulation experiments were collected in the databases, where they are used to support decision processes. The results of the experiments show that the maximum

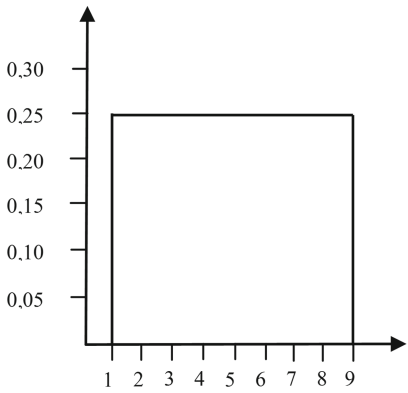


Fig. 3. Uniform distribution where *start = 1* and *stop = 9*

availability of manufacturing resources does not guarantee the maximum throughput of the manufacturing system.

On the basis of the data collected during the simulation experiments decision rules can be formulated which facilitate the determining of the throughput or average lifespan of products (the level of work in progress) for defined variants of resource availability and numbers of maintenance workers.

Table 1. The availability of manufacturing resources as input for the simulation experiments

Experiment	CNC1	CNC2	CNC3	CNC4	CNC5	CNC6	CNC7	CNC8	A1	A2	A3
Exp 01	100	100	100	100	100	100	100	100	100	100	100
Exp 02	99	99	99	99	99	99	99	99	99	99	99
Exp 03	98	98	98	98	98	98	98	98	98	98	98
Exp 04	97	97	97	97	97	97	97	97	97	97	97
Exp 05	96	96	96	96	96	96	96	96	96	96	96
Exp 06	95	95	95	95	95	95	95	95	95	95	95
Exp 07	94	94	94	94	94	94	94	94	94	94	94
Exp 08	90	90	90	90	90	90	90	90	90	90	90
Exp 09	89	89	89	89	89	89	89	89	89	89	89
Exp 10	85	85	85	85	85	85	85	85	85	85	85
Exp 11	80	80	80	80	80	80	80	80	80	80	80
Exp 12	75	75	75	75	75	75	75	75	75	75	75
Exp 13	70	70	70	70	70	70	70	70	70	70	70
Exp 14	90	95	90	95	90	95	90	95	90	90	90
Exp 15	85	90	85	90	85	90	85	90	90	90	90
Exp 16	85	90	85	90	85	90	85	90	95	95	95
Exp 17	80	90	80	90	80	90	80	90	99	99	99
Exp 18	90	80	90	80	90	80	90	80	95	95	95
Exp 19	90	80	90	80	90	80	90	80	99	99	99
Exp 20	90	90	90	90	90	90	90	90	90	90	90

Table 2. The variations in the operation times [minutes]

Machine	Uniform distribution V1	Decreasing constant V2	Increasing constant V3
CNC1	1:00;5:00	5:00	1:00
CNC2	1:00;5:00	3:00	2:00
CNC3	1:00;5:00	5:00	1:00
CNC4	1:00;5:00	3:00	2:00
CNC5	1:00;5:00	5:00	1:00
CNC6	1:00;5:00	3:00	2:00
CNC7	1:00;5:00	5:00	1:00
CNC8	1:00;5:00	3:00	2:00
A1	1:00;3:00	2:00	3:00
A2	1:00;3:00	2:00	3:00
A3	1:00;3:00	1:00	5:00

The values of availability for the simulation experiments are mandatorily selected on the basis of the experiences of and knowledge about the behaviour of discrete manufacturing systems. In Table 2 the variants of operation times for the simulation experiments are presented. The range of the operation times is from 1:00 to 5:00 min.

In the next section the results of the computer simulation are presented and examples of the decision rules for the IMMS proposed.

3 The Results of Simulation Research and Outlines for the IMMS

Computer-simulation experiments were carried out for three different operation times and three numbers of maintenance workers (1, 3 and 5). In Figs. 4 and 5 the throughput and average lifespan of products for *uniform distribution* (variant V1) are presented respectively.

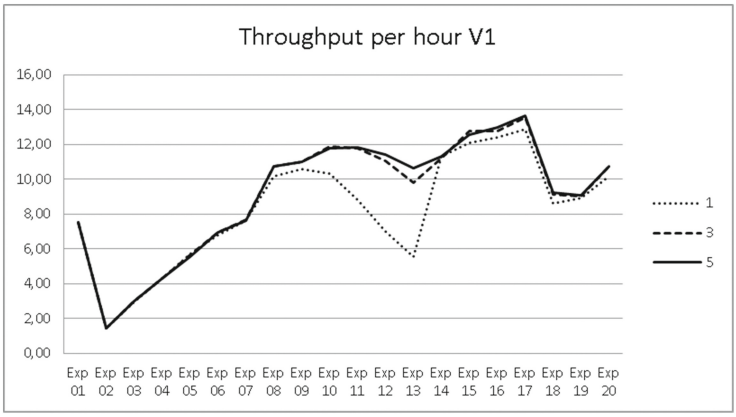


Fig. 4. The throughput of the system for *uniform distribution* variant V1

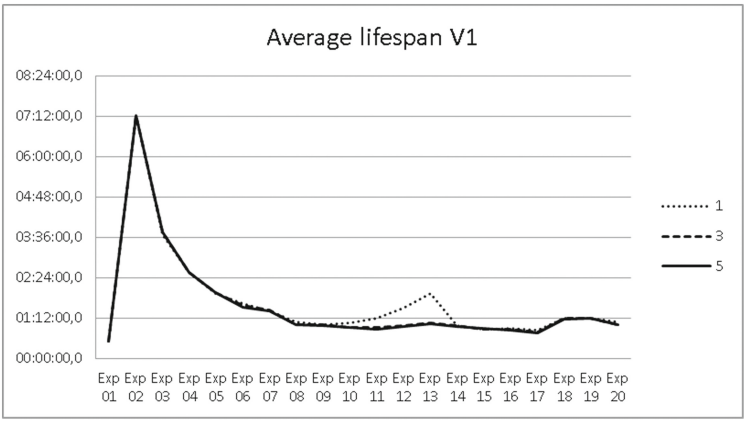


Fig. 5. The average lifespan of products for *uniform distribution* variant V1

The greatest value of the throughput (13.64 parts per hour) was obtained for experiment Exp. 17. The smallest value (1.45 products per hour) of throughput and maximum lifespan value was obtained for Exp. 02, in which the availability of all manufacturing resources was 99%.

The analysis of the results presented in Figs. 4 and 5 shows that the number of maintenance workers had an impact on the throughput and average lifespan only for some of the experiments (Exp. 07 – Exp. 14). Generally speaking. increasing the availability of assembly resources resulted in decreasing the throughput of the system.

In the Figs. 6 and 7 the results of the simulation experiments for increasing constant values of operation times (variant V2) are presented. The greatest throughput value (11.98 products per hour) and the smallest lifespan value, were obtained for Exp. 01.

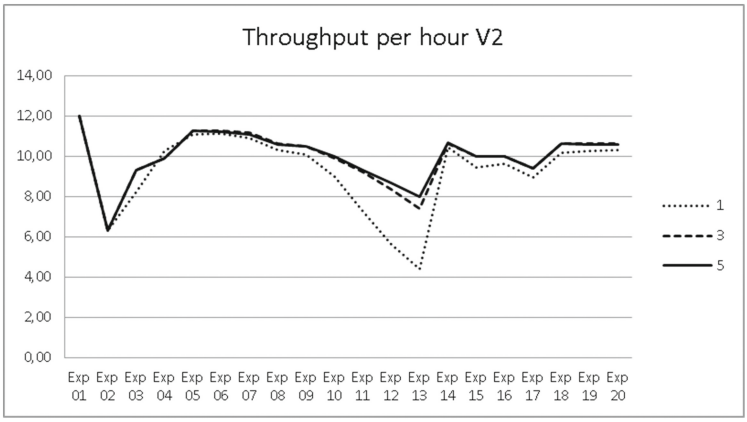


Fig. 6. The throughput of the system for decreasing constant operation times variant V2

The lowest throughput (5.50 products per hour) and longest lifespan (more than 2 h) was obtained for Exp. 13 and a single maintenance worker.

- The results of last series of experiments are presented in the Figs. 8 and 9 (constant and decreasing operation times – variant V3). Similar as for V1 the greatest value of throughput (11.81 products per hour) and smallest lifespan is reached for Exp 17. The smallest throughput (0.84 products per hour) and the greatest lifespan (about 12 h) is obtained for Exp. 02.
- On the basis of the presented results of the simulation research conducted for different variants of manufacturing and maintenance parameters, the following rules for decision support system can be formulated:
- the greatest value of throughput is reached for uniform distribution of operation times (V1),
- high availability of manufacturing resources (especially assembly resources) not results with high throughput and small lifespan of products,

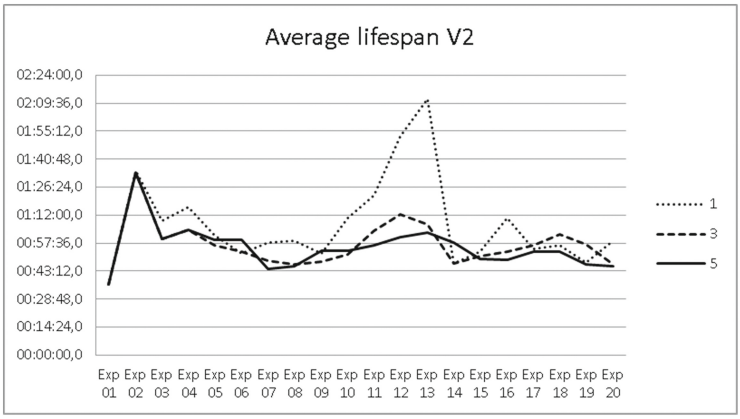


Fig. 7. The average lifespan of products for decreasing constant operation times variant V2

- the variant of operation times, number of maintenance workers and resources availability determine the throughput and average system lifespan.
- the results of the simulation experiments facilitate the defining of the configuration of manufacturing system for assumed throughput and average products lifespan.

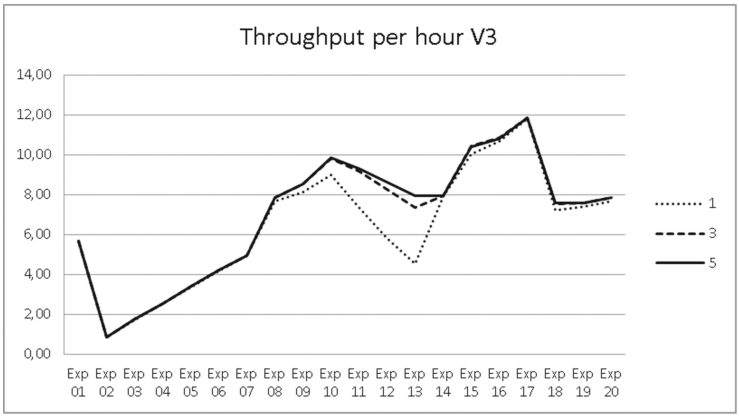


Fig. 8. The throughput of the system for increasing constant operation times variant V3

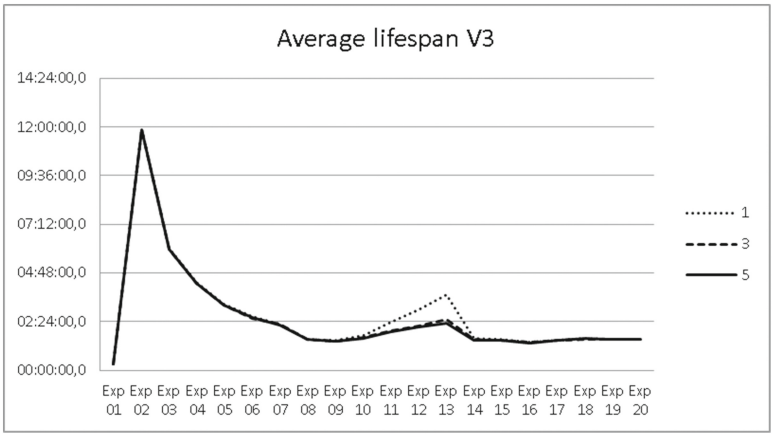


Fig. 9. The average lifespan of products for increasing constant operation times variant V3

4 Conclusions

In this paper a model for an intelligent maintenance management system (IMMS) is proposed. The system is integrated with a computer-simulation model for a manufacturing system which receives data for the knowledge database of manufacturing and maintenance parameters. In the knowledge database the results of the simulation experiments are recorded, and on the basis of the data the effectiveness parameters of the system can be determined. The proposed IMMS includes decision rules which describe the behaviour of the manufacturing system for different variants of input parameters (operation times, availability, number of maintenance workers, etc.). The data are presented as results of computer-simulation experiments. The analyse of the data allow the determining of correlations between configurations and the effectiveness of the manufacturing and maintenance system. The data processing facilitates the determining of the throughput or work in progress of the system on the basis of defined availabilities of manufacturing resources. In the former research the IMMS will be developed with risk analysis, learning and prediction mechanisms [11, 12]. As output parameters, OEE (the overall effectiveness of the equipment) will be taken into consideration.

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Sesion Separator “Intelligent Systems in Production Engineering”

A Heuristic and Simulation Hybrid Approach for Mixed and Multi Model Assembly Line Balancing

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Abstract. Industry 4.0 is focused on creating smart products, procedures and processes and calls for the need to create fully dynamic reconfiguration production lines in which products move autonomously through the system from one available resource to another. Planers should be equipped with the methods and IT tools required to develop a complex planning and explanatory models to control and re-configure manufacturing resource networks and production flow based on situation. In this paper a heuristics and simulation based approach for balancing of mixed and multi model assembly line is presented. The proposed IT solution is a computer hybrid implementation of combined data-driven automatic simulation models generation and heuristic for line balancing methods. A computer implementation of the proposed solution using the FlexSim simulation software with a practical example of its application are presented as well.

Keywords: Factory 4.0 · Mixed-model · Assembly line balancing · Data-driven · Simulation · Data mapping · Data transformation · Automatic model generation

1 Introduction

Increasing market competition, globalization, access to modern means of production and information cause that today the success on the market can be achieved by the manufacturers, who have the best and quickest ways to adapt to the new environment. Customer requirements become increasingly higher and still are modified, whereby are less predictable, but at the same time they are more specific and sophisticated. Constantly grows demand for different types and variations of the same product. Manufacturers must continuous improve the quality of products, periodically reduce the price of products (including production costs), and reduce the time of their execution to keep on demanding and often changing and highly competitive market. Meeting their requirements often occurs by changing the traditional approach towards more flexible production systems and up to the one-piece flow production system. In order to meet these requirements, the achievements of the Third Industrial Revolution are no longer enough. A third industrial revolution included Computer Integrated Manufacturing (CIM) and Flexible Manufacturing Systems (FMS) concepts of fully automated and unmanned factories, which were associated with the enormous investments and complexity in planning, operation, and maintenance [1, 2]. On the other hand, Lean manufacturing,

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Lean Management and Continuous Flow concepts were emerged with simple production principles. In this context, it calls for uses lean technologies, reduces in complexity for decentralized structures and self-organization [1–3]. Today, the answer to the growing word-market demand is to be the fourth industrial revolution (Industry 4.0) which will create the global networks – Cyber-Physical Systems (CPS) – containing manufacturing resources, warehousing and material handling systems and production facilities, capable of autonomously exchanging information to achieve increased flexibility and differentiation of management, planning and control of processes flow. It enables to simply changes to production plans and delivers the ability to respond flexibly to changing customer requirements. Industry 4.0 is focused on creating smart products, procedures and processes and on the aspect, i.e., digital integration of engineering and networked manufacturing systems. Research and development activities, among others, in the area of managing complex systems will need to be carried out if the concept of Industry 4.0 is to be successfully implemented. Engineers should be equipped with the methods and IT tools required to develop a complex planning and explanatory models. In this context, the modelling plays a key role in managing the increasing complexity of production systems [1–4].

Automatically planning and balancing of processing flow to use them in an online controlling of the production systems from available data is one of the big challenges. It will enable to control and re-configure manufacturing resource networks and production flow based on situation and geared towards meeting individual customer requirements. Current methods and tools are still based on "manual" data entry and analysing the results, neither on the full exploiting available data nor on the use of advantages on automated generated simulation models methods. Especially that the assembly line balancing problems traditionally consider the production resources as the only constraints in the system. The motivation regarding assembly line balancing results from the lack of intelligent methods and tools for an automatic creation of simulation model with simultaneous implementation of algorithms supporting the line balancing process. The proposed IT solution, which is a computer hybrid implementation of combined data-driven automatic simulation models generation and heuristic for line balancing methods, is consistent with the applications provided by CPS platform assumptions (support for collaborative manufacturing, service, analysis and forecasting processes [3]). The approach allow to eliminate the disadvantages associated with the traditional – expensive and time-consuming process of creating the simulation models. Methods of data mapping, data transformation and data exchange, between heterogeneous IT systems in the process of the simulation models generation have been used. It also suits the needs related to modularization and reuse strategies in order to enable ad hoc networking and reconfigurability of manufacturing systems [3].

The paper is organized as follows. Section 2 is dedicated to presenting a production organization in flexible continuous flow. Mixed Model assembly line balancing problem is discussed in Sect. 3. In Sect. 4 the methods for automatic generation of simulation models are presented. A computer implementation of the proposed solution and a brief description of the FlexSim simulation system with a case study of its application are presented in Sect. 5. Finally, in Sect. 6 our conclusions are presented.

2 Flexible Continuous Flow

Production in a continuous flow is a production organization in the manufacturing cells or production lines, where the parts are processed and conveyed directly from the work station to the next work station, one by one. It is the most efficient method of processing materials to the finished products and therefore should be used wherever it is possible [5, 6].

Continuous flow means that each station processes only one part that the next station expects, shortly before this, before actually needs it, whereas transport batch size is equal to one. Workstations are set close together in arranged sequence of technological operations for the product, the respective details are often transmitted directly from one station to another one. Employees are situated inside the manufacturing cell. The materials are supplied from the outside which does not restrict movement of employees. The result of such a production organization is that products flows continuously through all of the stations, without production downtime and stopping which are characteristic of the batch production.

The benefits from the use of the continuous flow is:

- minimization the flow time of the product through the process, which allows a quicker response to customer requirements,
- reduction of inventories of production (work in progress),
- short time of "turnover of money" (the time that elapses between paying for raw materials and receiving the money from the sale of products made from these raw materials),
- quick identification of the problems such as lacks, by possibility of quick identification of their occurrence,
- activating communication between stations which are connected together on the principle of "customer – supplier".

An important feature of industrial production is the type of production which results from customer demand for the product. Flow production system is well suited to volume production and mass production. In the case of the production in small or medium series although a flexibility of assortment plays a very important role, often are allocated designate groups of product with similar technological routes. This means the possibility of the production specialization which in practice transfers into the ability to build the manufacturing cells.

Moreover, the continuous flow is suitable for the type of production in which machines satisfy or could satisfy (after achieving the required improvements) two conditions:

- flexibility condition – quick change of the produced assortment in the manufacturing cells—which is possible in the case of short machine set-up times,
- specialization condition – avoiding universal machines but utilizing the machines performing a few operations in the one production cycle.

Assembly line is a specific example of flow production system and it is very typical for production of large quantities of standardized product. Due to the mass production

character the assembly lines contain a certain number of stations located around the transmission belt or other conveyor system. Produced semi-finished products comprising on the final product, are they placed on a conveyor belt and transferred from one station to the next. At each stations suitable tasks are performed, necessary to produce the semi-finished products and thereby the finished product.

Industry 4.0 calls for the need to create fully dynamic production lines in which products move autonomously through the system from one available resource to another and allow for dynamic reconfiguration lines (Fig. 1) [3].

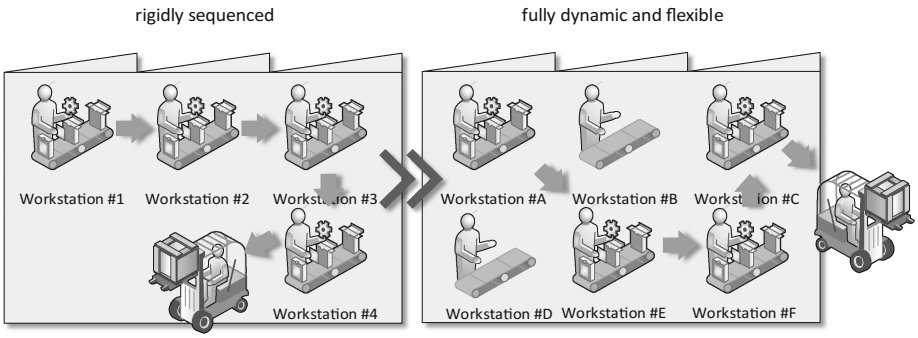


Fig. 1. Flexible dynamic manufacturing mixed/multi model line [3]

3 Mixed Model Assembly Line Balancing Problem

Over several decades the problem of balancing the assembly line is considered and solved by many scientists and engineers involved in scheduling. Description of the assembly line balancing problem requires knowledge of the number of tasks, their execution times and the relation of the order occurring between tasks assigned to the workstations. To achieve satisfactory efficiency of system, the assembly line has to be balanced, which means such and tasks assignment to respective stations, so the load on each of them is as equal and reasonable as possible. The basis of balancing problem is assignment a set of task to ordered set of work-stations so as the succession relationship are sustained while simultaneously and total idle time for all workstations is reduced [7, 8].

The assembly line is considered to be balanced when it performed all the operations according to the assumptions on the production in assembly lines, viz:

- operations are indivisible each task is assigned to exactly one station,
- previous relations (production technology) exacts earlier performed the appropriate tasks,
- time of performing the tasks on all the workstations does not exceed the duration of the time cycle,
- when all of workstations have to perform the same amount of work, then the line is balanced. In fact most of the line is unbalanced, because the actual amount of work at respective positions is different.

The first described line was serial line, but in relation to today's production systems it was the line without any restrictions. Today, the issue of balance line refers to a much wider group of production lines (lines with parallel stations, lines in the U-shaped, mixed- and multi-line, with positional constraints, with tools constraints, with surface around the workstation constraints, etc.). However, the solution in each case, taking into account constraints, comes to minimize. Minimization criteria may be different, depending on what is desired, for example, to minimize the time or to minimize the cost. Mixed assembly line has better benefits compared with the traditional one in respect of system flexibility, lead time, cost and product quality. The versatility of the system with the application of flexible operators and machines, means that the set-up times between models could be reduced enough to be ignored. Multi lines are the assembly lines for the production of two or more models belonging to different product groups. They are used in a range of industries and it improves the flexibility to cope with the changes in global demand. Multi-model lines, produce one set of products before proceeding with different set of products on the same production line.

3.1 Heuristic Algorithms in Assembly Line Balancing Problem

Assembly line balancing problem belongs to the NP-hard class problems. Therefore heuristic methods are used for finding the solution. Heuristic methods are very useful for finding acceptable solutions. Some measures of solution quality allow for assessment and acceptance of the resulting solution. The heuristic methods to be implemented with proposed simulation IT toll are [7, 9, 10]: Largest – candidate rule (LCR) method, Kilbridge and Wester column (KWC) method and Ranked positional weight (RPW) method. LCR method determines the minimum number of stations necessary to obtain the desired cycle time. Cycle time is defined as the ratio of the total available time and demand rate. The aim is divide tasks among the workstation. KWC column method is a heuristic procedure that assigns work elements to stations in accordance to their positions in the precedence diagram. In the KWC method the work elements are arranged into the columns. The biggest difference between this method and LCR is that the tasks which are at the end of precedence graph may first be assigned to the station with the reasons for the large value of task time. RWP combines the strategies of the LCR and KWC method. In this method tasks are ranked according to their importance in the precedence graph. Ranked positional weights take into account the positions in the precedence graph task and time value [9, 10]. These are only selected heuristics that we implemented in the proposed software solution, nothing stands in the way to add more methods to the software.

4 Data-Driven Automatic Simulation Models Generation

The proposed IT solution is a computer hybrid implementation of combined data-driven automatic simulation models generation and heuristic for line balancing methods. Automatic model generation approaches can be classified into three main categories: parametric approaches, structural approaches and hybrid-knowledge-based approaches. Our

software is based on hybrid parametric-approach, data mapping and transformation methods. The distinguishing feature of the proposed solution is that the simulation model is created automatically based on specific data instances, obtained from the existing in the enterprises MRP/ERP systems, simultaneously with its parameterization according to data about the planned assembly process. The models could therefore be created by planner without knowledge of how to build the simulation model. In this approach to build a simulation model does not require the use of specific modules of simulation systems which are used in traditional approach (the model is created automatically using data analysis methods and algorithms processing) [11–13].

The results of the simulation model generator is script code in internal script language (FlexScript) of FlexSim simulation software, creating specific parts of the simulation model for the specific structure of the production system based on data obtained from the MRP/ERP systems [14]. This code is responsible for creating simulation objects that make up the manufacturing system, i.e.: manufacturing resources, inter-operational buffers, warehouses, input and output buffers, and information resources, i.e.: tables containing data about the number of models to be produced, the set of tasks and task times for each model, the quantity to be produced for each model and data on processes routes as a function of carrying out the connection between appropriate objects in the model to perform calculations and simulation experiments. The model is supplemented by scripts containing the algorithm for the sequencing heuristic where the work elements are assigning to different workstations in generated balancing feasible solution (Fig. 2). Apart from supporting the balancing process the generated model can be used by the planner for the analysis of the production flow, which include, among others, resource utilization, storage capacity optimization, completion date of production orders

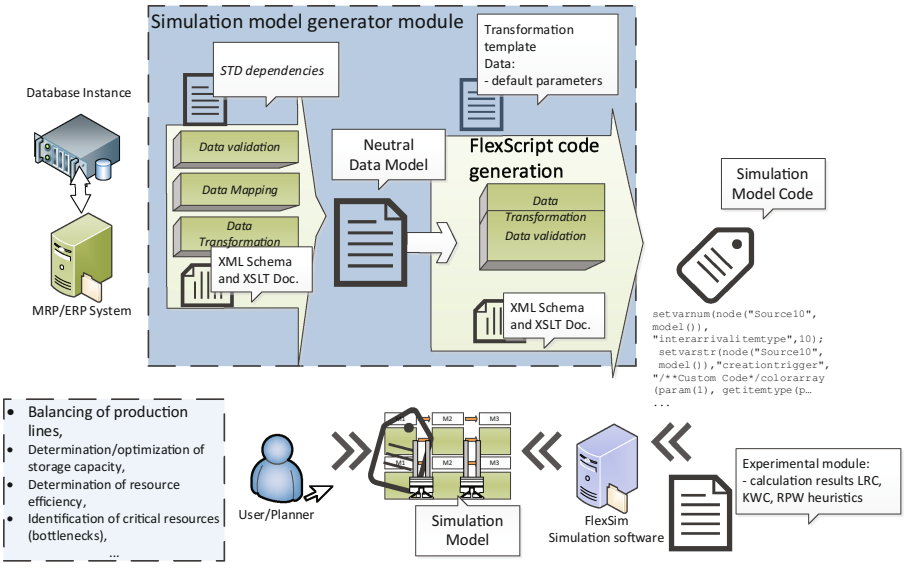


Fig. 2. Data-driven automatic simulation models generation

verification and to manage the quality of the production system (working without deadlocks and starvations).

5 Practical Implementation Example

Practical implementation of the presented method was carried out using a commercial FlexSim simulation software [14]. The process of data transformation (model generation) was carried out using RapidSim software, which is computerized implementation of the previously described methods. FlexSim provides extensive support for building, analysis and verification simulation models developed by the FlexSim Software Products, Inc. FlexSim is fully customizable, graphically-oriented simulation software that integrates modelling, simulation and 3D visualization and animation in 3D object oriented drag-drop-connect environment. In FlexSim, discrete or fluid pre-defined modelling object are the most basic building element of a simulation and allows users to change the behavior of objects, which can be parameterized at the stage of creating the model. The discrete objects (objects that create, send, store items awaiting processing, move items through the model, group and perform operations on products, etc.) are used to develop discrete-event simulation models where model behavior results from events that occur at discrete points in time [15]. Objects are available in the libraries of objects the extent corresponding to the possible uses of the various versions. Further provides mechanisms that import and export data and facilitate the analysis of data. Most of the tasks related to the construction and parameterization of the model and writing custom logic can be realized using the internal programming scripting language FlexScript. Also, FlexScript is nearly identical to C++ in its syntax and application.

The data mapping and transformation is realized in the RapidSim author software [14], for which the data transformation documents (XSLT) can be developed independently. Input files to the RapidSim are XSLT documents constitute the definition of transformation functions for data where the process of data exchange and data transformation between the data source (from MRP/ERP system) and the target (FlexScript) is executed. Finally, the code of the simulation model is generated (Fig. 3).

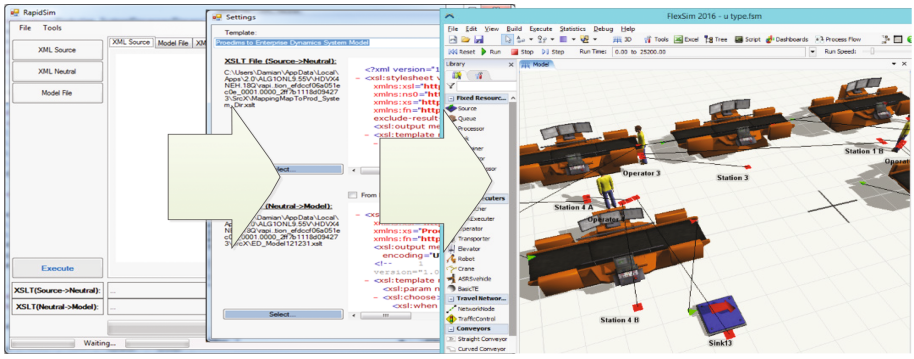


Fig. 3. RapidSim—data mapping and transformation

To analyze the solution of assembly line balancing problem, using 3 heuristic methods described above, an example of gear motor production (two models) was considered.

Figure 4 shows a precedence graph, which is constructed to help visualize the preceding tasks. Numbering of the nodes in the graph, corresponds to the number of a task and values in the upper right corner of each node correspond to duration of this task. Table 1 includes the processing times for 12 tasks.

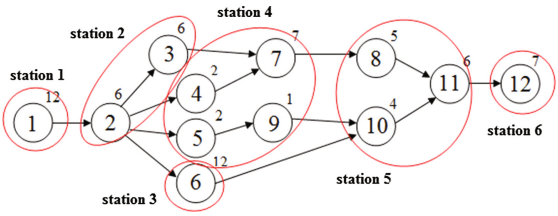


Fig. 4. Precedence graph and task assignment

Table 1. Tasks and operations times

Model #1				Model #2			
Task No	Task times	Task No	Task times	Task No	Task times	Task No	Task times
1	12	7	7	1	10	7	1
2	6	8	5	2	6	8	5
3	6	9	1	3	7	9	1
4	2	10	4	4	6	10	5
5	2	11	6	5	5	11	2
6	12	12	7	6	13	12	6

With the help of RapidSim software, the script code of the model has been generated. Loading the resulting output document (MOD) in FlexSim software allows for automatic creation of a complete simulation model (Fig. 5), which is ready to carry out calculation and simulation experiments, including, i.e. analysis of available quantity and capacity of means of transport, timetables and potential hazards collisions.

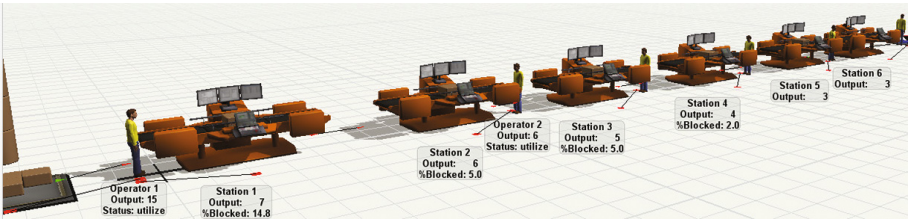


Fig. 5. Simulation model

Both models have been balanced using RPW method. Lines consist of six assembly stations, which carry out individual assembly operations. The generated feasible solutions for fixed number of stations (task assignment) are shown on Fig. 4. After conducting analysis of two manufactured models, following results were obtained. The work on the assembly line is evenly distributed. Data analysis was done for the steady state period of simulation – without taking into account the start-up and cease phases of production in the system. Processing at stations 1–5 is between 77%~95%, except last station, which is utilized in 46%. Similar values were obtained for the utilizer of individual operators in the system. Last station has idle time which is effect of completing its tasks faster. Total processing time of station 6 is shorter than previous station. The results in Table 2 show that workload is evenly distributed amount operators. Efficiency of the all workstations is 81%.

Table 2. Simulation results

Object	Processing/utilize	Idle	Blocked	Waiting for operator	Waiting for transport	Travel empty	Travel loaded
Station 1	77,53%	0,42%	21,99%	0,00%	0,06%	0,00%	0,00%
Station 2	86,85%	0,19%	12,87%	0,03%	0,06%	0,00%	0,00%
Station 3	86,85%	0,15%	12,91%	0,03%	0,06%	0,00%	0,00%
Station 4	94,10%	0,16%	5,65%	0,04%	0,06%	0,00%	0,00%
Station 5	94,51%	5,43%	0,00%	0,00%	0,06%	0,00%	0,00%
Station 6	46,08%	53,78%	0,00%	0,08%	0,06%	0,00%	0,00%
Operator 1	77,53%	21,99%	0,00%	0,00%	0,00%	0,23%	0,17%
Operator 2	86,85%	12,98%	0,00%	0,00%	0,00%	0,03%	0,08%
Operator 3	86,85%	12,96%	0,00%	0,00%	0,00%	0,03%	0,09%
Operator 4	94,10%	5,71%	0,00%	0,00%	0,00%	0,04%	0,09%
Operator 5	94,51%	5,36%	0,00%	0,00%	0,00%	0,00%	0,06%
Operator 6	46,08%	53,64%	0,00%	0,00%	0,00%	0,08%	0,14%

6 Conclusions

The proposed combined method of data-driven automatic simulation models generation and heuristic for mixed and multi model assembly line balancing can become an efficient and effective IT tool to support the engineers in planning, control and re-configure manufacturing resource networks and production flow. The proposed RapidSim software solution enables, among others, to perform rapid analysis in many aspects and to achieve increased flexibility of management, planning and control of processes flow. It allow to eliminate the disadvantages associated with the traditional – expensive and time-consuming process of creating the simulation models and enables to simply verification of changes in production plans and deliver the ability to respond flexibly to changing customer requirements. Thanks to its openness it may be commercialized with practically any ERP or simulation software. The subject of further work in this area will

involve analysis of operator assignment to the station and interoperation buffers (place and time) consideration.

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A New Petri Nets Based Approach for Modeling of Discrete Manufacturing System

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Abstract. This paper presents a new approach for modeling discrete manufacturing systems using Petri nets. Starting with the literature review of the classical approaches, this paper describes the new approach known as Activity-Oriented Petri Nets (AOPN). The AOPN approach provides expressive Petri net models that are powerful enough for modeling complex and large-scale manufacturing systems. The AOPN approach provides compact Petri net model too when a large number of resources are used in the manufacturing system. GPenSIM is a software implementation of AOPN on MATLAB platform. Using a flexible manufacturing system as a running example, this paper also shows how a real-life manufacturing system can be modeled and simulated with the GPenSIM software using AOPN approach.

Keywords: Modeling of manufacturing systems · Discrete event systems · Petri nets · Activity-Oriented Petri Nets (AOPN) · GPenSIM

1 Introduction

Modern manufacturing systems are intelligent, complex, large, and expensive. For modeling these sophisticated systems, we need advanced tools. This paper focuses on discrete manufacturing systems and presents a new approach that is based on Petri nets.

Petri nets, because of its graphical nature, are self-documenting and easy to understand. The mathematics behind Petri nets is also easy to grasp. Hence, Petri nets are a suitable framework for modeling discrete event systems [1]. However, there is indeterminism in Petri nets, and it has a tendency to become huge when many resources are involved in the system.

This paper introduces a new approach known as the Activity-Oriented Petri Nets (AOPN) that provides a solution by developing discrete models in two phases: in the first phase, a simpler static Petri net model ("skeleton") is developed, and in the second phase, the run-time details are added. This approach, while keeping the Petri net model size to a minimum allows implementation of sufficient logic on the model so that advanced discrete manufacturing systems can also be modeled.

In this paper: A short literature review is given in Section 2. Section 3 presents the classical approach for modeling manufacturing systems with Petri nets. Section 4 presents the new approach AOPN. Finally, Section 5 presents some discussions.

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2 Literature Review: The Subsystems of a Manufacturing System

According to [1], a manufacturing system is composed of two main parts: The physical system and the decision-making system (DMS).

2.1 The Physical System

The physical system can be divided into subsystems [2]:

- The active systems (e.g. machines).
- The passive systems (e.g. buffers).

Some of the physical systems can be active or passive (e.g. robots) depending on the situation. For instance, a robot can be used as an active system (machining an input material), whereas in some other situations, it can be used as a passive system (handling). Since this paper focuses only on modeling with Petri nets, the physical system is modeled as a decision-free Petri net, consisting of many modules that represent the functional entities (e.g. the machines, transportation systems, buffers, etc.). When modeling manufacturing systems with Petri nets, there is a degree of indeterminism involved in the model. For example, which transition is to fire if there are several transitions enabled by the same enabling tokens? In addition, Petri nets are incapable of realizing all the modeling logic of real-life manufacturing systems, despite some Petri nets extensions can do so at the expense of the analytical power [3].

2.2 The Decision-Making System (DMS)

The decision-making system (DMS) is to cope with the incapability of the physical system to make decisions on its own and to manage the indeterminism in the Petri net model. The DMS can be further divided into two subsystems: Physical System State-based DMS (P-DMS) and Environment State-based DMS (E-DMS) [1].

- P-DMS is the subsystem that computes the decisions based on the input from the physical system; for example, the control decisions that are made based on the sensor data from the machines.
- E-DMS is the subsystem that computes the decisions based on the inputs from the external environment. For example, the decisions that are made based on the market conditions, and unplanned stoppage of production due to unavailability of transportation of products.

The P-DMS is further partitioned into two subsystems: iP-DMS and oP-DMS:

- The iP-DMS includes all the P-DMS decision processes that can be modeled as a decision-free Petri net (iP stands for inside Petri net).
- The oP-DMS includes all the P-DMS decision processes that cannot be modeled as a decision-free Petri net (oP stands for outside Petri net).

Since we are primarily interested in modeling manufacturing system with Petri nets, we group the set of decision processes belonging E-DMS and oP-DMS into the subsystem called Outside-DMS (O-DMS). Thus, O-DMS = (E-DMS) U (oP-DMS) [1].

For practical modeling of a manufacturing system, not all the subsystems that are shown in the Fig. 1 are needed. The most needed and often used subsystems are the active and passive physical systems, and the iP-DMS and the O-DMS.

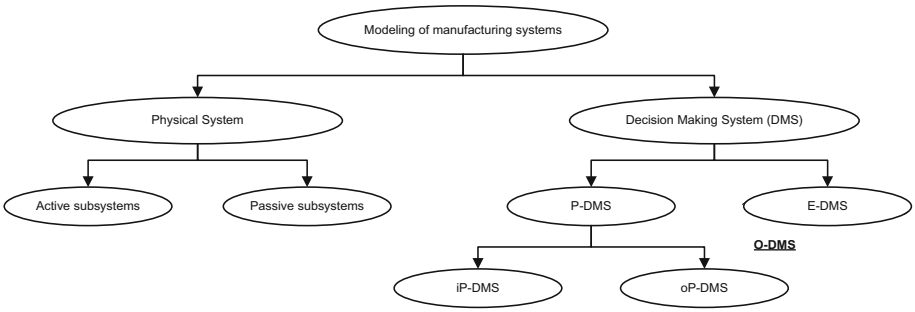


Fig. 1. The subsystems of a manufacturing system

2.3 Interaction Between O-DMS and iP-DMS

A Petri net model of a large manufacturing system consists of several modules that represent functional entities of the manufacturing systems. These Petri net modules makeup the iP-DMS; O-DMS is the decisions that are made outside the Petri net modules. The interaction between the iP-DMS and O-DMS subsystems happens through the control places [4], as shown in the Fig. 2.

In the Fig. 2, the Petri net model consists of two subsystems, the iP-DMS and the O-DMS. The iP-DMS consists of six Petri net modules, representing the arrival of raw materials, two machines, one robot for handling, a testing station, and a unit for transportation of products out of the manufacturing facility. The Petri net modules are controlled (enabled) by the control places (represented by two concentric circles), which are under the complete control of the O-DMS. Unlike ordinary places in a Petri net, the control places do not loose tokens when the input transitions (that are connected to the control places) fire. The tokens in the control places are only for enabling the respective transitions. The tokens are deposited into and removed from the control places by the O-DMS.

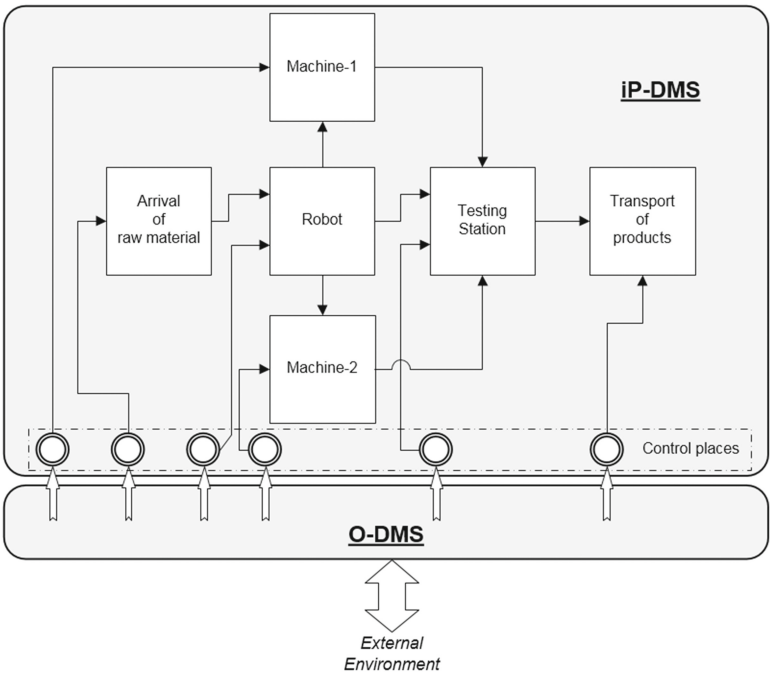


Fig. 2. Classical approach: the interaction between the iP-DMS and O-DMS subsystems happens through the control places

3 The Classical Approaches for Developing Petri Net Models of Manufacturing Systems

We start this section with an example to illustrate the classical approach for modeling a manufacturing system with the subsystems O-DMS and iP-DMS. Then, we show how the new approach can provide more expressive and yet compact Petri net models.

3.1 Modeling by the Classical Approach: An Example

Figure 3 shows the Petri net model of a simple Flexible Manufacturing System (FMS). This FMS consists of an input conveyor belt, an output conveyor belt, a horizontal CNC machine (H-CNC), a vertical CNC machine (V-CNC), and a testing station. The FMS also has a robot to move raw material and parts between the elements mentioned above. Since the model is so simple, the transitions and places are not grouped into modules as shown in the Fig. 3.

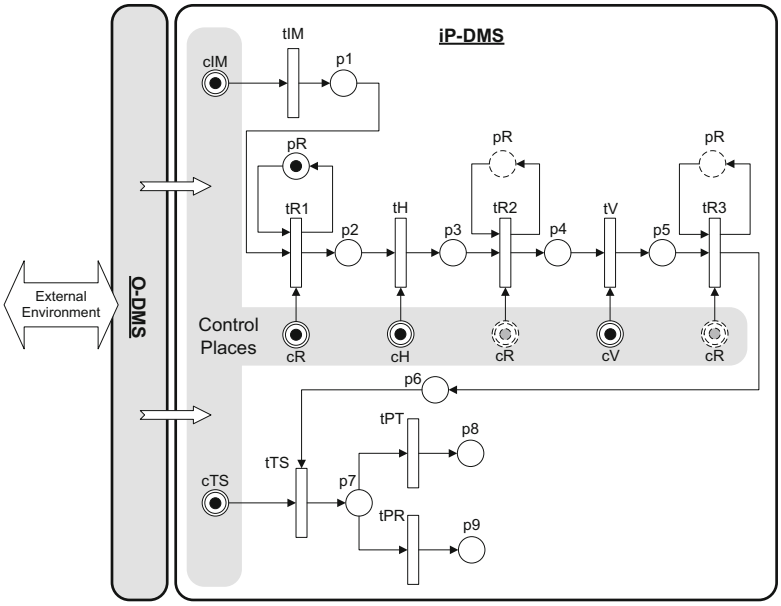


Fig. 3. The model of a simple Flexible Manufacturing System.

When the input material arrives (represented by the transition tIM), the robot picks them from the conveyor belt (tR1) and places into the H-CNC machine. The FMS performs a simple job with two operations: the first operation (tH) is performed by the H-CNC machine and the second one (tV) is performed by the V-CNC machine. After these two operations, the robot put the product into the testing station (tR3). If the product passes the quality test (tTS), it goes into (tPT) the output conveyor belt; otherwise, it will be discarded automatically (tPR).

Table 1. The elements of the Petri net model.

Part	Purpose	Part	Purpose
tIM	The flow of input raw materials	tPT	Transportation of quality products
tR1	Moving raw material from input conveyor belt into H-CNC	cIM	Control place for controlling the flow of input material
tH	Operation on the H-CNC	cR	Control place for enabling the robot
tR2	Moving parts from H-CNC into V-CNC	cH	Control place for enabling H-CNC
tV	Operation on the V-CNC	cV	Control place for enabling V-CNC
tR3	Moving parts from V-CNC into testing station	cTS	Control place for enabling the testing station
tTS	Tests on the testing station	p1-p9	Buffering places
tPR	Removal of disqualified products	-	-

Table 1 lists the transitions and the places involved in the Petri net model. In the Petri net model, the control place cR and the place pR are shown three times, in order to avoid cluttering of connections.

3.2 The Control Places

In the classical approaches, control places are the main mechanism for interfacing iP-DMS and O-DMS, as shown in the Figs. 2 and 3 [1, 3, 4]. A control place contains at most one token, where the token is deposited into and removed from by O-DMS. However, the implementation of the token addition and removal is not defined in any works. Also, the control places can only offer Boolean ON/OFF control, which is very limited in scope when it comes to modeling present day intelligent, complicated, and large-scale manufacturing systems.

4 A New Approach

In the previous section, the control place based mechanism was introduced for Petri nets based modeling of manufacturing systems. This mechanism has the following limitations:

1. The control places have to be treated as special places, as they do not behave like normal places. Thus, the mathematical tools that are so useful for analysis of Petri net models (such as reachability tree) become useless.
2. As stated earlier, for large Petri net model, the O-DMS has to control a large number of control places.
3. Most importantly, the control place based mechanism offers a very primitive control power, namely Boolean ON/OFF type control.

In the new approach proposed in this section, the control places are eliminated altogether. Instead, the transitions are controlled by the O-DMS. To allow O-DMS directly control the transitions inside the iP-DMS, each transition is equipped with pre- and post-processors. The new approach is known as the Activity-Oriented Petri Nets (AOPN) [5]. The software tool General purpose Petri net simulator (GPenSIM) is a realization of AOPN on the MATLAB platform; GPenSIM is freely available from the website [6]. Both the AOPN methodology and the software GPenSIM are developed by the author of this paper [2, 7].

4.1 Activity-Oriented Petri Nets (AOPN)

In the AOPN approach:

1. There are no control places. A Petri net model or module only consists of ordinary places, transitions, and arcs.
2. Every transition in the Petri net module can have a pre-processor. The pre-processor of a transition will be executed whenever the transition becomes enabled. Only if

the conditions coded in the pre-processor are satisfied, then the transition is allowed to start firing.
3. Every transition in the Petri net module can have a post-processor. The post-processor of a transition will be run immediately after the transition completes firing.
4. The O-DMS control every transition through the pre-processors and post-processors.
5. The transitions in a Petri net model usually represent active physical systems only (e.g. CNC machines). The passive physical systems (e.g. AGVs transporting materials), referred to as 'resources' in AOPN terminology, are not usually represented by transitions in the Petri net model.
6. When an active system (represented by a transition) needs a resource to perform an operation, the active system requests the O-DMS for the resource. If the resource is available, the O-DMS allocates the required resource to the transition so that the transition can start firing. When the transition finishes firing, it releases the resource back to O-DMS.
7. O-DMS also computes details about the resource usage: how many resources were used, their efficiency of utilization (line efficiency), the costs involved in the resource usage, etc.

The pre-processor and the post-processor are MATLAB files (M-files). Since these are M-files, we can write any code, as much as we want, for bidirectional information flow and control flow between O-DMS and the Petri net model (iP-DMS) (Fig. 4).

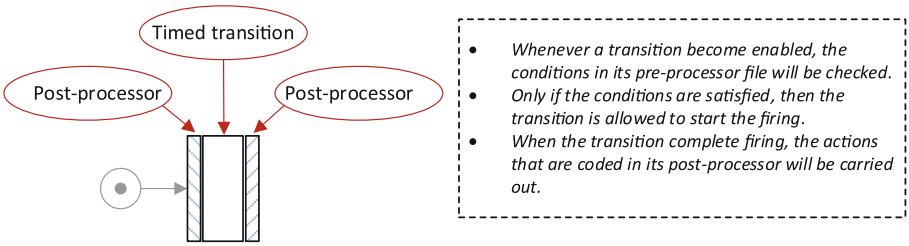


Fig. 4. Firing of a transition: the pre- and post-processor files.

Modeling a discrete event system by the AOPN approach consists of two phases [5]:

- Phase-I: Developing the static Petri net model
- Phase-II: Developing the run-time model

4.2 Phase-I: Developing the Static Petri Net Model

In the Phase-I, the static Petri Net model is developed. In this phase, mainly the activities are considered and they are represented by transitions interleaved with buffering places (e.g. places p10–p15 in the Fig. 5). The resources (passive physical systems) are grouped into two groups such as 'focal' resources and 'utility' resources. Only the focal resources are included in the static Petri Net model; the utility resources will be considered later in the phase-II (the run-time model). Thus, a compact Petri Net model is obtained with only the transitions representing the activities and, if there are any focal resources, they

will be represented by places. Using the tool GPenSIM, coding the static Petri net in phase-I will result in the Petri net definition file (PDF).

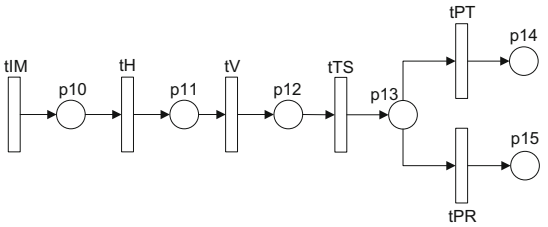


Fig. 5. The static Petri net model resulting after phase-I of the AOPN modeling approach.

Figure 5 shows the static Petri net model. In this model, the robot is assumed as a utility resource thus not shown in the model. The active physical systems such as H-CNC, V-CNC, and the testing station are represented by the transitions tH, tV, and tTS, respectively. Also, the arrival of raw materials is represented by tIM and the outflow of the testing station, namely accepted and rejected parts are represented by tPT and tPR, respectively.

The Petri net definition file (PDF) is the GPenSIM code for implementing (programming) the static Petri net model in GPenSIM software. The PDF for the static Petri net shown in the Fig. 5 is given in the Fig. 6.

```
% Conference ISPEM-Wroclaw, Sep 2017
% PDF: (fms_pdf)

function [png] = fms_pdf()

png.PN_name = 'A Simple FMS';

png.set_of_Ps = {'p10','p11','p12','p13','p14','p15'}; % set of places
png.set_of_Ts = {'tIM','tH','tV','tTS','tPT','tPR'}; % set of trans
png.set_of_As = {'tIM','p10',1,'p10','tH',1,'tH','p11',1,... %tIM and tH
                 'p11','tV',1, 'tV','p12',1, ...          % tV
                 'p12','tTS',1, 'tTS','p13',1, ...        % tTS
                 'p13','tPT',1, 'tPT','p14',1, ...        % tPT
                 'p13','tPR',1, 'tPR','p15',1, ...        % tPR
```

Fig. 6. PDF for the static Petri net model shown in the Fig. 5

4.3 Phase-II: Developing the Run-Time Model

In the phase-II of the AOPN approach, the run-time details that are not considered in the phase-I are added to the Petri Net model; e.g. transitions (activities) requesting, using, and releasing of the utility resources are coded in the run-time model (Fig. 7). Using the tool GPenSIM, the run-time details in the phase-II will result in the pre-processor file COMMON_PRE.m and the post-processor file COMMON_POST.m.

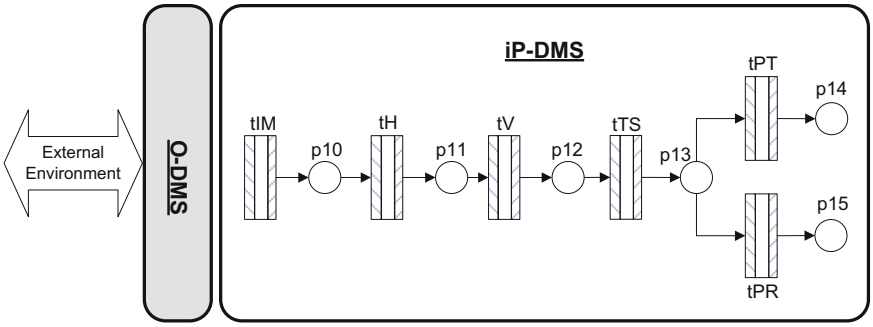


Fig. 7. The run-time Petri net model obtained after the Phase-II of the AOPN approach. The run-time details are coded in the M-files COMMON_PRE and COMMON_POST

In the COMMON_PRE file (Fig. 8), the following two conditions are coded:

- The transitions tH, tV, and tTS will be requesting the robot to load the part into the respective machine.
- About 2% of the products are rejected by the testing station.

```
function [fire, trans] = COMMON_PRE(trans)
% any conditions for enabled transitions are coded here

% if the transition is either tH, tV, or tTS
if ismember(trans.name, {'tH','tV','tS'}),
    % reuqest the robot to upload the part
    % fire, only if robot does its job
    fire = requestSR({'Robot',1});
    return
end

% if the transition is either tPT or tPR
if ismember(trans.name, {'tPT','tPR'}),
    % about 10% of products get rejected
    random_value = rand(); % random value between 0 and 1

    % if the transition is tPR
    if strcmp(trans.name, 'tPR'),
        fire = lt(random_value, 0.1); % tPR fires if value < 0.1
    else % this is 'tPT'
        fire = ge(random_value, 0.1); % tPT fires if value ≥ 0.1
    end
    return
end

fire = 1;  % allow all other transitions (e.g. 'tIM') to fire
```

Fig. 8. The COMMON_PRE file.

In the COMMON_POST file shown in the Fig. 9, the transitions tH, tV, and tTS will be releasing the robot after usage.

```
function [] = COMMON_POST(trans)
% any code for post-firing actions are coded here
% if the robot was aquired for loading the parts
% then release it after its service
release();
```

Fig. 9. The COMMON_POST file.

4.4 GPenSIM Code for Simulations

For simulation of the FMS problem with GPenSIM, four M-files are needed:

- Petri Net Definition File (PDF): this is the GPenSIM code of the static Petri net. For example, the PDF given in the Fig. 6 is the GPenSIM code for the static Petri net model shown in the Fig. 5.
- Main Simulation File (MSF): In this file, the initial dynamics (e.g. initial tokens in the places: none in this example), the firing times of transitions, and the availability of the resource 'Robot' are declared. The MSF is shown in the Fig. 10.

```
% Conference ISPEM-Wroclaw, Sep 2017
% Main Simulation File (MSF): fms.m
clear; clc; close all;
global global_info
global_info.STOP_AT = 350;

pns = pnstruct('fms_pdf'); % Declare the PDF

% Assign the initial dynamics
dyn.ft = {'tIM',10, 'allothers', 1}; % the firing times
dyn.re = {'Robot',1,inf};  % the systems resources

% combine the static graph with initial dynamics
pni = initialdynamics(pns, dyn);

% Run the simulations
sim = gpensim(pni);

% pront the results
plotp(sim, {'p14','p15'});
```

Fig. 10. The main simulation file.

- COMMON_PRE: In this file, the conditions for the enabled transitions to start firing are coded, mainly about reservation of the required resource 'Robot' by a transition, and using the resource if it is allocated.

- COMMON_POST: the post-firing actions of the transitions are coded here, usually releasing the resource 'Robot' after usage.

For reproducibility, the complete code for simulation (the four files mentioned above) is given on the web page [8]; interested readers are encouraged to visit the web page for downloading the codes and experimenting with them.

4.5 Simulation Results

Simulation results show that some products with the probability of 10% get rejected by the testing station. The rejected parts end up in the buffer p15, whereas the quality products are placed in the buffer p14 (Fig. 11).

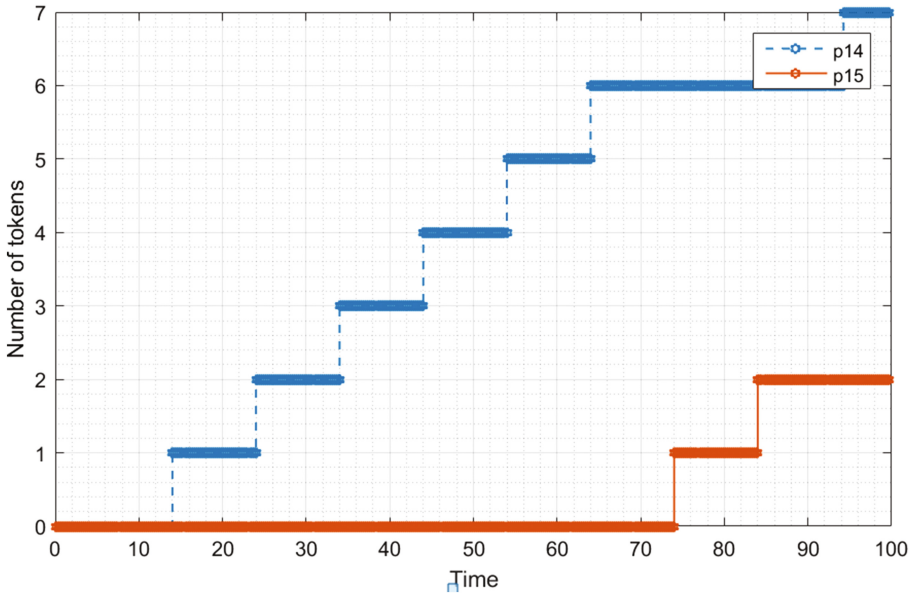


Fig. 11. Simulation results.

5 Discussion

The FMS example shows that the AOPN approach provides a simple two-way information and control flow between the Petri net model (iP-DMS) and the surrounding decision-making system (O-DMS) via the pre- and post-processors. The classical approaches that use control places for interfacing the iP-DMS and O-DMS provide only primitive Boolean ON/OFF control, whereas with the AOPN approach any control algorithm can be coded into the pre-processors and post-processors. The FMS example also shows that implementation of the Petri net models using GPenSIM usually results

in compact code as none of the files (PDF, MSF, and the pre- and post-processors) is more than half page long.

In summary, the duality – the compact Petri net models because of the activity-oriented view and the powerful and flexible resource management by the O-DMS, enables modeling, simulation, performance analysis, and control of any discrete event system.

6 Conclusion

GPenSIM is the software realization of the new AOPN approach. Though AOPN approach and the software GPenSIM are new, there are Doctoral dissertations, and many Master theses are done based on AOPN/GPenSIM. GPenSIM is used to solve many industrial and research problems in diverse fields of engineering. For example, in discrete manufacturing systems and production planning, airport capacity modeling, fish supply chain, Speech recognition, computer gaming, Marine-Diesel Engine Control, Service-Oriented Architecture, Grid-Computing, E-commerce, and Bluetooth Devices, to name a few [9, 10].

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Algorithm of Autonomic Shaping of Workflow

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Abstract. In the article there is a presentation of the model of shaping level of workflow which is possible to use in formulation of autonomic software of production system. Application with model in intelligent production system is on the second level – level of gathering and processing data. Assumptions of presented models assume customization (personalization) of created product in elastic production system. Flexibility of production system achieved by flexible production sockets with use of economic robots with full cooperation with operator. Exemplary production system have been shaped due to the level of workflow of m input streams and n processing phases. In consideration there is a single production where number of orders k_p in time Δt is deterministic value smaller than 30. The rest of parameters as realization time in consecutive processes are random variables with characteristic designation of probability thickness. Presented model of the whole production system can be used as a system of early warnings before anomaly situations of overstretching or under-stretching single sub-systems of the whole system.

Keywords: Shaping of the level of workflow · Balancing of the production line

1 Introduction

In current production structure based on ERP (Enterprise Resource Planning) systems, most common are ideas of intelligent production compatible with Industry 4.0. Technological development based on artificial intelligence forces changes in production management, basing on so called cyber-physical systems. Those systems enable global communication between autonomic systems which makes integral unity. Inception of those systems in particular economic areas totally changes ideas of production management. New, complex and dynamic systems can assure unreachable level of efficiency with minimal input of human. Factory of future is efficient in terms of costs but also digitalized and automated production structure. Modern systems of production should be elastic without regard for dynamics of changes, variability and customized production. Production compatible with Industry 4.0 idea is remotely steered, autonomic and robotized structure. In these structures it is necessary to process and analyze large amount of data in real time. Putting analytical and calculation system in data cloud with implementation of advanced decisive algorithms enable access and management from everywhere, anytime.

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New production model resign from “mass production” and focus on “mass customization”. Responsive production – fully customized production forces flexibility from production structure. Flexibility is a pure form of customization with short reaction time from a moment of need. Aforementioned parameters are determinant of changes in production system status. To minimize losses on operational level, it is important to keep stability of production structure. This stability can be define in a few different ways – as a cycle of repetitions in certain frequency or invincibility of particular values in realized processes. In the article there is a elaboration on algorithm of intelligent production line balancing. Balance parameter is a level of workflow in single production sockets in dependence to complex production structure as a whole.

In the article there is a presentation of model of indicating level of workflow for complex production system in which a product fully customized product is created. Final products in production chain are analyzed. Those are not input components for any other production systems. The purpose of this model is to indicate variants of workflow levels in complex structure composed from n independent processes (phases of production). Model is based on random variables and on next steps it will help with shaping decisive variables to indicate optimal conditions of work in dynamic and autonomic production system.

2 Characteristics of Analyzed System

There is a consideration of exemplary production system made of n processes (phases of processing). In the model there is assumption that variable machine resources dependent on process. In first phase of modelling there is general theory of complex systems accordingly to this in which analyzed system has been grouped for n independent sub-systems. In consideration there is another assumption that in separated subsystem there is realization of only one process on m_n machine resources. Figure 1 presents a scheme of analysed system.

Complex production system of h input streams for $l = 1, 2, \ldots, h$ has been modelled and shaped in terms of workflow. In each and every stream there are n independent processes for $i = 1, 2, \ldots, n$. Single final product Y^L consists of N components for $L = 1, 2, \ldots, K$. In each and every process for $i = 1, 2, \ldots, n$ there are k_p elements done, where k_p is a number of single tasks determined by the number of orders from clients for $p = 1, 2, \ldots, s$ in t time and from number of y^N components from BOM (Bill of Materials). structure. Figure 1 presents a scheme of analyzed structure.

Formulated model of shaping of level of workflow takes into consideration size of production party. Case for $k_p \leq 30 \; \forall \, p = 1, 2, \ldots, s$ has been considered. Level of workflow has been set, basing on time necessary to do all the tasks and processes of single final product Y^L. In the article it has been set that all single final products (Y^L) are created from the same number of element y^M. Realization time for the single task is random variable marked as $\tau_{l,i,j}$ compatible with exponential distribution with characteristic parameter $\lambda_{l,i}$ separate for i – process in l – stream for each j – $\tau_{l,i,j} \sim \text{Exp}(\lambda_{l,i})$. of level of workflow

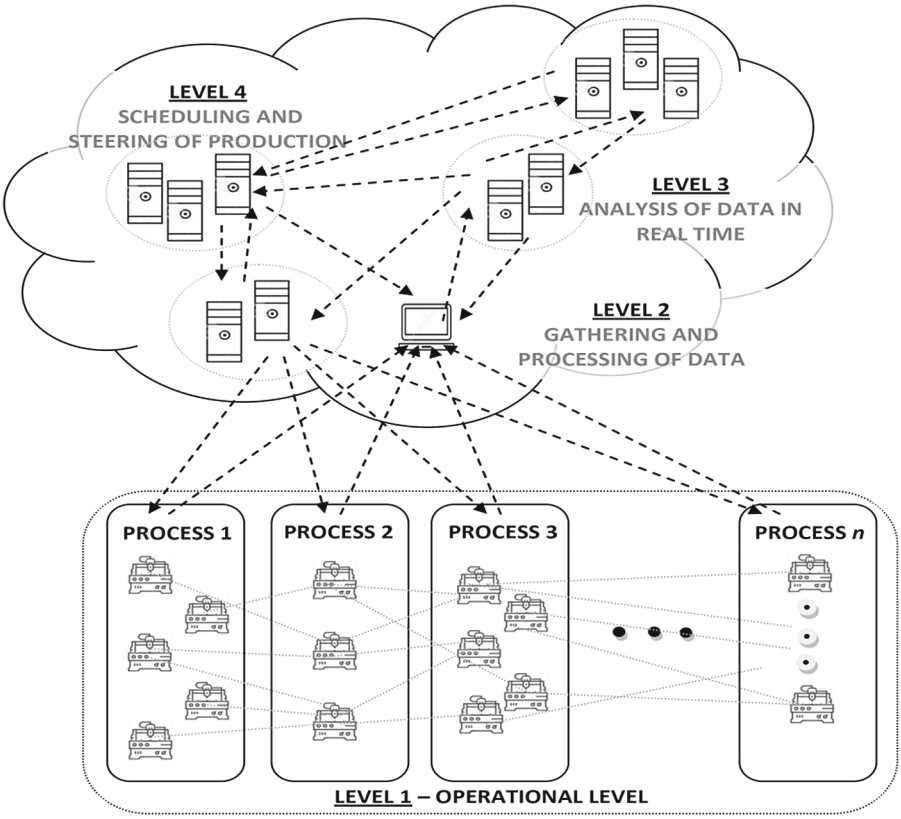


Fig. 1. General scheme of considered production system

for single final product Y^L are expressed with a time necessary to conduct all parts of the processes and can be determined with a formula [1]:

$$P\left(\tau \in \langle \tau_1, \tau_2 \rangle\right) = \left[\prod_{i=1}^{n} \lambda_{i,l}\right] \cdot \int_{\tau_1}^{\tau_2} \sum_{j=1}^{n} \frac{e^{-\lambda_{j,l} \cdot \tau}}{\prod\limits_{\substack{k \neq j \\ k=1}}^{n} (\lambda_{k,l} - \lambda_{j,l})} d\tau \tag{1}$$

where: $\lambda_{i,l}$ – parameter of exponential composition depends on i – process and l – stream.

Shaping level of workflow for the whole production structure should adjust all processes and all tasks realized in time Δt. Level of workflow is determined by implemented in company technology, BOM structure and production schedule which comes from clients' orders. In next part of article, there will be a presentation of model to assign level of workflow for particular processes in time Δt for k_p necessary to execute tasks in i – production process(Fig. 2).

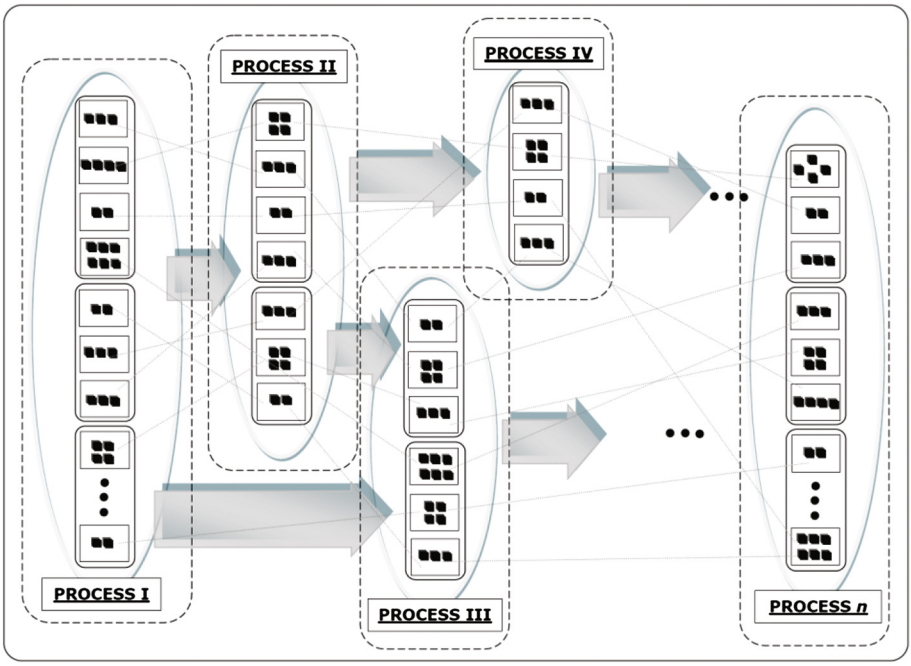


Fig. 2. Scheme of analyzed structure in process

3 Shaping of Workflow of *i* – production Process

In statistic field we can set so called "small trial" for which it can be assumed that amount of elements in considered system is smaller or equal to 30; and also so called "big trial" for which amount of elements in analyzed system is bigger than 30 [2, 3]. Taking into consideration aforementioned examples for considered structure there was a model created which is used to shape level of workflow which assumes that there is k_p for $2 \leq k_p \leq 30$ necessary tasks connected to amount of clients' orders. We do not consider possibility of $k_p = 1$ as value of workflow level will have been a sum of random variables with exponential configuration. Then level of workflow of single separated sub-system will have been marked with a formula (1). Assumption $k = 1$ will mean that in whole production structure in time Δt there are different products Y^K produced (one stock of each). In considered example there is assumption that situation is rare, that is why it has been skipped.

When $k > 30$ – we can use so called "scale effect" which is about shaping level of workflow in big production party. In this example, we can use property of stability in structure of random variable $\tau_{l,i,j} \sim \text{Exp}(\lambda_{l,i})$ we can use central border statement (CLT). Basing on CLT specifics – for sum of variety of independent random variables with the same composition with ended variants – we have to assess of analyzed random variable with normal composition with particular standard aberrance σ and approximate value μ [4].

Level of workflow for particular phase (process or characteristic group of processes) in considered production structure is also a level of workflow, assigned due to the theory of complex systems, separated system [5] (in our consideration it is also production department). To assign level of workflow for the process (or group of processes) realized in area of single department there is a need to set sum of all components of elementary times of realization of each sub-products. Figure 3 shows scheme of acting in shaping of the level of workflow for considered production structure.

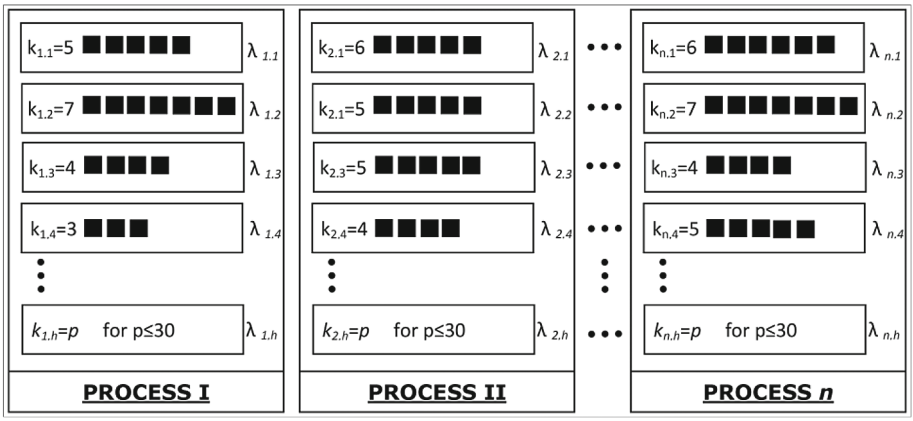


Fig. 3. Scheme of workflow in shaping level of effort

To assess level of workflow for i – process (department), where $k_p \leq 30$ in time t_{i,k_l} there was random variable marked. It is a sum of all realization each $k_{n,h}$ times in i – production process. We know that single realization time for one sub-product $\tau_{l,i,j} \sim \text{Exp}(\lambda_{l,i})$ so:

$$t_{i,k_l} = \tau_{i,l,1} + \tau_{i,l,2} + \ldots + \tau_{i,l,k_l} \tag{2}$$

where: t_{i,k_l} – random variable which describes all time of realization k_p necessary elements (tasks) in i – process (phase) of production for l – stream of value. Moreover, we know that if $\tau_{l,i,j} \sim \text{Exp}(\lambda_{l,i})$, for all $j = 1,2\ldots k_p$, so $t_{l,i} \sim \text{Erl}(k_p, \lambda_{l,i})$. If there are any e x, y: $\lambda_{l,x} = \lambda_{l,y}$, then $t_{l,x} + t_{l,y} \sim Erl\ (x + y,\ \lambda_{l,y})$. Where the $t_{l,i} \sim \text{Erl}(k_p, \lambda_{l,i})$ mean that random variable $t_{l,i}$ is corresponding with Erlang distribution about k_p, and $\lambda_{l,i}$ parameters.

Random variable T_i assess time of k_p tasks in i – process is a sum of independent random variables t_{i,k_l}.

$$T_i = t_{i,k_1} + t_{i,k_2} + t_{i,k_3} + \ldots + t_{i,k_l} \tag{3}$$

where: $T_i \sim Erl\ (k_i,\ \lambda_{i,l})$, T_i – random variable describing the whole time of production processes realization for i – process; t_{i,k_l} – are random variables which set the realization time for k_p elements (tasks) on i – process.

To assign level of workflow for process (or group of processes) realized in area of single department it is necessary to name formula of thickness which is a sum of random variable with Erlang composition. Basing on [6, 7] there was formula of realization time k_p of grouped tasks in single production department:

$$f_{Ti}(\tau) = \sum_{p=1}^{s} \left(\lambda_{i,l}\right)^{k_p} \cdot e^{-\tau \cdot \lambda_{i,l}} \cdot \sum_{j=1}^{k_p} \frac{(-1)^{k_p - j}}{(j-1)!} \cdot \tau^{j-1} \cdot \sum_{\substack{m_1 + \ldots + m_s = k_p - j \\ m_i = 0}} \prod_{\substack{g=1 \\ g \neq i}}^{s} \binom{k_g + m_g - 1}{m_g} \frac{\left(\lambda_{i,g}\right)^{k_g}}{\left(\lambda_{i,g} - \lambda_{i,l}\right)^{k_g + m_g}} \tag{4}$$

where: $f_{Ti}(\tau)$ – probability density function of a T_i variable random; $\lambda_{l,i}$ – parameter of exponential configuration, k_h – parameter of shape in Erlang composition, $m_1,\ m_2,\ \ldots,\ m_n \in \mathrm{N}$ – parameters of combination in which $m_i = 0$ and $\sum_{g=1}^{n} m_g = k_p - j$ for all $i = 1, 2, \ldots, n$ and $j = 1, 2, .., k_p$. Medium of random variable T_i is $\tau > 0$.

Value ET_i marked with a formula (4) of thickness in random variable T_i is expected value in necessary time for execution of k_p tasks in area of one department. In the same time ET_i is nominal level of workflow for i – phase of production (department). ET_i is counted accordingly to the formula:

$$ET_i = \sum_{l=1}^{h} \frac{k_l}{\lambda_{i,l}} \tag{5}$$

To assign differences in level of workflow from average value for separate process it is important to assign variation of random variables T_i. Variant of random variable $VarT_i$ is assigned accordingly:

$$Var\ T_i = Var\ t_{i,k_1} + Var\ t_{i,k_2} + \ldots + Var\ t_{i,k_h} \tag{8}$$

Assigned variants of level of workflow for particular processes informs us about stability (or about lack in stability) which is connected to the fact of the differences in realized tasks. Equipoising level of workflow for all particular processes (or groups of processes) should be adjusted to the expected value (ET) for all production system. That is why in the next part there will be designation of level of workflow for production system considered as a whole.

If with T we assign random variable which is a sum of independent random variable T_i, we are able to assign expected level of workflow for whole production structure. Random variable T is assigned accordingly to the formula:

$$T = T_1 + T_2 + \ldots + T_n \tag{9}$$

Expected value of the random variable and its' variant look like:

$$ET = \sum_{i=1}^{n} \sum_{l=1}^{h} \frac{k_l}{\lambda_{i,l}} \tag{10}$$

$$Var\ T = \sum_{i=1}^{n} \sum_{l=1}^{h} \frac{k_l}{\lambda_{i,l}^{\ 2}} \tag{11}$$

In reference to assigned level of workflow for whole production system and for single processes (or groups of processes) we can assign sensitive (critical) departments (production sockets) in which there are wastes of 3M – (jap. "*muri*", "*mura*", "*muda*"). Department (production socket) which expected value of level of workflow is significantly bigger than value of level of workflow in comparison to other process (or group of processes) and it is "narrow throat" of whole production structure. On the other hand, department (production socket) in which there are significant lacks in average expected level of workflow can generate over-production or there is unnecessary awaiting in sockets. In this case there is waste of "*muda*" group. We can notice that 3M wastes are dependent and strictly connected. Elimination of one can cause elimination (or decrease) or all the rest [8, 9]. That is why optimization of production processes should adjust analysis of single (separated) processes but not in separation of whole production system [10].

3.1 Balancing Production Line

Balancing production line is this kind of assignment in which there is constant flow in n production processes and indicator of changes of workflow level V_P for grouped processes is near to zero in whole production stream [11, 12]. In complex production structure there are limited technological possibilities in constant decrease of production cycle (C/T). In result – it is important to assign it in particular phases of production, necessary to execute elementary tasks in way in which expected value of designated levels of workflow is the same and stable for whole structure.

Assigned variant of levels of workflow for particular processes enables assignment of probability to execute system of h tasks in area of three standard deviations ($\pm 3\ \sigma$). In next consideration there is a formula which sets probability that value of workflow level for single, particular phases of processing can be set in area of maximum three standard deviations ($\pm 3\ \sigma$) from expected value of the whole production structure – ET. Basing on formula (4) of thickness function in random variable T_i and with formulas (10), (11), accordingly to expected value and variant of random variable T will be set with formula to count probability that random variable T_i will take value from $\left(ET - 3 \cdot \sqrt{VarT}\right)$ do $\left(ET + 3 \cdot \sqrt{VarT}\right)$. Probability is assigned accordingly to the formula:

$$P\left(ET-3\cdot\sqrt{VarT}<T_i<ET+3\cdot\sqrt{VarT}\right)=\int_{ET-3\cdot\sqrt{VarT}}^{ET-3\cdot\sqrt{VarT}} f_{T_i}(\tau)\,d\tau$$
$$=\int_{\sum_{i=1}^{n}\sum_{l=1}^{h}\frac{k_l}{\lambda_{i,l}}-3\cdot\sqrt{\sum_{i=1}^{n}\sum_{l=1}^{h}\frac{k_l}{(\lambda_{i,l})^2}}}^{\sum_{i=1}^{n}\sum_{l=1}^{h}\frac{k_l}{\lambda_{i,l}}+3\cdot\sqrt{\sum_{i=1}^{n}\sum_{l=1}^{h}\frac{k_l}{(\lambda_{i,l})^2}}}\left[\sum_{p=1}^{h}(\lambda_{i,l})^{k_p}\cdot e^{-\tau\cdot\lambda_{i,l}}\cdot\sum_{j=1}^{k_p}\frac{(-1)^{k_p-j}}{(j-1)!}\cdot\tau^{j-1}\cdot\sum_{\substack{m_1+\ldots+m_g=k_p-j\\ m_i=0}}\prod_{\substack{g=1\\ g\neq i}}^{h}\binom{k_g+m_g-1}{m_g}\frac{(\lambda_{i,g})^{k_g}}{(\lambda_{i,g}-\lambda_{i,l})^{k_g+m_g}}\right]d\tau \tag{12}$$

In other changes we receive difference of incomplete Gamma functions [13]:

$$P\left(\sum_{i=1}^{n}\sum_{l=1}^{h}\frac{k_l}{\lambda_{i,l}}-3\cdot\sqrt{\sum_{i=1}^{n}\sum_{l=1}^{h}\frac{k_l}{(\lambda_{i,l})^2}}<T_i<\sum_{i=1}^{n}\sum_{l=1}^{h}\frac{k_l}{\lambda_{i,l}}+3\cdot\sqrt{\sum_{i=1}^{n}\sum_{l=1}^{h}\frac{k_l}{(\lambda_{i,l})^2}}\right)$$
$$=\sum_{p=1}^{h}\sum_{j=1}^{k_p}\frac{(-\lambda_{i,l})^{k_p-j}}{(j-1)!}\cdot\sum_{\substack{m_1+\ldots+m_g=k_p-j\\ m_i=0}}\prod_{\substack{g=1\\ g\neq i}}^{h}\binom{k_g+m_g-1}{m_g}\frac{(\lambda_{i,g})^{k_g}}{(\lambda_{i,g}-\lambda_{i,l})^{k_g+m_g}}\cdot$$
$$\left[\Gamma\left(j;\left(\sum_{i=1}^{n}\sum_{l=1}^{h}\frac{k_l}{\lambda_{i,l}}-3\cdot\sqrt{\sum_{i=1}^{n}\sum_{l=1}^{h}\frac{k_l}{(\lambda_{i,l})^2}}\right)\lambda_{i,l}\right)-\Gamma\left(j;\left(\sum_{i=1}^{n}\sum_{l=1}^{h}\frac{k_l}{\lambda_{i,l}}+3\cdot\sqrt{\sum_{i=1}^{n}\sum_{l=1}^{h}\frac{k_l}{(\lambda_{i,l})^2}}\right)\lambda_{i,l}\right)\right] \tag{13}$$

Finally, after changes we receive:

$$P\left(ET-3\cdot\sqrt{VarT}<T_i<ET+3\cdot\sqrt{VarT}\right)$$
$$=\sum_{p=1}^{h}\sum_{j=1}^{k_p}\frac{(-\lambda_{i,l})^{k_p-j}}{(j-1)!}\cdot\sum_{\substack{m_1+\ldots+m_g=k_p-j\\ m_i=0}}\prod_{\substack{g=1\\ g\neq i}}^{h}\binom{k_g+m_g-1}{m_g}\frac{(\lambda_{i,g})^{k_g}}{(\lambda_{i,g}-\lambda_{i,l})^{k_g+m_g}}\cdot$$
$$(j-1)\cdot e^{-ET\cdot\lambda_{i,l}}\cdot\left[\sum_{r=0}^{j-1}\left(\begin{array}{l}e^{3\cdot\sqrt{VarT}\cdot\lambda_{i,l}}\cdot\dfrac{\left(\left(ET-3\cdot\sqrt{VarT}\right)\lambda_{i,l}\right)^r}{r!}-\\ e^{-3\cdot\sqrt{VarT}\cdot\lambda_{i,l}}\cdot\dfrac{\left(\left(ET+3\cdot\sqrt{VarT}\right)\lambda_{i,l}\right)^r}{r!}\end{array}\right)\right] \tag{14}$$

Value of three standard deviations has been set after basing on three sigma rule, strictly connected with its' standard deviation. In practice, it is rare tahat there are results which are different than value $\pm 3\,\sigma$. It does not mean that their appearance is impossible. Situation in which difference bigger than $\pm 3\,\sigma$ appears means that circumstances which appeared were anomaly. Figure 4 presents process of balancing production lines in area of level of workflow for single, grouped production tasks in reference to three standard deviations for whole production process.

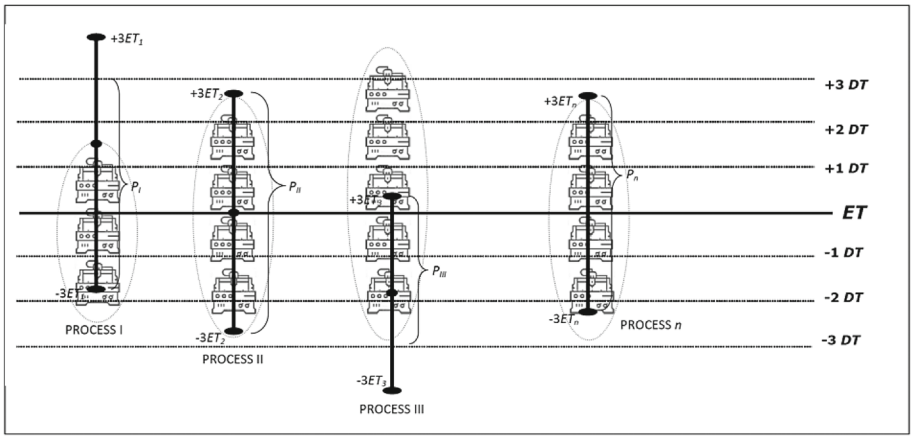


Fig. 4. Scheme of balance in the level of workflow

If probability of realization time is not in area of three standard deviations of whole production structure means that production system was overstretched or under-stretched. In case of overstretch – it will result with losses like awaiting for components for all of the next processes – process 1 Fig. 4. In case of under-stretch – process 3 Fig. 4 – we have a situation in which there are too many resources to execute tasks (processes). In this phase of processing (process 3) there is permanent expectation. Optimization based on balancing of workflow in real time Is obliged to permanent expectation of resources. It is possible to achieve with use of digitalization of whole production process and interaction of physical objects (machines) with virtual (software).

In intelligent production systems aforementioned algorithm of shaping workflow of separated areas in complex production structure will help with programming the steering process of assigning the production resources. Presented model enables control of workflow levels of assigned tasks in single production processes. Use of advanced counting algorithms based on formula number (14) enables assignation of optimal parameters customized to resources and fully-correlated to clients' needs.

4 Conclusion

Level of workflow in particular production subsystems is different and depends on implemented technology, type of product, level of its' complexity and phases necessary to process. Moreover, depending on availability of resources (or their lack), single elements can be produced unto different technologies. This situation significantly change level of workflow in considered time. In the article there is a presentation of a model of shaping level of workflow for production structure which consists of *n* phases. In optimized, autonomic production system decomposition of tasks for single machines must be correlated with all mechanical and human resources. In consideration there is an assumption that cooperation between robot and operator is necessary (when operator

has universal abilities of operating with variety of machines and operator is able to execute a lot of tasks in different processes). Presented model assumes flexibility of separated subsystems in area of realized processes in which tasks are assigned accordingly to autonomic decisive systems.

Wrought software with the use of presented model can be an element of intelligent production system in area of analysis and calculations. Exceeding borders in range of three standard deviations in whole production system can be an alert of early warning before critical situation.

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An Intelligent System for Core-Competence Identification for Industry 4.0 Based on Research Results from German and Polish Manufacturing Companies

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Abstract. This article aims to present the concept of an intelligent system for core-competence identification for Industry 4.0, and is based on a survey and data obtained from 62 Polish Manufacturing Enterprises in the Lubuskie region and from 23 German Manufacturing Enterprises from the Brandenburg region - so from 85 manufacturing enterprises in "the region: cross-border cooperation". Special attention is placed on the determination of the weightings of the competencies of employees in the context of the adoption and use of technologies related to Industry 4.0. This is followed by a discussion of the supporting literature and of the results of the empirical studies. Finally, part of an intelligent system for core-competence identification for Industry 4.0 is presented.

Keywords: Core competence · Industry 4.0 · Intelligent system · Manufacturing company

1 Introduction

Human resources are one of three interconnected factors describing the concept of the Fourth Industrial Revolution or Industry 4.0. The term "Industry 4.0" is defined as the resulting interconnection of people, objects and systems through real-time data exchange [4, 13]. This concept includes the vision of digitally enabled production [2]. Thanks to technologies such as the Internet of Things (IoT), the Internet of Services (IoS), the Internet of People (IoP), and the Industrial Internet, Cloud-based Manufacturing, Smart Manufacturing employees' activities within a company and in the company's environment are interconnected. Manufacturing companies operating in Industry 4.0 also need to introduce the challenges to the employees, especially to their competences, arising from the ongoing automation and digitisation.

In this paper, special attention is paid to core-competence model identification for Industry 4.0. The general objective of this research is to develop a general framework for identifying employees' competencies, especially in terms of the determination of the weightings of those employees' competencies in the context of the adoption and use of technologies related to Industry 4.0. So it is very important for them to adequately

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understand the technologies related to Industry-4.0 usage. Based on the definition by Hsieh and Wang [8], the use of technologies by employees in a company is understood as the work by employees in defined technologies, and their work must consist of at least 6 h per day [10].

Therefore, we maintain that an approach for the core-competence model related to the new technologies and processes of Industry 4.0 is needed in manufacturing companies. A competence is an ability to achieve the defined goals [12], and moreover is a set of special skills [7]. According to our previous research [11] we have determined that the competencies of employees to accomplish tasks are often referred to as qualifications and skills. Our motivation to study this approach came from the research results obtained from Polish and German Manufacturing companies. Using survey data from 62 Polish manufacturing companies in the Lubuskie region, and from 23 German manufacturing companies in the Brandenburg region (in the cross-border cooperative region of Lubuskie/Poland-Brandenburg/Germany), this study discusses the competences needed in manufacturing companies in terms of Industry 4.0. The researched companies are in the automotive and construction sectors and constitute 20% of such enterprises in the cross-border cooperative region. This paper develops a core-competence model and shows an implementation of this approach in the form of the author's intelligent system for companies related to Industry 4.0.

Section 2 shows the literature studies related to a competence model for manufacturing companies in Industry 4.0 and presents the main competences of employees based on the research results from German and Polish manufacturing companies. Section 3 develops the authors' core-competence model for Industry 4.0. Finally, Sect. 4 presents a part of an intelligent system for the core-competence identification for Industry 4.0. Section 5 summarises the research results.

2 Core Competences for Industry 4.0

In the literature are defined the core competencies as a set of a combination of organisational, behavioural and technical skills which give an individual the potential to implement the prescribed processes effectively [1, 3, 5].

Hecklaua et al. [6] defined the four main categories of core competencies for employees in Industry 4.0: technical competencies, methodological competencies, social competencies, and personal competencies. They analysed the defined sets of competencies and described the significance of each competence through references. Based on this study, and in order to describe the core competences for Industry 4.0, survey data were collected from 85 manufacturing enterprises in the cross-border cooperative region of Lubuskie/Poland and Brandenburg/Germany, in which the companies were categorised as "construction" or "automotive", or "others". The respondents consisted of managers (over 80%) and chief executive officers, and they were surveyed in the form of direct meetings, email surveys and/or phone surveys. The chosen 85 manufacturing companies from the "automotive" and "construction" sectors contribute about 20% of those enterprises in the cooperative region.

The respondents were asked to evaluate the characteristics of employees in terms of the most important for Industry 4.0. They stated, that they have sufficient knowledge about the assumptions the of the Industry 4.0 idea. Figure 1 presents, based on the research results from the German and Polish manufacturing companies, the most-important characteristics of employees in Industry 4.0. For all kinds of characteristics which were measured, a five-point Likert scale was adopted in which 1 = strongly unimportant and 5 = strongly important.

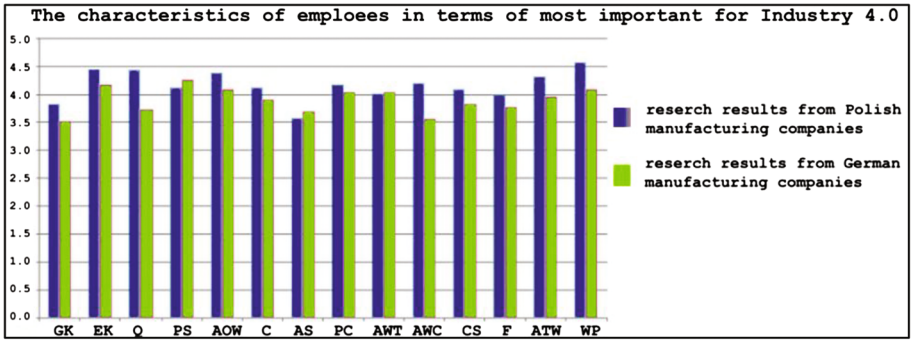


Fig. 1. The most-important characteristics of employees for Industry 4.0. research results from German and Polish manufacturing companies

For a model of core competences for Industry 4.0, fourteen characteristics of employees were identified: general knowledge (GK), expertise knowledge (EK), qualifications (Q), problem solving (PS), the ability to organise work (AOW), creativity (C), analytical skills (AS), personal culture (PC), the ability to work in a team (AWT), the ability to work with customers (AWC), communication skills (CS), flexibility (F), the ability for task-oriented work (ATW), and working under pressure (WP).

Similar results were obtained only for the characteristic *the ability to work in a team (AWT)* in the context of the ability of employees to absorb and use a new technology in Industry 4.0 (average result: 4.02). In other results it can be observed that, for industry 4.0, for the managers of Polish manufacturing companies these characteristics of employees are more important than for the managers of German Companies. Only the characteristic *problem solving (PS*) was scored by managers of German companies as more important than by the managers of the Polish Enterprises.

Based on the study by Hecklaua et al. [6] the following groups of core competences in the context of the ability to absorb and use new technology in Industry 4.0, are defined: Technical Competencies (TC), Methodological Competencies (MC), Social Competencies (SC), and Personal Competencies (PC). The authors defined the following groups of core competences, including the characteristics of employees, in the context of the ability to absorb and use new technology in Industry 4.0, are defined (see Fig. 2):

- Technical competencies (TC): general knowledge (GK), expertise knowledge (EK), (Q) qualifications.

- Methodological competencies (MC): problem solving (PS), the ability to organise work (AOW), creativity (C), analytical skills (AS),
- Social competencies (SC): personal culture (PC), the ability to work in a team (AWT), the ability to work with customers (AWC), communication skills (CS).
- Personal competencies (PC): flexibility (F), the ability for task-oriented work (ATW), working under pressure (WP).

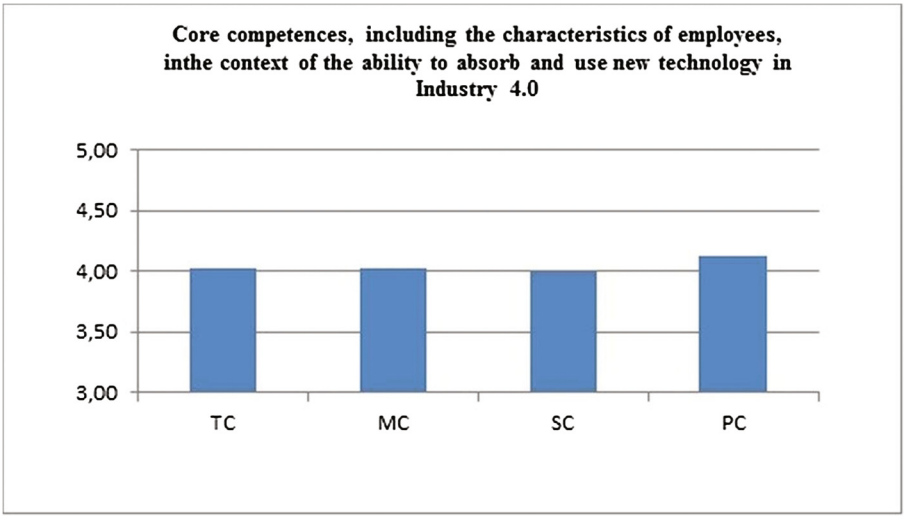


Fig. 2. The core competences, including the characteristics of employees, in the context of the ability to absorb and use new technology in Industry 4.0 - the research results from German and Polish manufacturing companies

In the research results the identified core competence as a set of characteristics of employees for Industry 4.0 are scored as important (more than 4 with on five-point Likert scale) - see Fig. 2.

3 The Concept of an Intelligent System for Core-Competence Identification for Industry 4.0

The problem in this paper is how to assess the qualitative factors in core competences for Industry 4.0 in manufacturing companies, and how to select the employees with the appropriate skills to undertake projects in companies. The proposed approach, presenting the weightings of core competences, provides an opportunity to evaluate a potential employee in manufacturing companies. Therefore the following stages are involved in an intelligent system for core-competence identification (see Fig. 3).

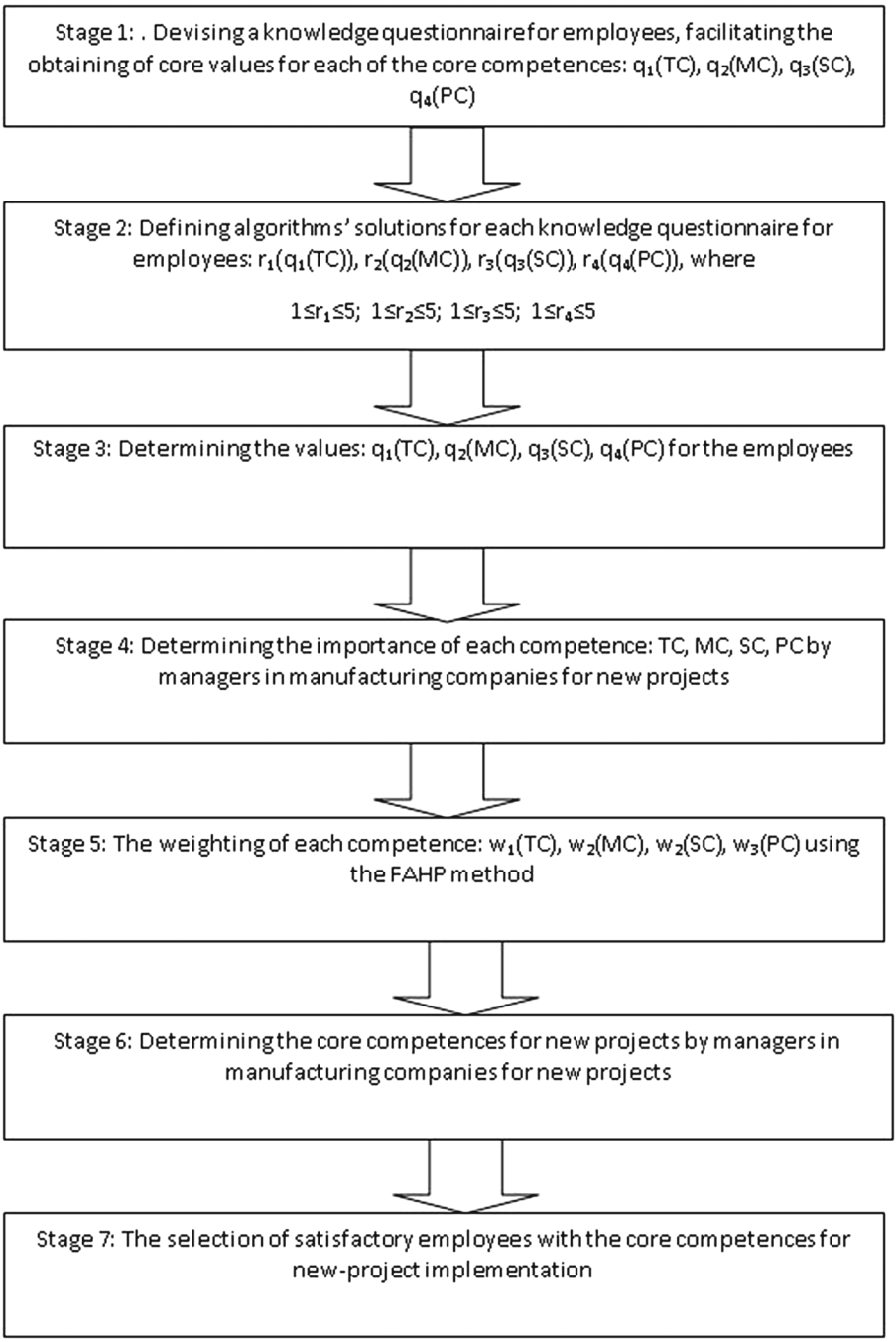


Fig. 3. The concept of an Intelligent system for core-competence identification for Industry 4.0

Stages one to three were based on the literature research results and empirical research results from German and Polish manufacturing companies (see Chapter 2). So we proposed four web-based questionnaires for each employee in the manufacturing companies in the survey to obtain values for each of the core competences q_1(TC), q_2(MC), q_3(SC), q_4(PC). The employees selected by the managers in the companies had to complete web-based questionnaires. He/she selected one answer for each question. Based on the results, and on the algorithms' solutions, values for each competence TC, MC, SC, PC for the employees were created.

In stages three & four the FAHP method (The Fuzzy Analytic Hierarchy Process) was implemented. Using FAHP it was possible to determine the relative predominance of a particular factor from the immeasurable elements of the framework for the core-competence model; furthermore it was possible to evaluate these factors. According to Nydick and Hill [9], a linguistic variable can be described by a fuzzy number $\tilde{a} = (l, m, u)$ with a triangular fuzzy-membership function. The triangular fuzzy number $\tilde{a} = (l, m, u)$ is defined in the set $[l, u]$, and its membership function takes a value equal to 1 at the point m. The fuzzy scale of preferences is strictly defined by Nydick and Hill [9]. Each group of competences is compared at peer level in terms of importance.

Stages five & six are outcome of the previous stages. The presented concept of an Intelligent system for core-competence identification for Industry 4.0 (see Fig. 3) in the form an IT tool was implemented and is presented in the next section.

4 An Intelligent System for Core-Competence Identification for Industry 4.0 (IS-CI)

Stages five & six are outcome of the previous stages. The presented concept of an Intelligent system for core-competence identification for Industry 4.0 (see Fig. 3) in the form an IT tool is implemented, and in the next section presented.

In order to illustrate the possibility of answers to our research questions, let us consider the situation: the problem being considered entails selecting employees with the appropriate abilities to undertake new projects in a company, involving Industry 4.0.

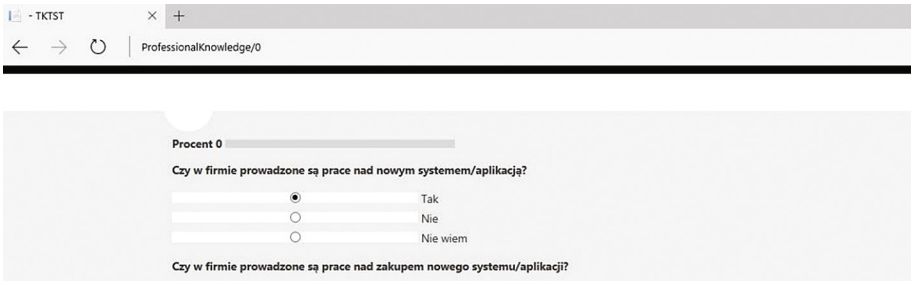


Fig. 4. An extract from the web questionnaire for employees facilitating the determining of core competences - technical competencies in IS-CI (the web-questionnaire is currently only in the Polish language)

Below is an extract from the Intelligent system for core-competence identification for Industry 4.0, based on the proposed concept (see Fig. 3).

According to Stage 1 (see Fig. 3) for each core competence a knowledge web-questionnaire is defined. Figure 4 presents an extract from the web-questionnaire for employees facilitating the obtaining of values for core competences: technical competencies.

According to Stage 2 in Fig. 3, the defined and implemented algorithms' solutions for each knowledge web-questionnaire enabled the obtaining of values for core competences - technical competencies - completed by the employee,

From the results we can derive the values of each competence: q1(TC), q_2(MC), q_3(SC), q_4(PC) for the employees - see Stage 3 in Fig. 3.

In the fourth stage of the proposed model, managers determine the importance of each competence - TC, MC, SC, PC - for new projects, according to the following rules.

- TC - equally important or moderately more important or of greater importance or of the most importance compared with MC.
- TC - equally important or moderately more important or of greater importance or of the most importance compared with SC.
- TC - equally important or moderately more important or of greater importance or of the most importance compared with PC.
- MC - equally important or moderately more important or of greater importance or of the most importance compared with SC.
- MC - equally important or moderately more important or of greater importance or of the most importance compared with PC.
- SC - equally important or moderately more important or of greater importance or of the most importance compared with PC.
- PC - equally important or moderately more important or of greater importance or of the most importance compared with TC.
- PC - equally important or moderately more important or of greater importance or of the most importance compared with MC.
- PC - equally important or moderately more important or of greater importance or of the most importance compared with SC.



Fig. 5. An extract from the use of the FAHP method for the weightings (the importance) of the of the core-competence identification for new projects in the IS-CI (the determination of the importance of each competence is currently only in the Polish language)

According to the defined rules, the FAHP method was implemented and used. Based on the fuzzy scale of preferences, the fuzzy weightings matrix of core competences for new projects was defined. By the use the FAHP method, the weightings of the of the core competences for new projects were assigned - Stage 4 -the weighting of each competence: w_1(TC), w_2(MC), w_3(SC), w_4(PC) using the FAHP method - see Fig. 5.

Therefore, by using the FAHP method, it is stated, that the most-important core competence of employees for the new-project implementation is – see Fig. 6.

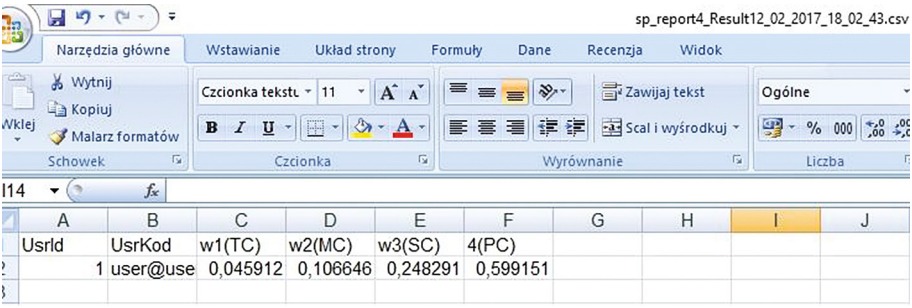


Fig. 6. An extract from the defining of core competences for new projects by managers in manufacturing companies for new projects in the IS-CI

So, the results are similar to the research results from German and Polish manufacturing companies (see Fig. 2). The most-important competences are personal competencies (PC) for new-project implementation.

In the stage seventh the managers select the satisfactory employees with the core competences for new project implementation based on the set of the values of each competence: q_1(TC), q_2(MC), q_3(SC), q_4(PC) for the employees (see stage 3, Fig. 3).

Naturally, this concept for the Intelligent system for core-competence identification for Industry 4.0 is dynamic, and can be adapted to the needs of companies. Besides, the whole proposed system is a tool which can be modified to the needs of the company and can be adaptable to the profile of the company.

5 Conclusions

The research results from the German and Polish manufacturing companies surveyed in this study show the importance of competences, and also the characteristics of employees, in the context of the ability to absorb and use new technology in Industry 4.0. We can also observe the need to build an intelligent system to support the selection process of satisfactory employees with the core competences for new-project implementation in manufacturing companies. Our case study presents an intelligent system for core-competence identification for Industry 4.0 (IS-CI). This concept will be further developed in our future work.

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An Optimization Approach for Scheduling and Lot Sizing Problems in Electromechanical Industry Using GA-Based Method

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Abstract. The paper presents a method to determine the lot size and production schedule for variable ranges of products based on genetic algorithm. The computer simulation checks the established deadlines for the various orders and strives to minimize the total cycle of production times and machine setup times. The authors present the assumptions of the model and its results concerning generation of the optimal production sequence for the analyzed products. The paper also comprises the analysis if it is reasonable to combine orders or separate them according to individual customer needs.

Keywords: Optimization problems · Scheduling algorithms · Intelligent manufacturing systems · Lot size

1 Introduction

In the current highly competitive environment the strategy of the production is changing from mass production for the production in smaller lot sizes in order to include rapid changes in customer preferences and the demand [1, 2]. Customers do not want to receive large batches at once, since they want to minimize the frozen capital into the equipment and inventories. On the other hand, manufacturers also want to reduce their inventories including the WIP (work in progress), as well as the total cost of production and the production cycle. Due to the large variety of products and fluctuating demand production planning and scheduling problems for small batch sizes is very complex. It is very difficult to control costs and meet deadlines.

There is many specific definitions and concepts in the area of production planning and management [3]. The majority refers both to the strategic, as well as operating horizon and is finding application with reference to the production planning and the production structures design and the operational production management.

Since the mid-1950s production planning optimization problems have been the subject of an active research area. Johnson [4] is often regarded as the precursor in this

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field with his attempts of optimal two and three-stage production schedules. At that time two mainstreams research could be distinguished. The first one was an attempt to develop a method for finding optimal solutions. Test problems were generated randomly or practical oversimplified problems reduced in sizes were the focus of attention. The optimization methods applied were mainly complete search, integer programming, branch and bound method, and dynamic programming. The second mainstream of scientific research was a great variety of methods that explore the search space in order to find near–optimal solutions for problems of size and complexity found in real enterprises. The methods used in this area include heuristic methods, as well as expert systems [5]. One of the major problems emerging in the area of operational planning and scheduling is the problem of determining the lot size (lot sizing and scheduling problems). Determining the lot size is a part of the medium-term operational production planning. If the lot sizes are appropriately defined and arranged in the time, a production process should be profitable and run smoothly [6].

The paper presents the opportunity of using a computer simulation based on genetic algorithm to optimize the production schedule for many simple products with limitations in a finite planning horizon for dynamic demand. Algorithm and model assumptions will be discussed later in hereby work.

2 Application of Genetic Algorithms (GA) in the Area of Lot Sizing and Scheduling

2.1 Trends in the Models for Determining the Lot Size and Scheduling

There are many different procedures which have been developed for determining the lot size and the temporary deployment of supplies for the manufactured components in production planning systems. Although the number of developed procedures include methods applying simple decision rules to the extensive optimization procedures involving intelligent techniques, there is surprisingly small help for managers choosing procedure for the lot sizing under the specific production and organizational conditions.

Traditional methods do not consider the uncertainty of demand and refer to future demand as stable and constant leading to the situation that the precise and complex calculations become worthless at the time of any fluctuation in demand. Currently used traditional methods also have another weakness, which significantly limits their practical applications. Seeking optimum considering all possible cases, therefore when planning horizon increases the amount of optional schedules dramatically increases [7, 8].

2.2 The Review of Selected Methods Applying GA in Lot Sizing and Scheduling Problems

One of the first authors, who suggested the use of genetic algorithms in the field of scheduling and lot sizing was Davis [9]. He drew attention to the possibility of using

probabilistic methods of local search in environments with large search areas and developed representation in which genetic algorithm operates on the list, which continues to be decoded to generate the schedule.

Khouja [10] introduced a genetic algorithm for the problem of scheduling and determining the economic lot size that provided the average results 3–11% from the theoretical lower limit. The lot sizing problem in MRP systems using genetic algorithms was discussed by Stockton and Quinn [11]. They used a genetic algorithm to develop a multi-level technique for lot sizing.

Apart from the determination of an optimal delivery the essential part of production planning and control in a manufacturing company is to generate a production schedule. The production lines are now being used for the preparation of a variety of products forming a product family. The manufacturer depends on efficient production minimizes the total cost, total production cycle and production line setup changes. The problem is finding the proper sequence of produced models needed to meet market demands. In the case of assembly lines working under some tact time cycle, the time required to perform suitable work at each station is limited to a certain maximum value. Scheduling and determining the size of the lot was discussed by many researchers [12–20].

Optimality criteria of production scheduling problems for measuring performance can be classified into four basic families [21–24]: (1) first family minimizes the biggest value of a given function of the completion times for the whole set of jobs, (2) second family minimizes the average value of a given function of the completion times for the whole set of jobs, (3) third family minimizes the weighted sum of given function of the completion times for the whole set of jobs, (4) miscellaneous family. Sequencing, timing, routing, forecasting, labeling, grouping, aggregation, and disaggregation are the main issues of scheduling function [25].

Most of researchers consider objective functions that refers to costs (holding cost, setup cost) [26–28]. Models very often refers to economic lot sizes environments assuming that demand is stable and constant. On the basis of available articles it can be stated that the use of genetic algorithms within the issues of determining lot size and scheduling is quite common. In manufacturing companies it is often based on their own experience, practice, as they are not trusting complex mathematical models.

Much more frequently developed models refer only to the aspect of lot size. Only since 2007 has there been an increase in interest in the integrated area of batch determination and production scheduling. Most methods are constrained models assuming finite planning horizons and refer to single-level products. About half of the models assume static deterministic demand and the other half is dynamic demand. Approximately 50% of the selected models take into account the time of rearms as one of the constraints when creating a genetic algorithm. The authors considered that the little attention of researchers was devoted to scheduling production while simultaneously determining the size of batches for single-level items, with constraints - setup times where planning horizon can be fixed and dynamic as well, and demand: dynamic or probabilistic dependent on the model source of input data. Therefore they developed such model.

Due to the volume limitation of the article, other models and work in this area are not discussed here. The authors have compared metaheuristics in the discussed problem area in the article [29].

3 Characteristics of Problem Area

The goal of the research is to develop a production schedule for couplings based on customer orders indicating the order of production of couplings and the batch size to allow for shortening total production cycles. In the first stage of the simulation main focus is to create the best available production schedule based on standards of lot size and orders deadlines predefined by the customers.

The company manufactures production parts whose manufacturing process is based mainly on mechanical processing combined with both chemical and thermal treatment. There are also many special processes: soldering, surface sanding, smoothing. Unfortunately, none of the production lines is autonomous, which means that there is a need for co-operation in the production process, both internal and external.

Range of goods of manufacturing couplings on the line comprises about 70 pieces and 60 couplings is in fact active (they are really produced). Because of the specifics of the problem, i.e. the number of independent variables, the problem is solved using a genetic algorithm, which effectively searches the huge solution space of the problem.

The analyzed production line consists of 19 processing stations. Basically, based on the reports in the SAP system, the customer's demand forecasts can be seen and consequently how the order is made each month. The line is not adapted to lean production and there is no way of introducing a one piece flow, hence the size of the series is adjusted. The sales forecasts for the couplings are currently 20 months ahead, with a probability of around 80% based on past experience. Demand is changeable and unstable. The model refers to individual products (clutches) without penetrating into their structure the complexity of the BOM. Considered planning horizon is variable but no more than 130 days. Machines will have fixed production capacity and the production line runs 16 h a day.

4 Description of the Algorithm

At the beginning it is useful to define the basic concepts of the simulation scheme. The *environment* is a set of possible "orders" to carry out production of couplings (up to 16 different types were accepted), and the order for the same coupling may repeat any number of times, but to e.g. different deadlines. The *individual of environment* is the sample of realization of the contract with specific "genotype" determined in *chromosome*- unique sequence of production of couplings and each data is necessary for their production. A single coupling plays the role of "gene" (elementary part of genotype), which contains all the information related to its production process-types of machinery used and processing time and setup time as well. Coupling data can occur several times depending on the production schedule. Each coupling has its own symbol A, B, C, and so on. Example of genotype - BBAAKAPBPAPCCBOB.

As a *unit of the simulation* can be treated a *chromosome* (specific permutations of couplings) supplemented by the number of couplings and the time of the contract of realization. Each permutation with repetitions consists of a maximum of 16 couplings (each has specific lead time depending on the production schedule). Couplings has a symbol of {A,.. P}. The information contained in each simulation unit, allows for the initial selection of randomly generated sequence, due to the *evaluation function* is which to check whether the execution times of individual couplings are in the schedule of orders (*timeOfProduction* < *timeOfSchedule*).

In the first step, the algorithm generates a large number of individuals (thousands of them), then checks their suitability for further simulation through the evaluation function. Those individuals that meet the requirements of the evaluation function are ordered by the objective function, which is to minimize the *execution time* of the entire order. This is due to the assumption that the plant produces continuously at a constant number of employees (in constant shift mode), thus reducing the total execution time is equivalent to a reduction in the total cost of the order (shorter labor time and cost of production). From the point of view of the simulation the step is called checking the fitness of population.

When the group of sequences with the lowest values of execution time is selected (choose the best 50% of the population by ranking) mutations of the best are made by a small permutation of genes within the chromosome. This change in the order of the production cycle can be done by e.g. conversion of selected pairs of genes locations. The purpose of this mutation is to improve the individual.

The algorithm was written in C++ in VisualStudio2015. The basic classes defined in the library *defLineOfCoupling.h*. are presented below. The base of algorithm show UML diagram on Fig. 1.

The most important from genetic simulation point of view is the class *chromosome*. This class includes all the necessary information on the genotype of the subject, which is the set of genes-couplings *c* [16] in a particular combination - proper chromosome *ch_symbol* [3], a set of the number of ordered units *numC* [16] and a set of lead time s*execT* [16]. The *chromosome* class contains also two tables to store *timeIn, timeOut* for each coupling production. The Boolean variable *chromosomeApproval* can be true only if the individual meets the requirements of the schedule of the contract. In the class *chromosome* is defined *totalTime()* function, which is a simulation engine, because the lead time is calculated for the specified configuration, which is an essential element to the classification of the individual. In addition, there are defined some *save* and *print functions* to store results for each coupling sequence.

Further simulation is based on a random base chromosome reset and finding optimal execution time for its derivatives. At the end of each cycle-used to build a generation-chromosomes are ordered in terms of the *objective function*, which is the total time of the contract. The best 50% of individuals are used to build the next generation (and so on). The rest of population is generated by mutation procedure. The permutation of the chromosome at the level of 0.25 can form combinations that are relatively different from the original sequence. This allows to find new local extreme(s) of evaluation functions in the space of possible solutions. The usual optimization procedure requires several generations, where have been clearly seen the convergence of evaluation function.

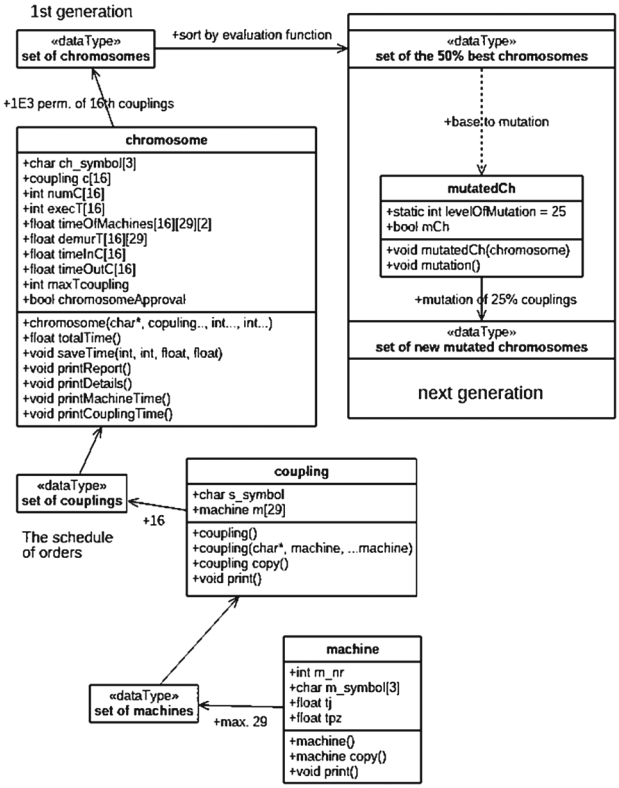


Fig. 1. The UML schema of GA

5 Results of the Simulation

In this work simulations for 1000 accepted individuals 3 consecutive generations was carried out. Figure 2 shows an example of the distribution of lead time for output generation. Maximum time is 4827.9 min, the minimum time - 4016.8 min, the average - 4667.25 min and the standard deviation - 152.15 min. It can be observed that the times of execution are repeatable (although the sequences are not the same) and oscillate around a certain characteristic values. The minimum results are sporadic, which justifies the use of simulation in their quest.

The new population is accompanied by a mutated individuals. A mutation scheme proposed is justified by the fact that the order of execution is of utmost importance for the whole time of production. This is due to the fact that if the same coupling (genes) are produced after each other, they do not require retooling of all the machines in the production process of the coupling. Therefore, the sequence ABA is less favorable than AAB. In every generation, individuals subjected to approval because of the timing of contracts evaluation function, then they were sorted from the point of view of execution time of an order. In the next step, individuals were grouped and counted in one hundred

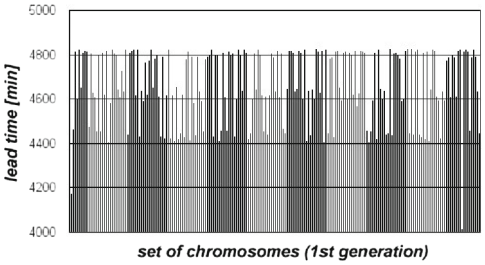


Fig. 2. Lead times for randomly generated chromosomes in the first generation. Normalized time periods (bins) '0–100' designated by the principles: the beginning of the time axis '0' means 't_min', the end of the time axis '100' means 't_max', width of each interval equals to 'tmax − tmin/100'.

periods-bins of the execution time, normalized between minimum and maximum value, each of the same width t_max − t_min/100 and a signed as "0–100". On this basis execution time histograms were found for each generation, the results are presented in the Fig. 3.

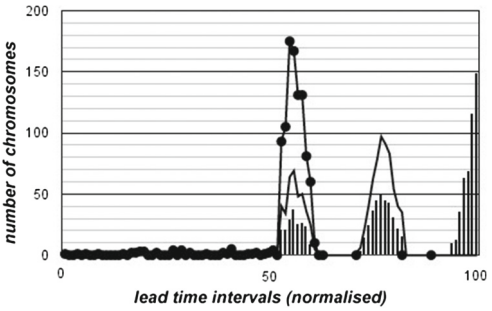


Fig. 3. Histogram of individuals of the first generation (poles), the intermediate generation (solid line), the final generation (solid line points).

In the first generation it can be seen that the histogram bars are not compatible to any known regular distribution, but grouped around three distinct maxima. This is due to the fact that certain tasks in the production cycle of the couplings (genes, their sequences or repetition) have a dominant influence on the total execution time, because of the size of the order and time-consuming production process. Position of such dominant genes determines the total time of the contract. Around these peaks normal distributions is observed, which is associated with less dominant gene permutation (couplings of short runs). In this work, this issue will not be dealt with in detail. It should also be noted that the maximum time found 4827.9 [min] is one of the local maxima of the histogram. In subsequent generations, it can be seen that the rejection of the longest execution time (according to the objective function) leads to moving the histogram peaks towards shorter lead times.

The final sequences with the optimized execution time were occurred in the third generation. In the following sequences the advantageous of mutations was found. The frequent repetition of genes of the same type is present (for example 'OFFFNNAAIKNCCHFF'), however due to the separation of the repeated tasks ('F' appears 5 times in two groups of 'FFF' and 'FF'), one can be expected that further simulations would result in a more favorable solution, but is not obvious.

From 16 production orders, 8 of them decreased in duration due to optimization and downtime. Total downtime for all production orders decreased by 5 753.01 min, which was a decrease of 16.13%. On 11 machines decreased the total size of downtime

It is possible to say that the search for the optimal sequence of production of couplings and minimal execution time, although it is practically impossible from the point of view of analytics (the vast number of potential solutions); it is achievable in the process of genetic algorithm simulation in a relatively short period of time. Conducted research proves that production in small batches seems more optimal. Short sequences of couplings with the same type are better optimized in terms of objective function. Optimal sequences are not necessary strings A, A, A but are distributed between various orders. Cumulated big orders (A+A, F+F+F, N+N) clearly worse they are arranging themselves in optimum sequences. It results from the block of machines in the "cycle for the longer time" and need to wait for the dismissal of machines by other couplings in the queue. Extending downtimes influences for increasing the value of the function of the objective. Accumulated big orders are fulfilling the criterion of purpose in the minute step - 21% orders are only obtaining approval on account of the established completion date resulting from the schedule. For remaining we are dealing with delays and the need to negotiate the new completion dates or to withdraw orders from the production schedule. Methodology drawn up has a few simplifications and of restrictions of the problem on account of the computational complexity and the scale developed referring to the amount of investigated orders during one simulation, considered planning horizons, accepted resulting productive times from production routes. However it is possible to modify existing model and rely on dynamic table with freedom of choice of orders and their production routes and lot sizes without the need of the manual alteration to include software in the model.

Elaborated model can also be appropriately adapted for different production real terms enabling generating the production schedule and the optimization throughputs. It will be necessary to actualize databases with input data and consider new constraints.

6 Conclusions

The developed algorithm can be perceived as universal one and can be easily adopted to changeable lot sizes (orders). Authors also have proved that the method used has a relatively high convergence and simulations for three generations eliminate inefficient solutions. Simulation results received do not always correspond to our intuition and optimal often prove sequences mixed difficult to predict for the production planner.

The use of the model based on genetic algorithm for production scheduling and optimization of batch size production quickly and efficiently generate a production

schedule, to determine the sequence of orders and load workstations in such a way that the entire production cycle was minimized downtime on the machines where possible eliminated and the load machinery increased. This represents significant added value compared to traditional methods of production scheduling based on the experience of planners and tools without the possibility of dynamic optimization in terms of a fixed objective function as MS Excel, MS Project. The program, after many random trials can find one acceptable chromosome between 10–50 s (for processor 2,66 MHz). So the simulation of 3,000 chromosomes is about 1,500 min = 25 h of processor work. Calculations can be also performed on a multitask mode on cluster and reduce computing time.

Conducting a simulation using a genetic algorithm allows for the analysis of machines used in the production process following couplings resulting from production orders included in the production schedule. In addition to this analysis is the load of all machines used in production (both analyzed line couplings as well as machines with cooperation). The production process is moved when another machine according to the production route is busy. The waiting period is generated in the form of a report and the information contained under the parameter downtime. Downtime is the norm for further couplings chromosome (they have already designated production cycle previous couplings so waiting for the free device). As a consequence, the total duration of the sequence is determined by: the times resulting from technology - set-up times, cycle time; the size of production batches manufactured and existing downtime on the production line.

Further work should go in the direction of extension of the existing model and its input parameters by entering them into a dynamic array. When operating in dynamic data structures may be that such a structure should be increased or decreased during the program. One can dynamically change the size of the structure taking into account the variable amount of production orders in a single simulation on a regular basis in an integrated way to update the production technology and perform scenario analysis by introducing new engines, new production orders and modifying batch sizes and lead times and taking into account the multi-level structure of products and multi-stage planning production. The model can also be adapted accordingly in the future for other actual production conditions allowing the generation of production scheduling and optimization of production. In such case there is a need to update databases of input parameters and taking into account the limits imposed the new production environment. Without a doubt, this is a helpful tool for efficient production planning for a large number of production orders, the variable range of production with the need to minimize production bottlenecks, minimize inventories of work in progress and to take account of various constraints of time, cost and resource.

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Application of Neural-Fuzzy System in Prediction of Methane Hazard

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Abstract. In the paper there are presented possibilities of use of artificial intelligence to build predictive models based on the measurement data. Fundamental problems concerning fuzzy logic, neural network and ANFIS system were discussed. This system connects capability of representation and processing of fuzzy logic and capability of learning of neutral networks. The ANFIS interface has been characterized relating to training a fuzzy model of Sugeno type. An example of using its interface to predicting of methane hazard in the region of mined longwall was presented. Predictive model based on the real methane measurement data from this longwall was developed.

Keywords: Neuro-fuzzy systems · ANFIS interface · Prediction of methane-bearing capacity in a mine

1 Introduction

The artificial intelligence is an area of problems based on features specified for human intelligence. The algorithm mimics more or less these features; it is able to learn (by creating rules of reasoning) and next to act (generalization of knowledge, data classification and decision making). The fundamental problem of creating a model of an investigated phenomenon is its generation based on numeric data. One of the techniques of creation of a reasoning system is the ANFIS network [4] which is an adaptive system characterized by functionality of neural networks and fuzzy reasoning. The effective functioning of this algorithm allows us to determine the parameters of the model including an organization of its structure. The network just learned on the basis of historical data is able to predict future values.

Methane hazard is a very important issue with regard to safety in the Polish coal mines. This hazard consists in releasing methane from coal and rock deposits [1, 12]. Affecting the balance in strata caused by mining operations is the reason for methane releasing. A user's guide issued by the Central Mining Institute (GIG) describes the principles of longwall working under conditions of methane hazard. A value describing a working face area is its methane bearing capacity. This value is calculated on the basis of the averaged values of the measured methane concentrations and the air flow

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velocities (air flow volume streams). To characterize methane bearing capacity at the working face area the following concepts are defined:

– ventilation methane bearing capacity;
– absolute methane bearing capacity;
– criterial methane bearing capacity.

A value of the criterial methane bearing capacity may be a necessary condition for use of methane drainage or other methods to reduce methane emission into workings (e.g., air ducts) in case when the calculated value of the criterial methane bearing capacity is lower than the forecasted or the real one occurring during mining works at the working face area.

A subject matter of prediction of the methane hazard was discussed among others in [7–9]. With regard to method of data collecting being necessary for hazard assessment made by mining services (averaging the measuring results), the detailed data processing is characterized by a long delay. A current assessment of methane hazard concluded on the basis of analysis of a course of absolute methane-bearing capacity with reference to criterial methane-bearing capacity will allow us to control much better the ventilation parameters [11]. Thanks to use of Fuzzy Logic Toolbox library and ANFIS interface it is feasible to create a neuro-fuzzy network to be applied for prediction of value of methane-bearing capacity calculated on the basis of the parameters measured during mining operations carried out at a working face area.

2 Neuro-fuzzy Networks

2.1 Fuzzy Models

Fuzzy reasoning is generally used there where it is difficult to describe the investigated phenomenon by means of a mathematic model. A process of fuzzy reasoning is divided into three stages [11]. The first stage is fuzzifying which consists in computing a membership degree of input values to fuzzy sets. The second stage is an inference which is responsible for computing a resulting membership function on the basis of input values. The calculations are made with use of inference mechanism and base of rules. The third stage is a transformation of the resulting membership function into numeric value in the process of de-fuzzifying.

The most frequently used fuzzy models are:

1. Rule-based Mamdani-type fuzzy modelling defined so [10]:

$$R = \left\{ IF\ x_n = A_n,\ THEN\ y = B \right\}$$

   where: x_n – input linguistic variables; y – output linguistic variable; A_n, B – linguistic values.
2. Takagi–Sugeno (Sugeno) model – a connection of a model based on linguistic description with polynomial functions. The model includes a base of knowledge with the rules described as follows [10]:

$$R = \left\{ IF\ x_n = A_n,\ THEN\ y = f\left(x_n\right) \right\}$$

where: x_n – input linguistic variables; A_n – premise value, $y = f(x_n)$ – function in conclusion of "i-rule".

The fundamental difference between the Mamdani and Sugeno models consists in use of a function in rule conclusion (in Sugeno model). This improves considerably a computing performance of the system due to lower load for assessment of the output value of the system.

2.2 Neuro-fuzzy Systems

The artificial neural network is a system which operates on the basis of a human intelligence. Its aim is a modelling an input/output relationship [10]. The network consists of neurons which create the consecutive network layers. The output signals of the individual neurons are transferred to the neuron inputs of the next layer. The knowledge is recorded by means of the weights of each connection between the individual neurons. The weights are modified on the basis of examples in the learning process. The learned structure can associate the obtained knowledge and use it for replies to the states unprecedented before.

The operation of a neural network can be divided into a stage of learning and a normal operation. In the first stage the network defines the parameters necessary for its functioning according to requirements. In the normal stage the network solves the tasks on the basis of the knowledge obtained before.

The neuro-fuzzy systems are created by connection of artificial neural networks and fuzzy systems. The fuzzy model transforms into a neuro-fuzzy network. The weights of the network correspond with parameters of a membership function in premises and coefficients of polynomials in conclusions of rules of a fuzzy model. The first or zero degree polynomials are the most frequently polynomials used in rule conclusions (Sugeno model).

2.3 Creation of a Fuzzy System on the Basis of Numeric Data

In order to create a model representing a selected question it is first of all important to obtain knowledge required to organize a structure of a model. In fuzzy systems there are used two methods of obtaining knowledge. The first one is to obtain knowledge from an expert. A structure and parameters are determined arbitrarily on the basis of the expert's knowledge. This approach may dubious due to difficulties referred to precise determination of parameters in case of a complicated representation. Therefore the frequently used solution is a creation of an initial model which is next precisely trained on the basis of the measuring data [10]. The second method is automatic getting data on the basis of numeric data. The effective running such algorithm allows us to determine the parameters of the system including the organization of its structure. It is also possible to connect this method with the expert's knowledge. In this case a part of knowledge will be obtained from the expert and the next part from automatic selection of rules.

To create a fuzzy system it is necessary to aim at maximal simplification of a structure and base of rules. A complicated and extended base may not give satisfactory results at all. The training of this model may be difficult or simply impossible.

Clustering of measuring data consists in partition of a set of elements into subsets. Among fuzzy clustering methods one may distinguish: c-means Gustafson-Kessel method, a subtractive method and a clonal selection method [2]. The clustering methods can be used in the absence of a base of rules designed for creation of an initial model on the basis of a set of numeric data.

The final stage of selection of parameters of a fuzzy model can be its transformation into an equivalent multi-layer neural network. Such a network can be additionally subjected to the process of learning on the basis of a learning data set.

3 ANFIS

The ANFIS system is the abbreviation of the adaptive-network-based fuzzy inference system according to the Takagi–Sugeno model [6]. The system is equivalent to a neural network with four hidden layers.

The ANFIS network consists of the following layers [5, 10]:

1. input layer – distribution of the input signals; no calculations;
2. first hidden layer – calculating degrees of compliance of input values in premises of conditional rules;
3. second hidden layer – determination of a level of activation of every conditional rule for previously calculated values of degrees of compliance;
4. third hidden layer – calculating a standardized level of activation of every conditional rule;
5. fourth hidden layer – determining products of rule conclusions and standardized levels of activation of the rules;
6. output layer – determining the output value of the ANFIS network on the basis of the sum of the weighted signals from the previous layer.

The training of the ANFIS network consists in modification of parameters in order to obtain a set of conditional fuzzy rules. At the beginning of the process there are defined membership functions of fuzzy sets in premises of rules. The input data space is divided with use of a uniform grid distribution [10]. The disadvantage of this solution is a dependence of a number of rules on the space dimensions; this makes use of applications with many inputs difficult. After dividing the space there are obtained the initial values of parameters in rule premises.

A hybrid training method for a network consists in selection of values of parameters by means of various methods. In forward pass the algorithm determines the values of conclusion parameters by means of a recursive least-squares method. While in backward pass the error signals propagate backwards and the parameters of premises are selected by a modified gradient method [5].

The Fuzzy Logic Toolbox library [3] (a component of the MATLAB packet of MathWorks, Inc. Company) allows a generation of the ANFIS network. For that purpose

it is used a graphic interface ANFIS Editor which makes a training process for artificial neural networks with regard to training of fuzzy models. Running the ANFIS algorithm consists in transformation of the Sugeno fuzzy model into a neuro-fuzzy network. The obtained this way structure consists of six layers. The weights of the network correspond to parameters of a membership functions in premises and coefficients of functions in conclusions of rules of a fuzzy model.

Creation of a model of the ANFIS network in the MATLAB environment requires the definition of an initial structure of the model. As the initial model subjected later to a process of learning it is the most often used the loaded Sugeno structure, i.e., the model created on the basis of partition of the input data space (grid partition) or use of subtractive clustering as well as fuzzy c-means [3].

A training of the structure begins with loading the learning, checking and testing data. After the data have been loaded the process of learning starts. The interface makes possible to determine a method of optimization (hybrid method, backward error propagation), number of periods, and tolerance error to define conditions to stop running the algorithm. After all parameters have been defined the process of training the network begins. In order to check learning efficiency it is necessary to load the testing data and to start the testing procedure.

4 Example of Creation and Training of Neuro-fuzzy Network with Use of the ANFIS Interface

This chapter presents an example of prediction of methane hazard with use of a neuro-fuzzy network. A set of numeric data has been obtained on the basis of the trials carried out at the working face area N-2 in "Pniówek" coal. This is a longwall with high methane-bearing capacity with active methane drainage operations. The longwall has been designed with "Y" type ventilation. The intake air has been ducted through the incline N-1 and next the main gate N-2. A part of the air from the incline N-1 has flowed through the main gate N-3 and then has connected with the return air from the longwall N-2. The return air has been exhausted from the longwall through the main gate N-3 and the raise N-3. The assumed criterial methane bearing capacity for the working face area was 12.76 m^3/min. To determine the criterial methane bearing capacity, it was assumed methane drainage efficiency at the level of 45%. As a result of calculations it was obtained a value of 23.2 m^3/min. A project of the longwall contained a notation that a value of criterial methane bearing capacity will be calculated every day on the basis of indications of sensors and quantity of the air will be regulated depending on the output and methane bearing capacity of the longwall. In case of differences among values of the forecasted and real methane bearing capacity, a ventilation service officer will take a decision to increase if needed a quantity of the air to be provided to the longwall and/or to change a range of methane drainage works.

The numeric data set *METAN* was created on the basis of numeric data obtained as a result of the trials. The measurements were done in 14 days of a normal work of the longwall. The values of the criterial absolute methane-bearing capacity were calculated on the basis of the Instruction No. 17 (2004) developed by Central Mining Institute

(GIG) taking into account the parameters given in the project of the longwall. The methane-bearing capacity at the N-2 longwall area measured during the trials is shown in Fig. 1.

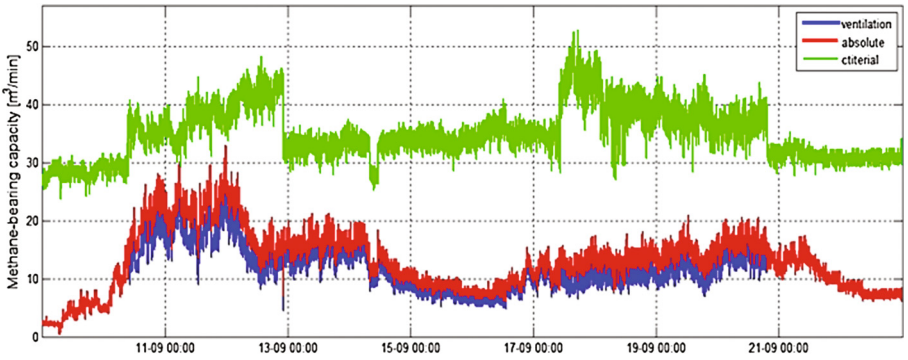


Fig. 1. Methane-bearing capacity at longwall N-2 area during trials

A task of the model is a prediction of methane hazard on the basis of estimation of the absolute methane-bearing capacity in relation to the criterial methane-bearing capacity. For test purpose it was defined a methane hazard rate which is a ratio of the absolute methane-bearing capacity to the criterial capacity. Depending on the value of the quotient it is determined a level of the hazard, where 0 means the highest level of safety, 1 – the real methane hazard which requires to take several steps in order to reduce methane content in the mine air. Figure 2 presents a methane hazard rate.

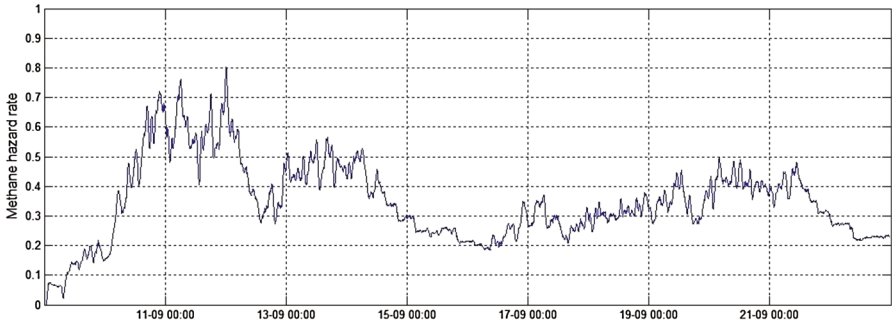


Fig. 2. Methane hazard rate during trials carried out at the working face area

The first stage of creation of a neuro-fuzzy model for prediction of methane hazard is a creation of the training and checking vectors of the time series. For purposes of tests there have been created the training vectors in the following form

$$w(t) = [\, x(t-60)\ x(t-40)\ x(t-20)\ x(t)\ x(t+20)\,] \tag{1}$$

where t – time of a current measurement, and t + Δ – times of measurements shifted by Δ [min].

The next step was a creation of an initial structure of a model on the basis of a grid partition of a numeric data set. A default number of bell membership functions (curves) of inputs of the model is 2, while at the outputs there are generated linear functions. The fuzzy model created in such a way was subjected to training with use of the ANFIS algorithm. The model has been transformed into a neuro-fuzzy network shown in Fig. 3.

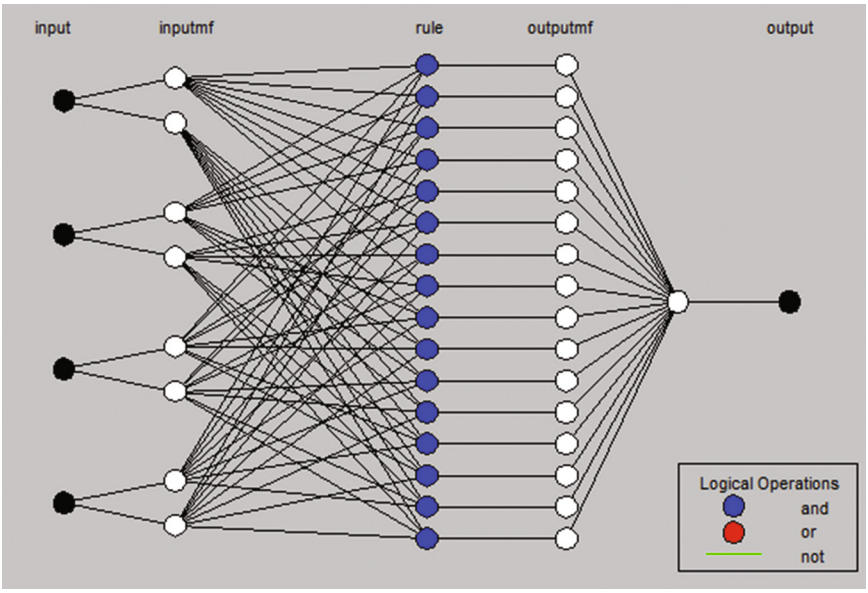


Fig. 3. Structure of a neuro-fuzzy network

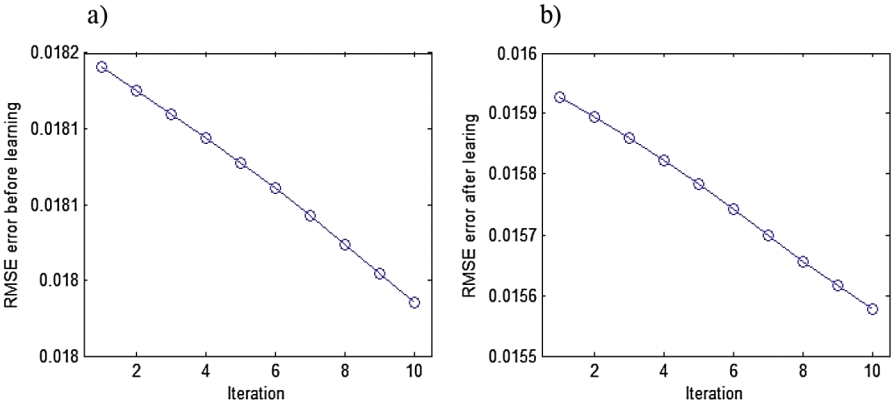


Fig. 4. Error of neuro-fuzzy network learning: (a) before learning; (b) after learning

In the training process of the network it has been used a hybrid method which is combination of the least-squares method and the backward error propagation method. Figure 4 shows the learning error of the network for further iterations of the training.

Figure 5 shows an exemplary inference of a neuro-fuzzy network. The way of inference for the created network is as follows. In the first place the outputs of the model are fuzzified by calculation of membership functions. The values are connected by means of a product creating this way levels of activation of every rule. The functions in conclusions of fuzzy rules are determined also on the basis of measurements. The final output value of the model is a weighted average of all elements of a rule base of the model. The weights are the levels of activation and the elements are the functions in rule conclusions.

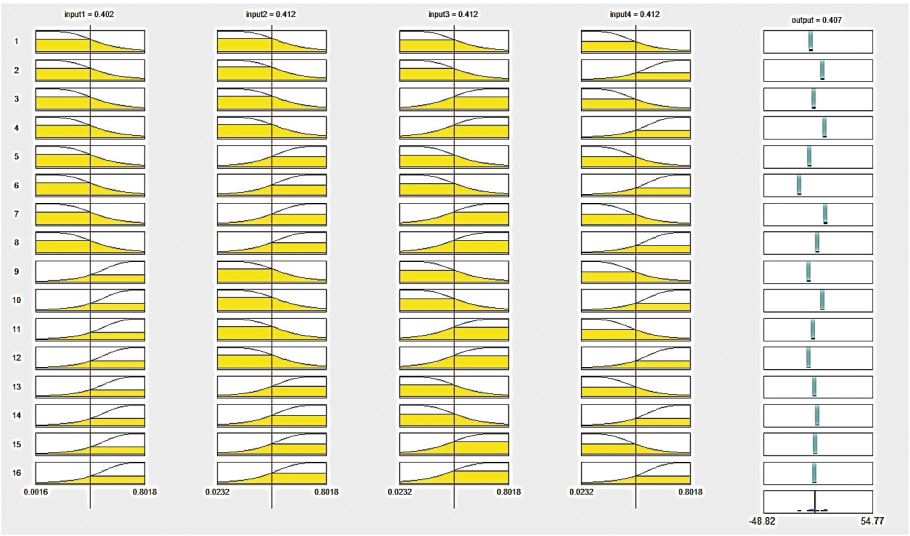


Fig. 5. Exemplary inference of the trained network

Figure 6 shows a prediction of a level of methane hazard at a working face area; Fig. 7 presents a prediction error. The trained neural network represents well a real time course; the average prediction error is 0.0114, and the maximum error is 0.0845.

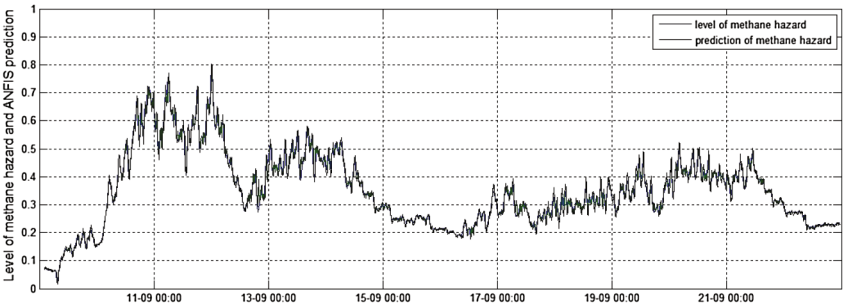


Fig. 6. Prediction of the neuro-fuzzy network

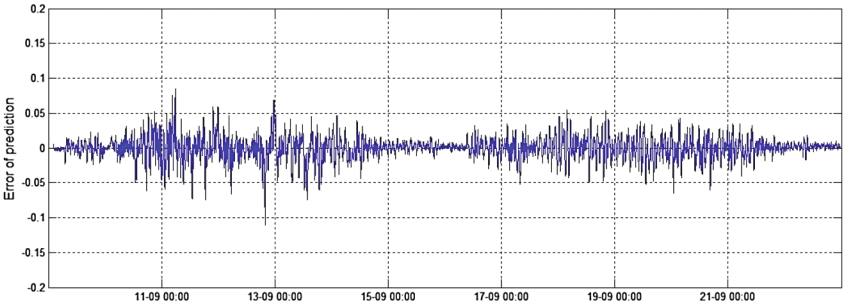


Fig. 7. Error of prediction

5 Summary

The paper presents the ANFIS interface in relations to use for creation and training of neuro-fuzzy models. A process of creation of the models is complex and depends on many factors such as selection of a method of input/output data space partition, a type of a fuzzy model and its parameters and also on numeric data themselves. A use of artificial intelligence methods gives great opportunities for creation of models representing the investigated phenomena on the basis of numeric data. It is possible to describe very complex phenomena. A description of them by mathematic functions would be difficult.

The paper shows an example of application of the ANFIS interface designed for prediction of methane hazard at a working face area during winning operations. With regard to method of data collecting being necessary for hazard assessment made by mining services, the detailed data processing is characterized by a long delay. It has been shown in the paper that a current assessment of methane hazard concluded on the basis of analysis of a course of absolute methane-bearing capacity with reference to criterial methane-bearing capacity may allow us to control much better the ventilation parameters in particular in situations of dynamic changes and when the limit values are exceeded.

A problem of safety in mining is a key issue. A prediction with use of a neuro-fuzzy network allows us to control on-line a level of methane hazard and to take appropriate

action in case of occurring dangerous situations. Therefore these methods can usefully complement the conventional methods of acquiring knowledge.

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Application of Support Vector Machine for Determination of Impact of Traffic-Induced Vibrations on Buildings

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Abstract. The aim of the article is to present an algorithm of Support Vector Machine created to forecast the impact of traffic-induced vibrations on residential buildings. The method is designed to classify the object into one of two classes. The classification into the first class means that there is no impact of vibrations on the building, while classification to the second class indicates the possible influence and suggests the execution of expert studies. Variety of factors affecting impact of vibrations on the structure were taken into account in the algorithm. These factors induce: condition of the road surface, condition of the building, soil type, the distance from the building to the road and type of the vehicle.

Keywords: SVM · Machine learning · Traffic-induced vibrations · Buildings

1 Traffic-Induced Vibrations

Vibrations of buildings may have different reasons. The most damaging ones are caused by earthquakes (see [1–6], for example) or mining tremors (see [7]). Other reasons, such as piling works, large mechanical vibrating entities, movement of people or vibrations resulting from vehicles/trains using the nearby road/tack, are considered to be less dangerous but still may be very problematic. Traffic-induced vibrations may occur not only in city agglomerations but also in the suburbs, wherever there are buildings located near roads or rail-ways. Polish standard PN-85 B-02170 *Evaluation of the harmfulness of building vibrations due to ground motion* [8] states that the distance of impact of vibrations on residential buildings is equal to about 25 m from the tram track axis or the outer road lane and about 50 m from the axis of the railroad track. Value of impact and effects depend on many factors, such as: distance, type of soil, building condition, condition of the road surface and type of the vehicle [9].

The effects of traffic-induced vibrations may be insignificant, for example cracking of paint or plaster in the building. They may be also more damaging, such as cracks in load-bearing elements or may even lead to the collapse of the structure [10].

The building which is within the range of impact of traffic-induced vibrations should be analyzed to verify the harmfulness. It is very difficult to execute such investigations for all potentially affected buildings, because tests are quite expensive and time consuming. Moreover, the tests must be carried out by accredited laboratories to be valid

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in the context of the law (for example in civil matters). In the next chapter, authors present a model of the algorithm which is intended to support the decision concerning the necessity of conducting the in situ measurements.



Fig. 1. Specialized measuring equipment and piezoelectric accelerometers mounted on the wall of the tested building (Source: own photographs)

The measurement methodology is described in [7], as well as in many expert publications and expertises dealing with diagnosis of impact of vibrations (see, for example [9, 11, 12]). Vibrations must be measured at the level of foundation on the ground wall



Fig. 2. Measurement situation of the building for which the analysis was performed (Source: own)

parallel to the street, using a specialized measuring equipment and appropriate sensors (see the example in Fig. 1).

The research subject concerns acceleration time history caused by different types of passing vehicles, i.e. columns of passenger cars, trucks with various weights. Acceleration values recorded during the measurements are analyzed in one-third octave frequency bands according to the criteria in the standard [8]. As a result, the amplitude values are obtained for all the centre frequencies in the range of 1–100 Hz. Then, peak values are selected and plotted on Dynamic Influence Scale I (DIS I) graph. Figure 2 shows an example of building for which the analysis was performed according to the standard [8], whereas Fig. 3 presents the example of the results for this sample structure.

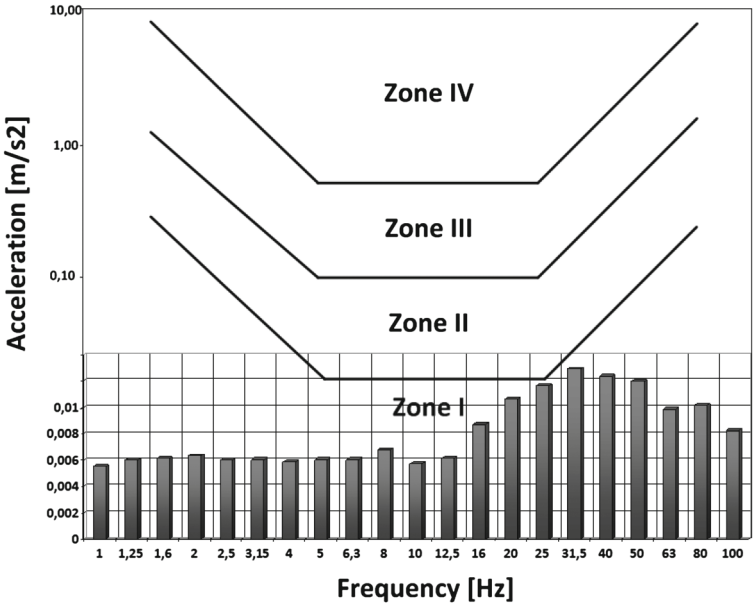


Fig. 3. The graph of peak accelerations with respect to the centre frequencies obtained for the sample building using the DIS I chart (Source: own chart based on [8])

2 Application of Support Vector Machine

Support Vector Machine (SVM) is one of the techniques of computing from the group of methods called machine learning. The aim of the SVM is the analysis and processing of data in regression and classification problems. The subject issue of impact assessment is considered as a binary classification.

The interest of SVM in civil engineering applications is unfortunately quite small. Some interesting results can be found in publications concerning the determination of the state of damage and the technical exploitation of the mining areas [13]. Another application example concerns the use of SVM in the management of location of floating houses (the problem is described in more detail in [14]).

The creation of SVM algorithm requires the results of experimental research. In addition to own research of the authors, other results, described in papers [9, 12, 15–17], were also used in the analysis. The problem of the method of SVM is to find the optimal hyperplane separating variable data sets (classes) [18]. In order to determine this plane, margin which is designated by supporting vectors, should be defined [18, 19] (see Fig. 4). The optimization problem is related to the determination of the margin (maximum or soft, depending on the degree of sough the data), so that the algorithm does not become overfitted or undertrained.

The algorithm is used to solve the optimization problem, which is a minimized margin (soft margin) [18], since it is not linearly separable. It is a binary classification algorithm. It is established by two classes of sets: a set of cases for which there is a risk of impact of vibrations and safe cases set. The aim of SVM is to solve the optimization problem by minimizing the target function TF [18]:

$$TF = \frac{1}{2}\langle w \cdot w \rangle + C \sum_{i=1}^{n} \xi_i \rightarrow \min \tag{1}$$

under the constraints:

$$y_i w^T \varphi(x_i) \geq 1 - \xi_i \tag{2}$$

$$\xi_i \geq 0 \tag{3}$$

$$i = 1, \ldots, n \tag{4}$$

where

- y_i – dependent variable, class affiliation, $y_i \in \{-1, 1\}$,
- w – vector coefficients,
- x_i – independent variable, input components,
- C – parameter related to the power of a penalty, $C \geq 0$, adopt of a set $[10^{-6}, 10^{-5}, \ldots, 10^{6}]$,
- ξ_i – deviations, variable weakness of margin, assuming the following values
  - if $\xi_i = 0$, x_i is classified correctly and it is outside the margin or at its border
  - if $0 < \xi_i \leq 1$, x_i is classified correctly and it is located on the margin
  - if $\xi_i > 1$, x_i is classified incorrectly
- $\varphi(x_i)$ – kernel function (linear, polynomial, potential functions, sigmoidal function) based on [19].

Input variables (independent) were adopted on the basis of performed tests and the standards. They include: distance from the roadway (a quantitative variable), surface road condition, building condition, type of vehicles and absorption of the soil (qualitative variables). Graduation was determined on the basis of expert experience [9, 11, 15, 16]. Possibilities of predictors were established by visual inspections and in situ measurements. Types of categories, i.e.: bad, standard, very good, were adopted by the authors so as to simplify the algorithm. It should be underlined, therefore, that the independent variables (predictors) were based on objective methodology and expert opinions.

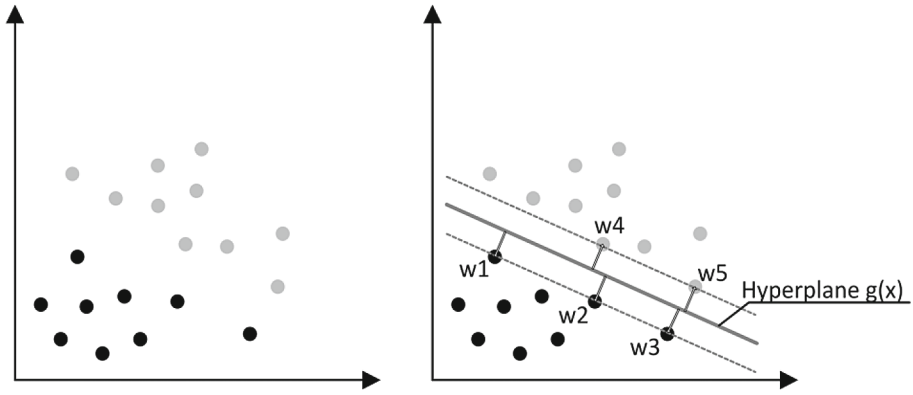


Fig. 4. Classification model of SVM, scheme of problem to be solved (on the left), defined hyperplane g(x) separating classes with indicated margin set by vectors (on the right) (Source: own)

Table 1 presents the characteristics of the input components (predictors). During the study of the SVM, other factors were also repeatedly tested (see [20]), however, after the sensitivity analysis it appeared that they do not have any considerable influence on the results.

Information about the threat of negative impact of vibrations on buildings is the dependent variable (output - class affiliation). The risk is determined on the basis of the criteria described in the standard [8]. If there is no risk, SVM indicates the first zone of impact of vibrations within DIS scale. If the algorithm predicts possible threat, it is an indication to make measurements in situ, because this could mean that the building is located in zone II or even in the upper one.

48 samples were used to build the algorithm of SVM. They were divided into learning samples within a fraction of 75% (total 36 cases) and the testing samples representing 25% (12 cases). To determine the optimal parameters of the model, cross-validation was performed, in which a set of all the cases was divided into 4 subsets. Penalty was used to prevent incorrect classification of samples nearly belonging to class 2, since classes were not equable (27 cases of class "1" – NO RISK and 9 cases of class "2" – DANGER). Therefore, the first class was imposed by a penalty amounting $P1 = 3$ and a penalty of $P2 = 1$ was used for the second class (no impact on the results). The kernel functions were taken as Radial Basis Functions (RBF).

Table 1. Characteristic of the independent variables (predictors)

Variable	Possibilities	Properties
Distance	1.91–20.0 m	The distance from the parallel wall of a building to the edge of the road
Surface road	Very good, standard, bad	Very good condition – surface homogeneous, no damage, breaks, manholes
		Standard condition – surface homogeneous, few damages
		Bad condition – patchy surface, a lot of damages, undulations, holes, cracks
Building condition	Very good, standard, bad	Very good condition – no damage of construction elements and plaster coatings
		Standard condition – no damage of construction elements, single damages of plaster coatings
		Bad condition – a lot of damages, wall cracks
Type of vehicle	Type 1, type 2, type 3	Type 1 - passenger car up to 3.5 t total weight
		Type 2 - bus, truck up to 10 t total weight
		Type 3 - truck from 10 t to 40 t total weight
Absorption of soil	Very good, standard, bad	Very good – condensed sand, dry clay, cohesive soils, compact and half-compact
		Standard – medium and fine moistened clayey sand, hard-plastic cohesive soils
		Bad – wet, loose silty sand, fine clay sand, fine plastic cohesive soils

3 Results and Closing Remarks

Statistica Data Mining computer software was used in the analysis. After completing the calculations, the cross-validation accuracy of 75% was obtained, and this value can be considered as satisfactory. 18 support vectors were designated (at 9 for each class). The algorithm correctly classified 75% of the cases in the learning sample (27 of the 36 cases was categorized successfully) and 91.667% in the test sample (11 out of the 12 cases were categorized successfully). The total reliability of the algorithm was therefore calculated as equal to 79.167%. These results indicate that the SVM can be considered as a good tool to estimate the impact of traffic-induced vibrations on buildings. The results are very promising but still further studies are needed to fully confirm the effectiveness of SVM. Further analysis is planned to be conduced by extending the database and improving the algorithm, so as to be able to increase the reliability up to at least 85%. It is planned to verify the effectiveness of SVM with other parameters and other configuration of factors to increase the reliability of model described in this article.

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Artificial Neural Networks as a Means for Making Process Control Charts User Friendly

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Abstract. The paper discusses usability of various pattern recognition methods, especially based on artificial neural networks for decision making support in process control chart analysis. Their effectiveness for detecting process instability is compared with the effectiveness of a human operator and of a widely accessed commercial statistical software. The results are verified on the basis of data obtained from real production processes.

Keywords: Statistical process control · Control chart · Pattern recognition · Neural networks

1 Introduction

Variability is one of the most troublesome factors of every process. It is caused by common (random) and special causes. Common causes are coherent to the process. They are usually accepted, as their identification and elimination often entail significant costs. Special causes, however, can and must be eliminated [4] because their impact on the process results can be significant. The sources of common causes of process variability are easily assigned. They are continuously present in the process (e.g. gradual wear of a tool's blade) or occur suddenly (e.g. the breaking of a blade).

A widely recognized tool for monitoring process variability is the process control chart (PCC). The concept was proposed by Walter Shewhart in the 1930s [4].

Implementation of a PCC is usually based on an approach where the process is characterized by a temporary normal distribution with constant mean (μ) and standard deviation (σ) values. If over time this assumption is not met, it is assumed that special causes of variation occurred in the process and the causes must be eliminated [4].

In its basic form, a PCC enables monitoring of the statistics (e.g. mean value or standard deviation) of selected process features (they are usually properties or qualities of machined products or processed materials). On the basis of probability of occurrence of certain statistics values, conclusions are drawn concerning the process stability [4].

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After recognizing that the process is running out of control a set of actions aimed at restoring it is undertaken. These actions consist of stopping the process, analysis of possible causes of instability and process correction. The use of PCC for process stability monitoring is grounded on the condition that the process capability measured by so called process capability indices (C_p, C_{pk}) is sufficient. For practical reasons, a PCC analysis involves many predefined patterns that indicate the loss of process stability (Fig. 1), for example: one point beyond control limits (LCL or UCL), seven consecutive points making an increasing or decreasing trend, the so-called mixtures, i.e. the occurrence of groups of three consecutive observations above, and then below the center line, and many more [4, 17].

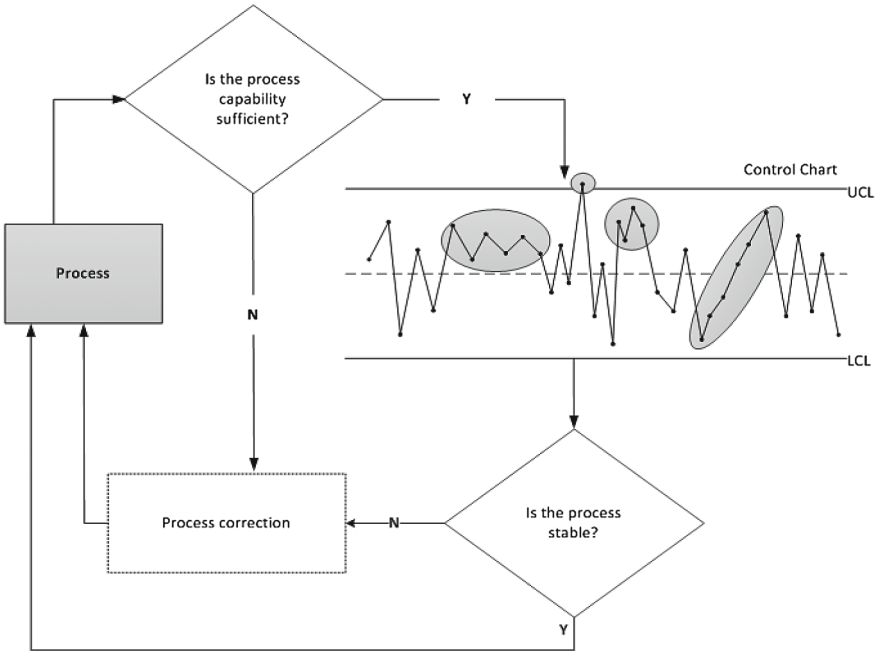


Fig. 1. The idea of a statistical model of the process (author's research)

In most common cases, patterns on a PCC are constantly observed by an employee that operates the machine. The employee, or "human operator" also makes decisions about possible actions to be undertaken if the process loses its stability. Taking into account that the main job of the human operator is to operate the machine and that the human operator's statistical knowledge is often insufficient [4] it can be expected that his decisions may be not sufficient enough.

Although Walter Shewhart published the theoretical basis of a PCC almost one hundred years ago, research is still conducted into expanding the field of their applications. Messaoud [10], for example, applied a PCC to monitor the process of drilling in order to discover unacceptable vibrations. Zhu and Lin [21] used Shewhart's control charts to monitor the density of wooden slabs. In 2011, Holmes and Mergen presented

a case where a PCC was applied to an automatically controlled process. Their study was conducted on the data from a process of brake drum production [5]. Chang studied the application of PCC to the operation of curing high-pressure hoses. He showed that application of a PCC made it possible to significantly reduce energy consumption [2]. Moore and Murphy analyzed the processes of surgical instrument production. These processes were characterized by frequent changes in machine settings and rebooting of machines due to the short run type of production. They proposed and applied a short run PCC [11]. Tangjitsitcharoen and Boranintr applied a PCC to monitor the surface roughness of a product processed through rolling with the use of a cutting force ratio. For the purpose of the statistical control of the process, they applied an I-MR (individual observations – moving range) PCC [18].

Many researches attempt to improve the methods of PCC analysis based on the assumption that sets of points on a PCC can be viewed as "images" of a process and may be interpreted on the basis of a set of previously developed patterns, without the need to apply the knowledge of assumptions concerning probability distribution and statistics. Here, the term "image" means a time series made by subsequent points on a chart, obtained as a result of measuring values or statistics for a given process. It may be called an image of a process in a specified time frame. Such an approach to PCC analysis becomes a classifying task. It involves classifying a set of points to a certain group of patterns using an appropriate classifier and on the basis of occurring cases, and assigning potential corrective measures. The results of this classification serve as a decision making support for the operator and can be very helpful in his every days' work.

The relevant literature offers a number of classification methods, for example: classification through the induction of decision trees, Bayes classifiers, metaheuristic (e.g. genetic algorithms), rough sets, k-nearest neighbor algorithm, and many other statistical methods constantly developed [6, 15, 20]. Another one is research of Lesany et al., in which the methods of classification of control chart patterns were analyzed in detail [7].

2 Process Control Charts Analysis with the Use of Artificial Neural Networks

Among classification methods artificial neural networks (ANNs) have a special place. Networks do not learn algorithms but do learn through examples. Therefore, they are highly useful in solving problems related to the classification of objects. Below, several selected applications of ANNs concerning classification in the area of broadly understood production engineering are presented.

In research carried out by Kujawińska and Hamrol, the best results in application of ANNs to control chart analysis were obtained with the use of MLP (multilayer perceptron) networks [3]. Lu et al. used an ANN to monitor the state of the process and eliminate disturbances that occur during production [9]. Yu and Xi observed that neural networks are characterized by significant resistance to the lack of data and other disturbances. In their research they applied self-organizing maps for the control of process quality [19]. In 2013, Lonkwic published the results of research into the extent to which the neural network method is capable of identifying the dimensional part in the process of profile

bending. The results were satisfying and not worse than in the case of the traditional approach [8]. Lesany et al. applied learning vector quantization and MLP neural networks to study atypical patterns. They emphasize that correct and quick recognition and analysis of unnatural patterns on Shewhart's control charts is important, and unfortunately, not always (or almost never) possible when using classical solutions [7]. In 2014, Rojek studied different types of neuronal nets for load prediction and failures location within a water-supply network [12, 13] and for the system supporting the design of a technological process [14] and other authors also [1, 16].

However, the application of ANN architecture is not free of difficulties. Above all, problems related to the choice of such parameters as the number of neurons in particular network layers and the parameters for learning should be mentioned. Another weakness of ANNs is the fact that eventually, the results of the classification also depend on variables used for the construction of models and on the length of the images. This element significantly influences the effectiveness of recognition. In the case of images where length increases, a tendency to faulty classifications of symptoms for MLP networks was observed [3].

The aim of this paper is to study usability of various pattern recognition methods, based on artificial neural networks for decision making support in process control chart analysis. Their effectiveness for detecting process instability is compared with the effectiveness of a human operator and of a widely accessed commercial statistical software.

In the first stage of investigation three different types of networks were investigated in relation to their usability for PCC analysis: MLP, RBF (Radial Basis Function) and Kohonen (SOFM Self Organizing Feature Map). MLP networks are considered as the most universal and widespread networks for various technical problems. The RBF networks have some advantages in comparison to MLP. They enable to model any nonlinear function. In Kohonen networks training is organized by using method of competitive self-organizing. The results of the first stage made it possible to choose the best settings of neural networks and use them as the input to the second stage of the research: comparison of their effectiveness with the effectiveness of the human operator and commercial statistical software. The data from grinding of roller bearings was utilized in the first stage and from grinding together with superfinishing of a TV screen surface in the second stage of study.

Over the course of the first stage of research, the number of neurons in the hidden layer and the number of learning cycles were also changed (after processing a complete learning cycle - the process known as epoch - the classification error for an epoch was calculated and the whole cycle was repeated until this error fell below an acceptable level). The number of neurons in the hidden layer was selected experimentally: for the MLP network from 5 to 30, for the RBF network from 5 to 60. The number of learning cycles changed from 10 to 150. In the case of the SOFM network, the topology of the network also changed (network topology is a network structure; neurons are connected to adjacent neurons by neighboring relations – typical network topologies are rectangular, hexagonal, or in the form of open or closed chains). Networks of the topology of 4×4, 10×10, 15×15 and 20×20 were used.

For the purpose of training of the MLP network the BFGS algorithm was used (Broyden – Fletcher – Goldfarb – Shanno; for example "BFGS 130" means that the

optimum solution was obtained in 130 steps). The RBF network was trained with the use of the RBFT algorithm (Reduced Breadth-First Search) in two stages. In the first stage, radial functions were distributed using only input variables from the data. In the second stage, weights connecting radial functions with output neurons were determined. In the case of the SOFM network, the training of the network took place with the use of Kohonen's method, which involves assigning nods to a layer of radial neurons.

For training 504 samples at the length of 5 or 10 elements were collected. The set consisted of typical patterns defined for PCCs. It was divided into a learning file (75% records), a test file (15% records) and a validation file (10% records). The sets of learning included classes of previously defined patterns. The results of training, testing and validating are presented in Table 1.

Table 1. Results of evaluation of training, testing, validation errors and classification effectiveness for various types of networks in grinding process (authors' research).

Network name	Training algorithm	Error (training)	Error (testing)	Error (validation)	ANN effectiveness (%)
MLP 5-25-1	BFGS 130	0.669640	0.425530	0.212770	95.64
MLP 5-22-1	BFGS 37	0.000000	0.000000	0.000000	100.00
MLP 5-13-1	BFGS 32	0.771433	0.538301	0.714897	87.92
MLP 10-12-1	BFGS 52	0.000000	0.000000	0.000000	100.00
MLP 10-25-1	BFGS 48	0.000000	0.000000	0.000000	100.00
MLP 10-29-1	BFGS 28	0.225992	0.000001	0.133333	98.80
RBF 5-41-1	RBFT	0.000000	0.000000	0.000000	100.00
RBF 5-31-1	RBFT	0.133934	0.425533	0.212771	97.43
RBF 5-17-1	RBFT	0.963215	0.829796	0.940434	70.36
RBF 10-21-1	RBFT	0.786442	0.566674	0.733333	86.71
RBF 10-31-1	RBFT	0.621472	0.933333	0.933333	91.71
RBF 10-60-1	**RBFT**	**0.000000**	**0.266671**	**0.133333**	**98.31**
SOFM 5-4 × 4	Kohonen 100	0.439724	0.537600	0.534939	98.49
SOFM 5-10 × 10	Kohonen 100	0.095634	0.099405	0.093437	99.71
SOFM 5-15 × 15	**Kohonen 100**	**0.000000**	**0.000000**	**0.000000**	**100.00**
SOFM 10-15 × 15	Kohonen 100	0.003876	0.002994	0.005495	99.99
SOFM 10-20 × 20	**Kohonen 100**	**0.000000**	**0.000000**	**0.000000**	**100.00**

Symbols:
MLP – number of neurons in input layer – number of neurons in hidden layer – number of neurons in output layer
RBF – number of neurons in input layer – number of neurons in hidden layer – number of neurons in output layer
SOFM – number of neurons in input layer – network topology

In the training and testing stage, the number of layers was selected along with the number of neurons, minimizing the network's error. This task was conducted by means of a training algorithm. The training process was at the same time the process of assigning parameters of the model represented by the network to available training and testing data. A network's error was determined with the use of an error function chosen by the researcher, which aggregates determined differences between the cases presented to the network. A testing error was used to evaluate the accuracy of the neural network model during the process of neural network training on the basis of data from the test sample that were not used in the first (training) stage. At the network testing stage there

may be one more change in the network parameters. The validation error evaluates the model of a neural network on the basis of data not used during the training and testing of the network. The experiments compared training error, testing error, and validation error. In the first experiments was used an RMS error. Next, entropy (single and multiple) was used. Table 1 also includes the network evaluation expressed with the so-called classification quality (ANN quality), defined as a number of correct indications of the network to the number of all the possible indications expressed as a percentage.

By analyzing the models of MLP, RBF and SOFM neural networks, it can be seen that the selected networks (Table 1, bold) take a high percentage value of the classification quality – reaching even 100%. This result was obtained through changing the parameters in the network structure at the training stage. In all types of networks, the first parameter of the structure concerned the number of inputs. The constructed models had 5 and 10 inputs. In the case of the MLP network, a greater number of inputs resulted in the change of the remaining parameters. In order to obtain 100% classification quality, a much greater number of learning cycles were conducted in the BFGS algorithm, 37 for MLP 5-22-1 network, 52 for MLP 10-12-1 and 48 for MLP 10-25-1 respectively, which extended the network's learning time. Another parameter, i.e. the number of neurons in the hidden layer of the network, also influenced both the classification quality and learning time. In order to improve the quality of training and shorten the training process, the neuron activation function in the hidden and output layers was changed. Networks cope well with tasks related to signal classification but require significant learning time and an ability to select an appropriate structure. The results of the research with RBF and SOFM networks showed great quality of pattern recognition. Another important feature was their speed of learning, especially through RFB networks.

It is worth mentioning that the number of accurate recognitions was increased in the course of training by introducing an additional number of neurons in the hidden layer, not by adding learning cycles.

3 Pattern Recognition on Control Charts – Comparative Study

Classification effectiveness of ANNs was compared with the effectiveness of the human operator and a commercial statistical module. The comparison was made for two industrial processes: grinding of roller bearings and the superfinishing of a TV screen surface. The study consisted of four stages:

1. Collecting data from grinding and superfinishing processes and analyzing the process stability and relevant sets of data by an expert.
2. Defining a set of patterns at the length of 5 or 10 points (observations). For both processes the set of 7 patterns (see Fig. 1): upper shift, lower shift, increasing run, decreasing run, increasing trend, decreasing trend, groups 2 out of 3 were predefined.
3. Recognizing patterns by a human operator, a chosen commercial statistical application (Statistica 12.0 [17]), ANNs used in previous research and the new ANNs.
4. Comparison of recognition effectiveness of all three approaches.

From each of the processes, 504 samples at the length of 5 or 10 elements were collected. The learning sets included classes of previously defined patterns.

As a measure of comparison, the quotient of the number of correct recognitions and the number of all occurrences of patterns in the analyzed set is expressed as a percentage (MP). The value of the measure changes from 0 to 100%. The measure takes its maximum value in a situation when all the patterns included in the analyzed set are correctly recognized.

In the research, the so-called false classification error was also observed, i.e. an error involving indication of a pattern in a case where there was none (MB). This measure was defined as a quotient of the number of erroneous recognitions and the number of all indications. It takes its minimum value in a situation when the method does not interfere with the random process (no false signals). In order to compare the effectiveness of recognition for particular methods, the values of both measures were analyzed simultaneously. In the study, the assumption was made that the analyzed method of classification is characterized with high effectiveness if the value of the measure of correct classification (MP) is larger than 95%, and at the same time, the value of the measure of erroneous indications (MB) does not exceed 1%. Tables 2 and 3 present the results of the classification verification in respect to the type of classifier and the kind of technological process. The tables show only the value of the classification quality (the measure of correct answers), because the value of the measure of false classifications was below 1% and it was assumed that its significance for the effectiveness of recognition is negligible. The results of the effectiveness of ANNs presented in the study were juxtaposed with the results of pattern recognition by the Statistica module and the classification quality of a human operator. The verification of the effectiveness of the classification of PCC images confirmed the assumptions that the weak chain in the analysis of control charts is the human operator—characterized by the smallest percentage of accurate recognitions. The effectiveness of the human operator in the classification of patterns for both processes equaled, on average, 84%. A decrease in the classification quality may be observed for patterns with a greater number of points. The human operator copes well with patterns of the trend, run or shift type. An exception significantly deviating from this rule are the patterns such as mixtures and with 2 out of 3 points located close to the control lines (in the so called warning zone).

Table 2. Comparison of classification effectiveness between a human operator, Statistica and ANN for images of length 5 (own study).

Grinding process		Superfinishing process	
Classifier	Classification effectiveness (%)	Classifier	Classification effectiveness (%)
MLP 5-22-1	100.00	MLP 5-22-1	96.35
RBF 5-41-1	100.00	RBF 5-41-1	97.84
SOFM 5-15 × 15	100.00	SOFM 5-15 × 15	98.42
Human operator	86.00	Human operator	83.00
Statistica	96.00	Statistica	95.00

Table 3. Comparing classification effectiveness between operator, Statistica and ANN for images of length 10 (own study)

Grinding process		Superfinishing process	
Classifier	Classification effectiveness (%)	Classifier	Classification effectiveness (%)
MLP 10-25-1	97.56	MLP 10-25-1	97.62
RBF 10-60-1	98.31	RBF 10-60-1	98.35
SOFM 10-20 × 20	99.59	SOFM 10-20 × 20	99.65
Human operator	84.00	Human operator	82.00
Statistica	95.00	Statistica	95.00

As mentioned before for training 504 samples at the length of 5 or 10 elements were collected. The set consisted of typical patterns defined for PCCs. It was divided into a learning file (75% records), a test file (15% records) and a validation file (10% records). The learning sets included classes of previously defined patterns. The PCC analysis module in the Statistica software had 95% of accurate indications. The Statistica software coped well with patterns such as increasing, decreasing, increasing run, decreasing run and 2 out of 3 in zone A The effectiveness of recognition decreased by unconventional patterns characteristic for both operations, mainly in the case of mixtures. The best recognition results were obtained for classifiers based on ANNs. The percentage of correct recognitions with the use of an ANN in the process of grinding was 100 in the case of images of length 5. Slightly worse classification quality was achieved for the process of superfinishing and in the case of images of a greater number of points. Nevertheless, the average level of correct indications was higher than the classification quality of the human operator and the Statistica module.

4 Conclusions

ANNs obtain great results in pattern recognition on control charts. They had significantly more accurate recognitions than the classification performed by a human operator or Statistica software.

Based on the authors' research and literature review, a comparison of the three discussed methods was conducted. The results are presented in Table 4.

All the discussed methods have their pros and cons. Which method to choose for specific use should be decided on the basis of technical, quality and economic conditions.

Table 4. A comparison of the three studied methods of pattern recognition on PCC.

Criteria	Method of control chart analysis		
	Artificial network (ANN)	Human operator	Commercial statistical software
Time needed to identify a pattern in a PCC	*Very short*	*Quite long* Depends on a human operator's experience and skills	*Short*
Possibility of wrong pattern recognition	*Low* Depends only on number of patterns used in the training phase	*High* Depends on human operator: skills, mental abilities, self-discipline, work conditions, time for making decision	*Medium* Is limited by number of predefined patterns
User friendliness Time needed to master the "method"	*Medium* Training and implementation of ANN requires specialized knowledge. Using ANN with a dedicated user interface is simple and requires no special skills from the process operator. Allows him to concentrate fully on operating the process	*Medium* Running a PCC and analyzing data gathered requires continuous engagement of a human operator and interferes with the main task (operating the process)	*High* Using commercial statistical software equipped with a dedicated user interface is simple and requires no special skills and allows a human operator to concentrate on the operating process
Pattern length (number of points in a pattern) and diversity	*No limitations* ANN recognized both short and long patterns. The only condition is that there are present in the training set	*Strongly limited* Human ability to recognize long, complex or rarely occurring patterns is limited	*Limited* In standard software, only a limited number of patterns are implemented
Essential technical and intellectual resources	*High* Expert for implementation of suitable software for modelling and training ANNs is necessary. Powerful computers with sufficient capacity and resistance against possible harmful environment influences are needed	*Low* In many cases, a pocket calculator, a sheet of paper and basic statistical skills are sufficient	*Medium* Commercial statistical software can be implemented on practically any computer. The computer should be resistant to possible harmful environment influences

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Assessment of the Feasibility of a Production Plan with the Use of an Artificial Neural Network Model

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Abstract. Models of artificial neural networks can be used to control a production system, and thus to ensure its stability. Such models are very useful tools, because they can be built quickly and easily. The paper presents the possibility to use an artificial neural network for forecasting the production volume. A production plant manufacturing flywheels was used as an example. The specific character of the plant consisting in a limited access to production resources and the need for timely execution of variable customer orders caused that an ANN model built in the SAS Enterprise Miner 6.2 environment was used to solved this problem. This paper presents the manner of building the ANN and the results of the experiments that consisted in forecasting the production volumes depending on the values of independent variables.

Keywords: Artificial neural networks · Production planning · Production forecasting

1 Introduction

The development of modern enterprises is driven by innovations and diversified products, while in the scope of management, production and designing, there occurs a progressive integration of tasks and functions in many areas that were separate previously. However, there appears a problem with ensuring the stability of production [1, 5, 7, 11]. The production in small batches with highly diversified products and low inventory levels is characterised by a much lower stability as compared with the large-batch manufacturing [2]. Additionally, innovations introduced to products or processes result in disturbances in the current operations. Although these disturbances are usually temporary, they may lead to a loss of the operating or manufacturing stability in a company, which in turn translates into financial losses and a loss of market [8].

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The development of the IT systems led to an increase in the amount of information collected in enterprises [9, 13]. In turn, the market requirements and the dynamics of the business environment caused that there is a search for new, faster methods of production system modelling [6, 12]. Such methods include models of artificial neural networks, which provide solutions that take into account the process of learning on the basis of available data. They allow skipping the stage of modelling complex relationships between elements of a production system. In order to build a model of a production system, it is enough to define the problem, select input and output variables, and create a training data set.

Artificial neural networks (ANN) constitute a modern method for mathematical modelling of phenomena and processes, which in the last dozen or so years found many applications in different areas of human activity. The reason why ANN are used in the science and technology is the possibility to treat dynamic, complex variables or imprecisely defined processes as a black box. In other words, ANN allow finding a relationship between many input variables and the output variable in the process without a need to build complex mathematical equations [3, 4, 10, 14].

Artificial neural networks are usually used to solve problems related to approximation, interpolation, prediction, classification, recognition, and control. Image recognition, which also includes classification, grouping and processing, accounts for approx. 70% of all industrial applications. In the management and operation of production systems, artificial neural networks are more and more often used for [15, 16]:

- control of production processes, robots,
- analysis of manufacturing problems,
- diagnostics of electronic systems of machines,
- selection of personnel and input materials,
- optimization of the business activity, waste disposal, robot movements,
- planning overhauls of machines,
- forecasting.

The primary objective of modelling the dynamics of a production process is to identify the temporal variability of its physical quantities or states. To this end, a time series, i.e. an ordered sequence of values of a certain variable over time, should be determined. A time series may have a form of a vector $[y(t_1), y(t_2), \ldots, y(t_N)]$. Due to the fact that process parameters may differ in separate phases of the process, the time series vector can take the form of a vector defined in N-dimensional space. Individual components of this vector will be the states of the production process stages in the past, which in turn can be regarded as points in a multi-dimensional output space. Thus the task of analysing the temporal variability of the production process can be reduced to searching N-dimensional space for a certain trajectory, on which the analysed output variable of the process "moves". Therefore, a given quantity in the form of a time series is determined in order to predict its value in future moments [4, 10, 15].

2 Method of Building the ANN Model for Assessing the Feasibility of the Flywheel Production Plan

2.1 Characteristics of the Flywheel Production Process

The analysis and feasibility assessment of the production plan will be carried out in an European company from the automotive industry. The company has 4 plants and manufactures 4 groups of products. One of these plants which manufactures flywheels and 4 types of torsional vibration dampers will be analysed and assessed in this study.

Flywheels are manufactured in 7 variants for 3 different customers. The main differences between the products are the thickness and the material properties of the main raw material (steel) as well as some additional elements in finished product. The products are assigned to one of two sales volume groups. The U and CO products are sold in a quantity of over 2000 pcs/week. Other products are sold in much smaller quantities. Table 1 presents the names, sales volume and steel type for the products manufactured in the plant.

Table 1. The sales volume and type of steel for the products manufactured

Item	Name	Sales volume [pcs/week]	Steel type
1.	U	>2000	Thick
2.	N	<2000	Thick
3.	CO	>2000	Thin
4.	CS	<2000	Thin
5.	BP	<2000	Thin
6.	CJ	<2000	Thin
7.	O	<2000	Thin

The differences in finished products also result from some components included in the finished products. There are two types of changeovers in the plant which are associated with the type of sheet metal (thick, thin) and various components fitted in the

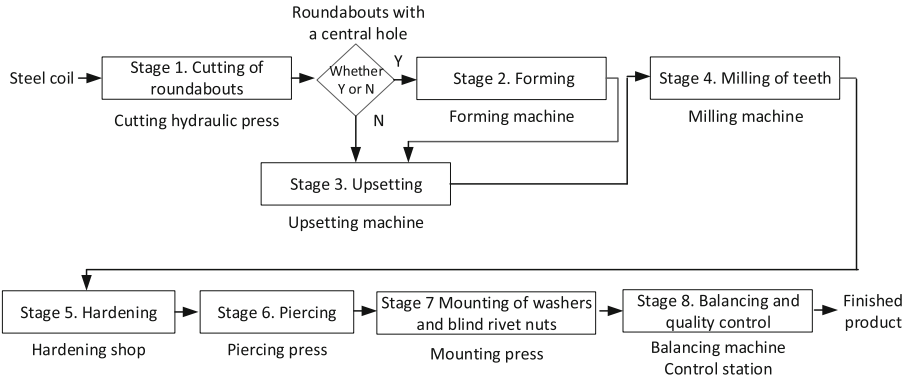


Fig. 1. Diagram of the main stages of the production process

individual variants of the product. The term "long changeover" refers to an operation that consists in a change of settings from the thick sheet metal to thin sheet metal and inversely, which lasts an entire shift (8 h). The second type of changeover, so-called "short changeover" refers to a change of settings and basic tools as well as retrieving the component assembly instructions for manufacture of products from thin sheet metal. The time of such a changeover is approximately 45 min. The flywheel production process takes place in stages and is shown in Fig. 1.

At the mounting press workstation, there are added washers and blind rivet nuts. The semi-finished product is balanced and then transferred to 100% final control. The productivity for all the designs is 845 pcs/shift. The production takes place in a 3-shift system, 5 days a week, which gives 15 shifts per week.

Due to the fact that in addition to flywheels also other products from other company's plants are manufactured on this production line, some production machines (hydraulic punching press and hardening heater) have a lower availability in the flywheel manufacture process. The availability may change depending on the production plan adopted. The list of the machines used in the flywheel manufacture process, their basic parameters and the percentage value of the availability in the process are presented in Table 2.

Table 2. List of workstations and their basic parameters

Item	Name	Max. productivity [pcs/shift]	Type of sheet metal	Number of shifts	Availability %
1.	Hydraulic punching press	1991		3	40–60
2.	Forming machine	1190		3	
3.	Upsetting machine	985		3	
4.	Milling machine	698/972	Thick/thin	3	
5.	Hardening heater	1410		3	80–100
6.	Piercing press	698/972	Thick/thin	3	
7.	Mounting press	845		3	
8.	Balancing machine	1991		3	

This limited availability of the machines causes problems when planning and implementing the production plan due to the fact that the customer can increase the product volume in the order by 30% four weeks in advance.

2.2 Characteristics of the Flywheel Production Process

Production planning is performed in the ERP system based on the customer orders. The main production plan is of mid-term character and provides a plan for next 3 months, broken down by weeks. On this basis, the orders for production materials are generated. Daily plans are prepared for a period from more than 2 weeks to 2 months. The detailed production schedules for each production shit are prepared for a period of 2 weeks. Weekly plans are already approved and should not be changed.

Order updates from the customer are received on a weekly basis. Customer order (equal to the plan of deliveries) for the subsequent week are "frozen" - they cannot be changed, but the customer has the right to modify the order (increase or decrease) by approximately 30% during the next 4 weeks.

Taking into account the customer's right to change the order volume, it is necessary here to use complex algorithms that allow determining the optimal plans both in terms of the company's production capacity and the satisfaction of the needs of the customer, who expects that the order will be executed within the appointed time limit. Assuming that the weekly production capacity for all design variants of the product keeps at a level of approx. 12,500 pcs/week, while most orders are for 20,000 pcs of one product, this means that the production planning system and the material ordering system must be perfectly matched to the characteristics of production. Although the production capacities of the plant are sufficient (comp. Table 2), in the event of an increased volume of orders from customers and an availability of machine at a level lower than 100% there is a risk of a failure to execute all the orders.

2.3 The Purpose and Method of Building the Artificial Neural Network

The purpose of building the ANN was to obtain a possibility of predicting the production volume. From the conditions in the production plant analysed it results that the production capacities depend on the availability of the press and hardening heater, as well as on the quantity of products manufactured from thick sheet metal and thin sheet metal. In addition, the contracts with customers provide for a possibility of increasing an order volume by 30% four weeks in advance, which exceeds the production capacities of the plant.

Due to this fact it was necessary to build a model based on the data that include: availability of machines, weekly sales volumes of individual products, orders contracted and orders placed, which would enable adequate planning of the use, changeovers and maintenance periods for the most important machines – in this case: the press and hardening heater. It is not possible to build linear models in such a diverse manufacturing environment. Adequate computing (planning) capabilities should be obtained from the model based on a neural network in order to plan the necessary events in time.

In order to predict the quantity of the products manufactured at the given input parameters, a unidirectional neural network (multilayer perceptron) was built. The dependent variable was to be the quantity of the flywheels manufactured. The following independent variables were selected:

X_1 – availability of the press,
X_2 – % of products from thick sheet metal in the production plan,
X_3 – % of products from thin sheet metal in the production plan,
X_4 – number of changeovers of the production line (lasting up to 8 h) in the period analysed,
X_5 – number of short changeovers (associated with a change of components used for assembly and lasting up to 45 min.),
X_6 – availability of the hardening heater.

The experiments were carried out with the use of historical data from production plans exported from the ERP system. There were used the data from 3 months of 2016 (September 5 – November 25). Only the data from full working weeks were included. The 44-th week of 2016 was discarded due to holiday breaks. A total of 165 production plans for a production shift were available. This set was divided into two parts, one of which served as a training set, while the second part was used for testing the network.

The experiment was performed in the SAS Enterprise Miner 6.2 environment. The first step was to investigate the correlation between independent variables and the dependent variable. The results containing the correlation value are shown in Table 3.

Table 3. Values of the correlation between variables

Independent attribute (variable)	Correlation value
Availability of the press	−0.25465
% of products from thick sheet metal in the production plan	−0.19872
% of products from thin sheet metal in the production plan	0.13583
Number of changeovers of the production line in the process	0.15471
Number of short changeovers	0.00276
Availability of the hardening heater	−0.17535

The obtained results indicate that it is pointless to use a linear regression method (absolute values of the correlation are below 0.5) for the analysed problem. Therefore it is justified to the use neural networks which build non-linear regression models.

As a part of further experiments, a model of a multilayer perceptron network was built, for which the values of the number of neurons in the hidden layer were changed. In order to confirm the results of the correlation analysis, a neural network according to the generalized linear model was also built.

For the neural network models built, a series of experiments for different numbers of independent variables was performed. The goal of these experiments was to find out for which combination of independent variables the neural network will provide the best prediction as to the number of the flywheels manufactured. When building the models, different numbers of independent variables were considered. Their selection was dictated by previous experiments, i.e. it depended on the absolute value of the correlation (see: Table 3). In Experiment No. 1 all input attributes were used, while in Experiment No. 2 the parameter "number of short changeovers" (the lowest absolute value of the correlation) was discarded. In Experiment No. 3 the parameter "% of products from thin sheet metal in the production plan" (the next lowest absolute value of the correlation) was discarded in addition. The results are presented in Table 4, where the values obtained represent the criterion of network selection, i.e. the mean square error. These results concern the analysis of the input data set that was also used for the network training process.

Table 4. The results of the experiments for different variants of the neural network built

Neural network model	Mean squared error		
	Experiment No. 1	Experiment No. 2	Experiment No. 3
MPN – NN = 3	963.05	2407.71	1020.1
MPN – NN = 16	2501.86	1333.98	1401.86
MPN – NN = 32	836.49	731.69	339.39
MPN – NN = 48	1183.25	718.22	298.15
MPN – NN = 64	2339.39	**291.08**	963.05
GLM	29815.5	1914.28	1815.5

Where MPN - a multilayer perceptron network, NN - number of neurons in the hidden layer, GLM - generalized linear model.

The analysis of the results confirms that linear models are not suitable for solving this problem. In the case of each experiment, the worst results (with the highest mean squared error) were obtained for a neural network built according to the generalized linear model. The best results were obtained for a multilayer perceptron network with 64 neurons under the Experiment No. 2, a schematic diagram of which is shown in Fig. 2.

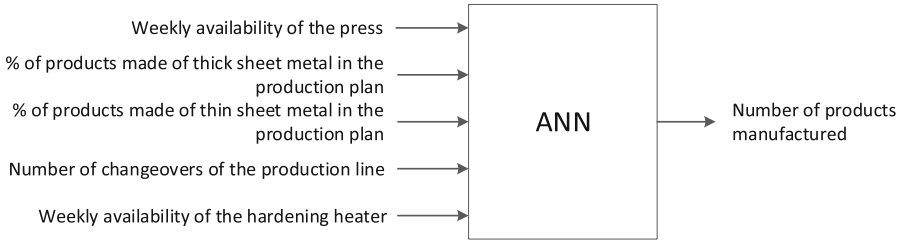


Fig. 2. Independent variables and the dependent variable used to build the artificial neural network (ANN)

The ANN model presented in Fig. 2 was used for further experiments, i.e. to predict the feasibility of the flywheel production plan at different values of independent variables.

3 Predicting the Feasibility of the Production Plan with the Use of a Neural Network with 64 Neurons in the Hidden Layer

In order to determine the feasibility of the production plan in the flywheel manufacture process, test data were prepared and the "score" node of the SAS Enterprise Miner 6.2 environment was used. The test data included various variants of changes in input attributes (independent variables). For such data, the selected neural network model predicts the values for the flywheels manufactured, which are interpreted in the context of the stability of the assembly process. Sample test data along with the predicted number of the components manufactured are presented in Tables 5 and 6.

Table 5. Expected production volumes for different values of the availability of the press

Network inputs					Network outputs
Availability of the press [%]	% of products from thick sheet metal	% of products from thin sheet metal	Number of changeovers [pcs/week]	Availability of the hardening heater [%]	Number of products manufactured [pcs]
60	60	40	1	80	13170
55	60	40	1	80	11973
50	60	40	1	80	10776
45	60	40	1	80	9578
40	60	40	1	80	8472

Table 6. Expected production volumes for a different number of changeovers

Network inputs					Network outputs
Availability of the press [%]	% of products from thin sheet metal	% of products from thick sheet metal	Number of changeovers [pcs/week]	Availability of the hardening heater [%]	Number of products manufactured [pcs]
60	70	30	2	85	15425
60	70	30	3	85	14764
60	70	30	4	85	12175
60	70	30	5	85	11039

The purpose of Experiment 1 was to examine how the availability of the press will affect the number of the products manufactured. In Experiment 1, a further assumption was made that the plant planned to manufacture 60% of products from thick sheet metal and 40% from thin sheet metal. The number of long changeovers was set at 1 a week, while the availability of the hardening heater was assumed at the level of 80%. The results of Experiment 1 are shown in Table 5.

As it results from Table 5, only in the first case, where the availability of the press is at a level of 60%, the production plan is feasible. In other cases, the production capacities are lower than the assumed level of 12,500 pcs/week.

The aim of the next experiment was to find out how the number of long changeover in a week affects the production volume. In Experiment 2, an assumption was made that the plant planned to manufacture 30% of products from thick sheet metal and 70% from thin sheet metal. The availability of the press was assumed to be at the level of 60%, while the availability of the hardening heater – at the level of 85%.

Like in Experiment 1, the production plan is feasible only in the first case (with 4 changeovers). In other cases, the production capacities are lower than the assumed level of 12,500 pcs/week.

Thanks to the ANN designed in this way, the production plant will be able to quickly assess whether it is possible to execute the production program in a given week, taking

into account the assumed production plan and the availability of the press and hardening heater. This assessment is particularly important for the plant due to the fact that it needs to perform the obligations resulting from contracts, in which customers reserved the right to change the order volume by 30%.

4 Summary

Models of artificial neural networks can be used to control a production system and thus to predict the production volume. Such models are very useful tools, because they can be build quickly and easily. The only issue is a large amount of data needed in the neural network training process. However, in the era of common availability of IT systems, the parameterisation and standardization of production processes is not a problem anymore.

Artificial neural networks (ANN) constitute a modern method for mathematical modelling of phenomena and processes, which in the last dozen or so years found many applications in different areas of human activity. The reason why ANN are used in the science and engineering is the possibility to treat dynamic, complex variables or imprecisely defined processes as a black box. In other words, ANN allow finding a relationship between many input variables and the output variable in the process without a need to build complex mathematical equations.

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Autocorrelation Analysis of Cu Content in Ore Streams in One of KGHM Polska Miedż S.A. Mines

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Abstract. Information about ore quality along its route from its source – the deposit, through long and complicated belt conveyor system till processing plant is not available in KGHM Polska Miedz on a daily basis. There were only few papers which analyzed variability of Cu content in feed to processing plant, on the transfer conveyor linking two mines and on the selected sectional conveyors. There were no such analysis regarding variation of ore lithological compositions. Such knowledge should improve metal recovery and reduce energy in processing plant by adjustment of milling and ore beneficiation parameters to known in advance copper ore quality data. Lack of data about ore composition prompted authors to analyze autocorrelations of Cu content time series in ore streams on the section and transfer conveyors as well as in the feed to processing plant. Determined differences in range of significant autocorrelations in ACF and PACF in different places along belt conveyor route have been explained by increasing difficulties in changing the average content of copper in ore coming from the growing area and a range of routes of loading machinery and face advance in comparison to range of directional semivariogram. The planned DISIRE experiment with application of Process Analyser Technology (PAT) sensors (containing ore information pellets), dropped into the transported ore streams and simulations of real flow of ore stream should show possibility to predict ore quality in advance to give enough time for necessary adjustments.

Keywords: SPIRE · DISIRE · Ore grade variation · Belt conveying · Autocorrelation

1 Introduction

In the southwest Poland KGHM Polska Miedz S.A. operates three underground mines (Lubin, Rudna and Polkowice-Sieroszowice), three Ore Enrichment Divisions (OEDs) and two copper smelter/refinery complexes.

Copper ore is extracted using room-and pillar method by drilling and blasting, cyclically loaded and hauled by low-profile LHDs and by continuous horizontal transport to shafts and bunkers using 130 km long belt conveyor system. Conveyors are also used to transport ore from shafts to preparation plants.

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The deposit comprises three different rock types (lithology): dolomite and sandstone separated by a main layer of copper-bearing black shale. The height of extracted seam (different in different mines) is established by channel sampling in the grid from 20 × 20 m up to 40 × 40 m. In each mining area both the Cu content and the proportion of different rock types can substantially vary (Holodnik et al. 2015). Variability of ore excavated in different locations and transported in a complicated network of belt conveyors with many loading, mixing and switching points as well as bunkers causes ore quality control to become a significant problem (Tasdemir and Kowalczuk 2014). It was confirmed that the ore type significantly influences the shape of the grade-recovery curve and its characteristic points and effectiveness of the beneficiation process (Drzymala et al. 2013).

2 Possibility to Improve Metal Recovery and Reduce Energy in Processing Plant

For better enrichment process, the identification of both the copper content and the proportion of type of rocks supplied is important. In fact, although the latter one is the key issue, it is never controlled on conveyors. The lithological compound of the copper ore delivered to the mills, when recognised in advance, is considered as the most important factor for the proper settings of grinding/milling equipment that can both decrease the specific energy consumption of ore processing and increase metal recovery (Kawalec et al. 2016).

Unfortunately, till now there are no research results published regarding changes in lithology content in ore streams along the transportation routes due to only Cu content is sampled on a regular basis from a specific point of the transfer belt conveyor that links two mines. Samples are taken in order to make financial accounting between these two mines after each shift (Jurdziak et al. 2016b, 2017).

Methodology of ore sampling on a belt conveyor influencing the Cu content accuracy estimation (Jurdziak et al. 2016a) as well as variation of Cu content in ore streams on conveyors were already analysed (Jurdziak et al. 2017).

Regular Cu content measurements are done also in ore feed to concentration plants. Their variability was analysed together with variability of separation products (concentrate and tailing) and other upgrading parameters such as concentrate yield and copper recovery in the concentrate (Drzymala and Kowalczuk 2010). Result were compared with variability of ore on the transfer conveyor as well as on sectional conveyors (Jurdziak et al. 2017). From the comparison it can be seen that the smallest variability of Cu content can be observed in ore feed to the processing plant (coefficient of variation, cov = 5.33%) and the biggest in ore stream on the transfer conveyor (cov = 11.85%). The grade distribution on the transfer conveyor cannot be described by a normal distribution as for the case of ore directed to the processing plant and ore supplied onto the sections conveyors. The smallest variability in the feed to the concentration plant is the consequence of almost perfect mixing and averaging of ore from different locations in mining fields and bunkers. Mixing on the transfer conveyor is only partial due to smaller number of ore sources as well as time separation between following loads from mining

faces. This gives in effect larger, instead of lower, spread between minimal and maximal Cu contents (range 1.36% Cu content in ore in comparison of 0.45% Cu for feed to processing plant and 0.99% Cu for the sectional conveyor) and asymmetric distribution. In this case the standard skewness is 4.79 in comparison to 0.2 for the feed to the processing plant and 0.96 for the sectional conveyor.

The findings indicate that normal distribution may be used to describe the distribution of Cu content in the ore transported to the processing plants and on the sectional conveyors. The situation is different at the transfer conveyor. It may be a result of insufficient mixing and time separation between following loads coming from different locations and having different grade and feed to neighbouring grizzlies or insufficient number of feeding points and so the capacity of the transfer conveyor was not fully utilized. Therefore, sometimes the following loads were not mixed with other loads at all. The averaging process was imperfect. In effect the Cu content distribution was best described by log-logistic or extreme value probabilistic distribution instead of normal.

Normal distribution can be expected in the case of perfect mixing of ore streams coming from, independent from each other, sources as loading points are spread all over in the mine.

In the paper (Jurdziak et al. 2017) there were suggestions to compare three run-of-mine ore streams considering them as a random time series of consecutive values rather than random variables, to check whether are there any autocorrelations between them. Such analysis was done for ore feed to concentration plants, separation products (concentrate and tailing) and other upgrading parameters (concentrate yield and copper recovery in the concentrate) (Tasdemir and Kowalczuk 2014). However there is an important difference in autocorrelation treatment. The aim of this paper is finding autocorrelations and order to future usage to improve prediction of Cu content. Tasdemir and Kowalczuk (2014) treated detected autocorrelations as an obstacle in application of statistical process control (SPC) for proper processing of copper ore.

3 Autocorrelation in Ore Feed

The data were obtained from the Fore-Sudetic Monocline copper ore flotation process gathered during 1-month production (Drzymala and Kowalczuk 2010) in the form of copper content in feed, concentrate and tailing, and three generated upgrading parameters, namely concentrate yield in the concentrate, copper recovery in the concentrate, and non-copper components recovery in tailings. Only the first time series was taken to comparison with copper ore data from the transfer conveyor and sectional conveyors analysed in papers (Jurdziak et al. 2016a, 2017).

The processing plant works three shifts in a day, therefore 93 records were used to investigate the effect of autocorrelation on the performance of the Shewhart individual control charts based on the original observations or the residual charts from the ARIMA models.

The process control charts can be applied, when the normality assumption is satisfied. Without a normal distribution, correct limits of control charts may fail. The normal

probability graphs of copper content in feed is plotted with 95% confidence interval (Fig. 1, Tasdemir and Kowalczuk 2014).

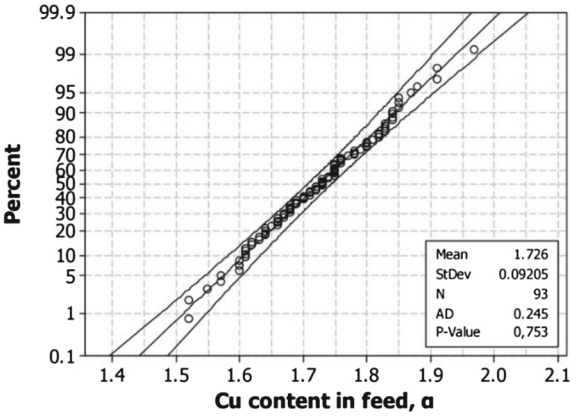


Fig. 1. Normal probability plots of considered copper content in feed (Tasdemir and Kowalczuk 2014).

The p value, which tests normal distribution, for analysed data was higher than 0.05, what means that the considered process data has normal distribution (there is no evidence that we can reject hypothesis about distribution normality). This fulfills the first assumption needed for applying the Shewhart control chart, what was expected by mentioned authors.

The statistical process control (SPC) can only be applied for a process, when the independence of data is also satisfied. If any correlation of data is detected, it has to be eliminated before use for the standard control charts. Data are autocorrelated when each value is correlated to the previous one. The autocorrelation (or time dependency) builds up automatically and occurs between observed data. It can be checked by scatter diagrams of each value (lag plot) against the previous one (Fig. 2, Tasdemir and Kowalczuk 2014).

Figure 2 shows the scatter diagram of analysed variable, where considerable positive correlations between two consecutive data values of variables are observed. It means that there is no non-random pattern in the data. Since each previous individual observation is dependent upon the next one, the degree of autocorrelation should be determined. For SPC charts and its applications autocorrelations should be removed but for better prediction of next values autocorrelations should be identified and used in prediction models. It can be done by using the ARIMA time series models.

Since the *P-value* in the ANOVA table is less than 0.05, there is a statistically significant relationship between Cu content in feed −1 and Cu content in feed at the 95.0% confidence level. Obtained *R-Squared* statistic indicates that the model as fitted explains 99.643% of the variability in Cu content in feed for concentration plant −1. The correlation coefficient equals 0.998214, indicating a relatively strong relationship between the variables. The standard error of the estimate shows the standard deviation

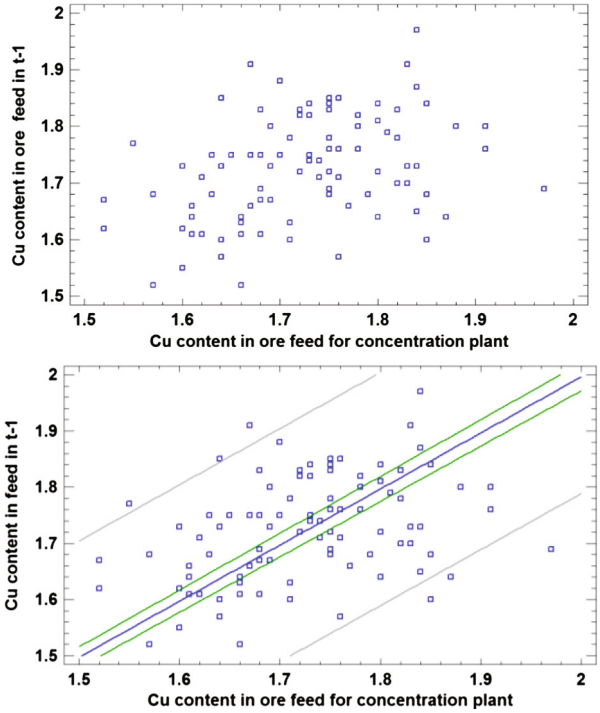


Fig. 2. Plot of Cu content in ore feed for concentration plant in t −1 versus Cu in time t with selected linear regression model (Xt = 0.998214 Xt − 1) (based on Tasdemir and Kowalczuk 2014).

of the residuals to be 0.103814. This value can be used to construct prediction limits for new observations. The mean absolute error (*MAE*) of 0.0817451 is the average value of the residuals. except that observation. In the analysed case, there are 6 studentized residuals greater than 2, but none greater than 3. We can see them outside 95% confidence interval for all data (Fig. 2).

The fact that the coefficient of the slope in the regression model is slightly lower than one acknowledge the declining quality of Polish copper ores and reflects general unfavorable trends observed in the World copper metallurgy (Chmielewski 2015).

For analysed data the assumptions of independence and stationary were also checked using the autocorrelation (ACF) and partial autocorrelation (PACF) functions. Figure 3 shows the time series plots of data set together with their ACF and PACF plots. The ACF plots show the correlation between Xt and Xt − k (where Xt is the response variable at time t, and k is the lag between two measurements).

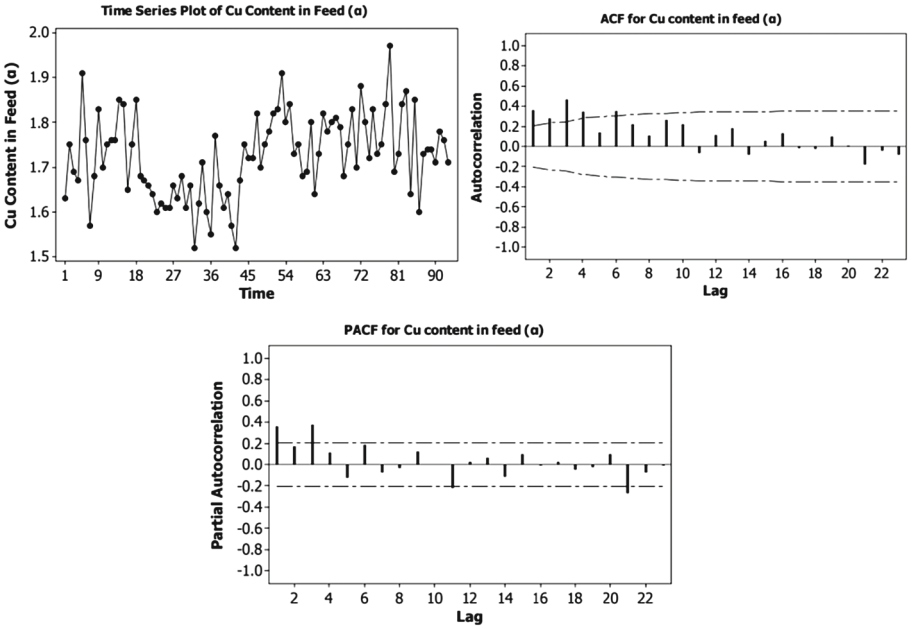


Fig. 3. Time series, ACF and PACF plots of copper upgrading variables (Tasdemir and Kowalczuk 2014)

The autocorrelation values for copper content in feed at the 1st, 2nd, 3rd, 4th and the 6th lag (0.3615, 0.2775, 0,4627, 0,3462 and 0,3541) were statistically significant at the 95% confidence level - lies outside confidence line, implying that the time series may not be completely random (white noise) (Fig. 3). The slow decay of autocorrelation coefficients for these variables in the ACF plots implies that they are not stationary.

The PACF plots show the partial autocorrelation function for a given lag k, where the partial autocorrelation at lag k is the autocorrelation between Xt and Xt − k, that is not accounted for lags 1 through k − 1. It can be used to judge the order of autoregressive model needed to fit the data. On PACF plot are also shown 95.0% probability limits around 0. If the probability limits at a particular lag do not contain the estimated coefficient, there is a statistically significant correlation at that lag at the 95.0% confidence level. In analysed case, 4 of the 24 partial autocorrelation coefficients are statistically significant at the 95.0% confidence level.

These plots are generated for 25 lags. The ACF and PACF plots (Fig. 3) clearly confirm the existence of autocorrelation between values for Cu content in feed.

4 Autocorrelation in Ore Stream on the Sectional and Transfer Conveyor

Similar data about Cu content in ore streams were analysed in papers (Jurdziak et al. 2017). The changes of ore quality are presented in time series of Cu content in ore

streams on the transfer conveyor and on the section conveyor (Fig. 4). Average Cu content on the transfer conveyor is calculated from series of samples taken from the conveyor belt (Jurdziak et al. 2016a). Data about quality of ore on the section conveyor is estimated based on the channel samples taken from faces near the loading points (Hołodnik et al. 2015). It can be seen that the Cu content estimated on the deposit data are slightly higher than calculated from belt samples (Fig. 4). The dilution was included in the estimation model, however the difference has a systematic character, according to miners' opinion (Fig. 5).

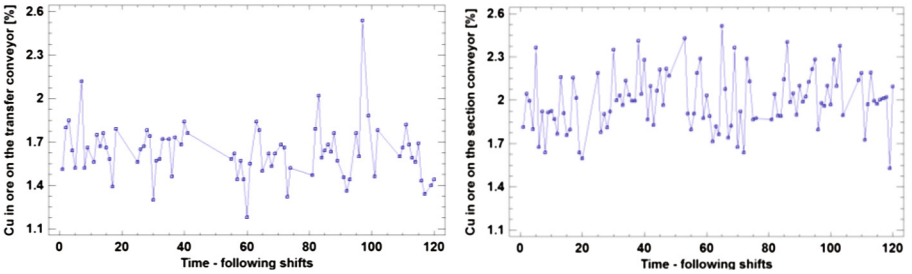


Fig. 4. Time series of Cu content in ore streams on the transfer and on the section conveyors.

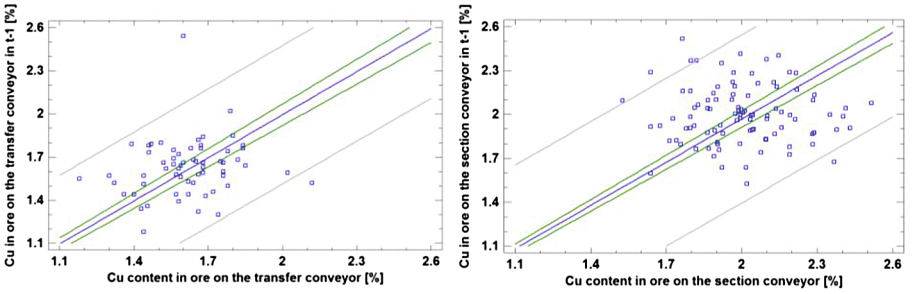


Fig. 5. Plot of Cu content in ore stream on the transfer and the section conveyor in $t - 1$ versus Cu in time t on both conveyors with linear regression models ($Xt = 0.99685\ Xt - 1$ and $Xt = 0.984408\ Xt - 1$)

Autocorrelation analysis was performed also for Cu content in ore streams on the transfer conveyor (Fig. 6) and on the section conveyor (Fig. 7). An observation may be made that in case of the transfer conveyor the autocorrelation force is greater but the range is smaller (limited to 2 shifts only). This is justified, as a smaller number of feeding points causes the cumulative stream to be more prone to variations occurring even in one of the points.

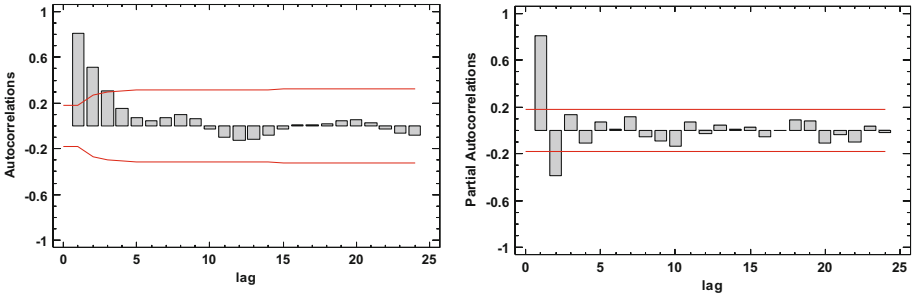


Fig. 6. Estimated ACF and PACF for time series of Cu content in ore stream on the transfer conveyor.

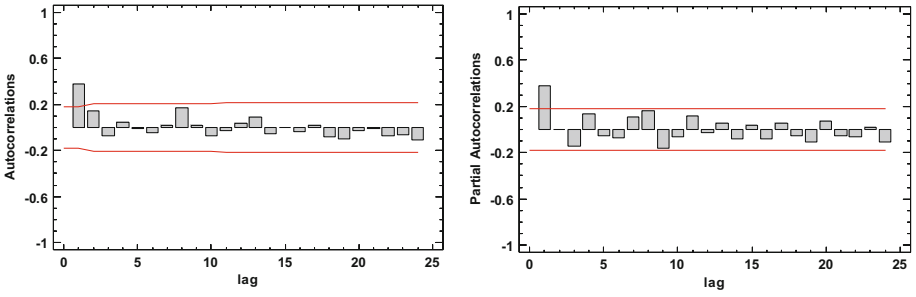


Fig. 7. Estimated ACF and PACF for time series of Cu content in ore stream on the section conveyor.

This assumption is proved by autocorrelation test on the section conveyor, in which the lag is only 1 shift.

It seems that due to the fact that consecutive excavation is continued in the very close area to the previous one, the average values should be correlated with next ones. Obviously it depends on the rate and scale of grade changes within the deposit. These should be recognised with the help of geological block model, developed and updated for the mined deposit (Holodnik et al. 2015).

5 Conclusions

Increasing number of significant autocorrelations from source of ore (1 lag) through the transfer conveyor (2 lags) down to processing plant (over 4 lags) can be explained by time required to change Cu content radically. At loading points average Cu content is estimated based on local ore quality which is changing within the vertical seam from cutoff grade up to over dozen percent of Cu in case of shale. So changes are quite big but the estimated value is an average from dozen samples taken during one shift. From shift to shift the average value of ore is not changing radically because the actual face advance is usually shorter than a semivariogram range (even in the worst directions). Unfortunately, the grade of ore in loading point depends not only on face advance (which

is rather small) but also on the actual length of haulage routes of LHD machines. This distance can be greater than the smallest range in semivariogram what means that sometimes quality of ore loaded on consecutive shifts will be uncorrelated. The transfer belt conveyor accumulates ore from seven preceding conveyors so the ore is blended and it is not so easy to change the average value significantly. It, of course can happen, when in few loading points the quality of ore has changed but it requires time and therefore significant autocorrelation is longer (2 lags). Due to imperfect mixing there are only 2 lags and not more. In the entrance to processing plant the ore from the whole mine, bunkers and stores are mixed almost perfectly and therefore significant autocorrelations are found on over 4 lags. The quality of blended ore still depends from quality of ore in the deposit and mining faces localizations have a direct impact on average ore quality on conveyors. Therefore, we cannot apply SPC methods directly to ore stream due to its changes are not random with normal distribution and are not independent and therefore do not fulfill SPC requirements.

The existence of significant autocorrelations in Cu content in feed that was proven by Tasdemir and Kowalczuk (2014) and acknowledged in this paper also for the transfer and the sectional conveyors is a very important prerequisite for the existence of statistically significant autocorrelations of the lithological composition of ore sent to the processing plant. It is necessary for reliable prediction of ore composition. Till now due to lack of lithological composition analysis of ore after their mining it is impossible to predict it in the way to processing plant. This situation can be changed by application of the novel idea of Process Analyser Technology (PAT) sensors – information carrying pellets, dropped into the transported or processed ore stream. Information (e.g. about Cu content in ore and ore lithology compound) can be read directly when needed e.g. at the entrance to processing plant or earlier in order to give necessary time for beneficiation process parameters adjustments. Such experiment is planned within the DISIRE project (http://spire2030.eu/disire (2015)) - a part of the SPIRE initiative, acting under the Horizon2020 framework program. More information about this project was presented in papers (Jurdziak et al. 2016a, Kawalec et al. 2016).

The DISIRE experiment and simulations of real flow of ore stream should show that prediction of ore quality is possible in advance enough to give time for necessary adjustments of beneficiation process parameters.

Currently real time data from monitoring and control of production sections in the Division of Concentrators of KGHM Polska Miedz SA. are utilized in sophisticated, fully automatic, still developing tool called Optimisation Platform. It improves decision making processes, eliminates errors and helps to maximize economy benefits being a base of Intelligent Production Chain (Kuzba et al. 2016). Regardless of its advantages it utilizes only current data and is not capable to forecast changes in feed quality including Cu content, lithology composition and geometallurgical parameters (Lund and Lamberg 2014). Autocorrelation analysis of Cu content in ore streams is a first step to predict feed quality in advance enough to adjust grinding, milling and flotation parameters for incoming ore and attain benefits from model predictive control (Bouffard 2015).

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Binary Linear Programming as a Decision-Making Aid for Water Intake Operators

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Abstract. The cost of energy consumed in the course of pumping water from its sources constitutes a considerable share of the total operating costs borne by a water company. In order to optimize the operation of a water pumping station, it is essential to devise an appropriate pumps schedule. The aim of the work was to develop a smart tool which would facilitate decision-making by the operator of a water intake, including a group of wells, supplying actual municipal waterworks. The tool creates a real-time schedule for wells and pumps integrated with them, which constitutes a basis for a final decision made by the operator, related to the degree and period of their usage. The main criterion of facilitating the decision-making pertained to achieving the minimum energy consumption during pumping water from a well to a reservoir tank, while simultaneously keeping all the wells on full stand-by. The schedule was prepared by means of binary linear programming. In this method, both the function of the goal and the limiting functions are linear, whereas the particular variables belong to the set {0,1}.

Keywords: Water pumping station · Pump schedule · Binary linear programming

1 Introduction

One of the main tasks of every water company is supplying the recipients with the required amount of water characterized by the adequate quality, and pressure, as well as delivering it at the right time. Simultaneously, an attempt is made to ensure the highest possible reliability of devices, especially the pumping station, while maintaining optimally low operating costs. In water pumping stations, the cost of energy consumed in the course of pumping water from its sources, through tanks and ultimately to the recipients, constitutes a considerable share of the total operating costs borne by a water

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company [1–3]. Optimization of these aspects is best conducted by means of a smart control system which governs the operation of all elements in waterworks [4–7]. In order to optimize the operation of a water pumping station, it is essential to devise a pump schedule and adjust the rotational speed of turbines (for systems with frequency converter), which ensures sufficient efficiency. Conducting optimization requires defining the following criteria beforehand: a water intake reference standard, which reflects the changes in water intake by consumers throughout the day, and the reference standards pertaining to the generation tariff, the level of water in tanks, etc. [2, 8–14]. The water intake reference standards cannot constitute the decisive variables; rather, the remaining system elements should be adjusted to them, taking into account the amount of water in the tank and the efficiency of the water intake which supplies it. The reserves of water are made when the water intake is lower than the capacity of water pumps. In reversed situation, the accumulated reserves are used to supply the water distribution system. The diversified operation time of water intake pumps and the necessity of their daily activation require devising special schedules by the operator.

Pump scheduling has been studied for several decades. It mainly aims at the optimization of network pumping stations which operate jointly with reservoir tanks. Various optimization methods are employed, including the popular genetic algorithms (GA) [15–17]. Earlier studies mainly involved determining a single objective function (i.e. operation energy or cost). Multi-objective evolutionary optimization algorithms have also been used recently [12, 18]. Behandish and Wu [17] proposed the generalized Multi-ANN (Artificial Neural Network) meta-modeling technique in conjunction with a modified Genetic Algorithm (GA) for optimization of pump operation and water levels in a reservoir tank. This method, employed in actual waterworks system, enabled to reduce the daily costs of pumping by 15%, also reducing the number of pump activations [17]. By employing Genetic Algorithms (GA) with Matlab Software, Alrheeh and Mahmoud [3] devised a pump schedule which optimized the costs related to the energy consumption of pumping and the operating expenses of pumps. Ormsbee and Lansey [19] presented a review of methods, including linear and non-linear, integer, dynamic and other, mixed types of programming. Pasha and Lansey [20] employed linear programming for optimization of pump operation by utilizing the relations between energy, pump flow, user demand and tank water levels. This model was tested in a system with a single tank. Giacomello et al. [21] also employed linear programming algorithm in conjunction with Grendy algorithm. Puleo et al. [14] presented the methodology for determining an optimal pump schedule based on linear programming. They have found that this approach does not guarantee the identification of the global optimum solution of the pump scheduling problem, due to the inaccuracies introduced by linearization. However, it is sufficiently accurate for practical application and requires lower computer performance in comparison to evolutionary algorithms, which is important for industrial conditions. The presented studies and their results, although valuable and innovative, do not solve all the issues related to the efficient functioning of waterworks [5, 6, 22–25]. In the era of highly advanced computer tools, striving for a maximum automation and employing cyber-physical systems (CBS) as elements of Industrial internet of Things (IIoT) requires conducting further studies which will contribute to the development of expert systems and other operators of complex production systems [7, 26]. One

of such challenging fields involves decision-making by operators of waterworks who are dealing with high degree of uncertainty, as well as the variability of process parameters or an entire system.

The aim of the work was to develop an smart tool which would facilitate decision-making by the operator of a water intake, including a group of wells, supplying actual municipal waterworks. The tool creates a real-time schedule for wells and pumps integrated with them, which constitutes a basis for a final decision made by the operator, related to the degree and period of their usage. The proposed tool, as a modular solution, could be incorporated into a comprehensive system facilitating the decision-making process carried out by the operator of waterworks, involving intake, treatment, accumulation, pumping and distribution of water. The main criterion of facilitating the decision-making pertained to achieving the minimum energy consumption during pumping water from a well to a reservoir tank, while simultaneously keeping all the wells on full stand-by (each well should operate for at least 1 h per day).

The paper is structured in the following way: Sect. 2 includes a description of the object and the constraints of the devised control algorithm. Section 3 contains both a description of the algorithm and the optimization of its parameters conducted with integer programming method. Section 4 comprises the obtained results and their discussion, whereas Sect. 5 contains conclusions.

2 Object Description

The considered waterworks system supplies a city with approximately 25 thousand residents. The average daily water demand amounts to 2432 m^3/d. The scheme of a system supplying the water distribution network is presented in Fig. 1.

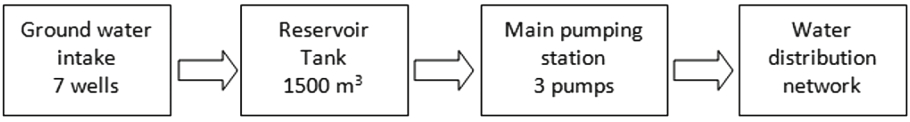


Fig. 1. Scheme of a system supplying the considered municipal water distribution network

The intake of groundwater is carried out by means of 7 wells equipped with deep-well pumps. The summary of the capacity and power output of deep-well pumps is presented in Table 1. Due to a lack of a control system, the pumps operate with a constant efficiency.

Water is pumped from the well to a single reservoir tank, described by: capacity ($V = 1500\ m^3$), inner diameter ($D = 21.08$ m), maximum water level ($hmax = 4.30$ m), total height ($hc = 4.65$ m), minimum water level, so-called fire-fighting reserve ($hmin = 1.5$ m). The water inside the tank should also be replaced at least once per day.

Water taken from the tank is pumped by the main pumping station (comprising 3 pumps of different sizes) to the distribution network. The intake varies throughout the day. This work assumes the data from 01.08.2015. The graph showing the changes in water demand is presented in Fig. 2.

Table 1. Parameters of deep-well pumps

Well	Capacity (m^3/h)	Pump power (kW)
1	75	15
2	133	37
3	157	33
4	176	33
5	59	22
6	69	33
7	120	22

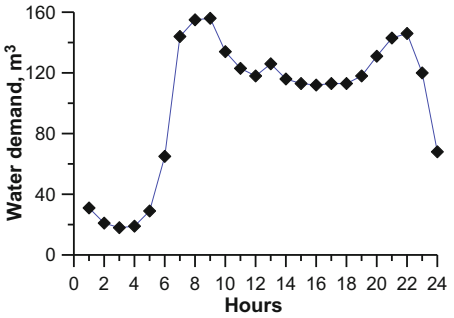


Fig. 2. Graph showing the changes in water demand, 01.08.2015

The diagram of the control system of the water intake and the main pumping station was presented in Fig. 3.

The number of pumps operating in the main pumping station, as well as their efficiency and their lift height ensures that constant pressure is maintained in the supply location of a distribution network, including the variable water demand. The pumping station is regulated automatically. However, the system operator can switch into manual operation.

Controlling the deep-well pumps installed in the water intake wells is carried out in a different way. Due to the lack of a regulation system, the pumps operate with a constant efficiency and lift height. The decision pertaining to the activation and shutting down of the pumps is made autonomously by the operator on the basis of the current and estimated water demand, as well as the fill level of the tank. The decision-making process must account for fact that each pump must operate for at least 1 h per day. Additionally, at least one well – and the pump integrated with it – must be kept as a reserve. Thus far, due to the complexity of the task, the system operators have practically neglected the issue of electricity costs, which are variable depending on the time of a day – tariff B23: zone 1 (morning rush hour 7^{00}–13^{00}) 283.00 PLN/MWh, zone 2 (afternoon rush hour 16^{00}–21^{00}) 336.00 PLN/MWh, zone 3 (remaining part of the day $13^{00}16^{00}$ and 21^{00}–7^{00}). The above-mentioned problems encouraged the authors to devise a tool which would help the system operator and enable to account for the costs of electricity consumed by pumps.

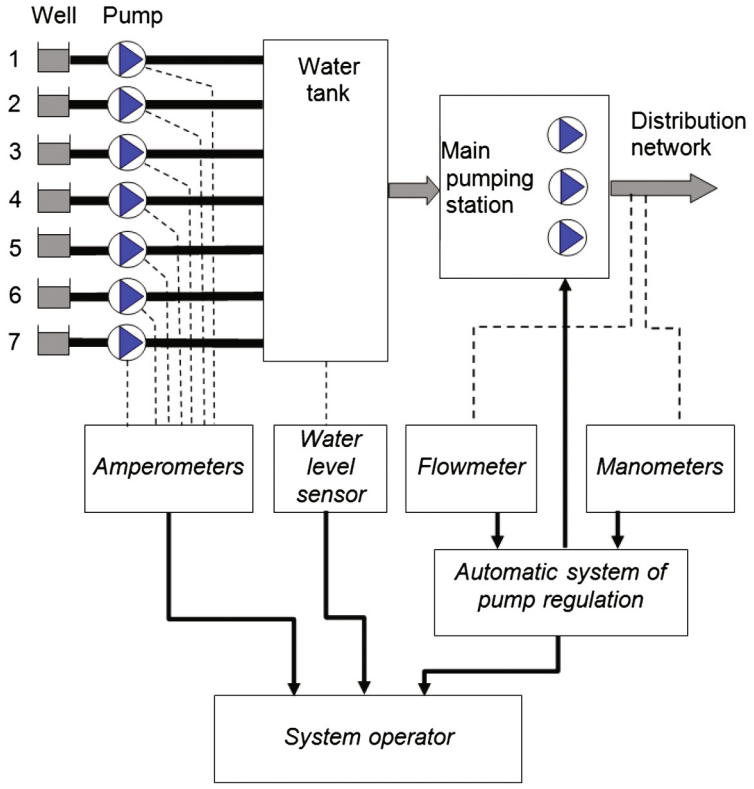


Fig. 3. Scheme of the existing controlling system

3 Methodology

The tool facilitating the decision-making carried out by the operator of water intake pumps was treated as an optimization task aiming at reaching minimum electricity costs for pumps, sufficient to meet the water demand of waterworks. The goal was to devise a schedule for all pumps in the water intake. The pump schedule will simultaneously constitute a plan for the intake operator.

The schedule was prepared by means of binary linear programming. In this method, both the function of the goal and the limiting functions are linear, whereas the particular variables belong to the set {0,1}.

It was assumed that the water intake comprises n wells equipped with pumps characterized by the capacity of (b_1, b_2,…, b_n) m3/h and the power output of (p_1, p_2,…, p_n) kW. The price of electricity (k_1, k_2, k_3) powering the pump engines varies depending on the tariff zone. According to the B23 tariff the vector of hourly rates for electricity was defined as

$$q_i = \begin{cases} k_1, \textit{ for } & j \in \{8, 9, 10, 11, 12, 13\}, \\ k_2, \textit{ for } & j \in \{17, 18, 19, 20, 21\}, \\ k_3, \textit{ for } & j \in \{1, 2, \ldots 7, 14, 15, 22, 23, 24\}, \end{cases}$$

where j corresponds to the hour of a day.

Water from the well is pumped to the reservoir tank. The permissible fill heights h_{min} and h_{max} were assumed in accordance with tank description. Knowing the diameter of the tank, the corresponding volumes v_{min} and v_{max} were determined. The water level in the tank is conditioned upon its supply from the well, as well as the intake carried out by the main station pumping water into the distribution network. The water taken from the reservoir is pumped directly into the distribution network. The intake of water from the tank, corresponding to the consumption of water by residents is presented in the form of a sequence $\{Z_j\}_{1 \le j \le 24}$ in which z_j, m^3 stands for the predicted water consumption for the corresponding hours $(j-1)^{00}$–j^{00}.

Creating an optimal pump schedule involves solving the linear programming task

$$\min_{X \in D} \langle X, C \rangle, \tag{1}$$

where the set of acceptable solutions D is defined as

$$D = \left\{ X \in \{0,1\}^{24 \times n}: \begin{array}{rl} \sum_{i=1}^{n} x_{ji} \le n - 1, & \text{for } 1 \le j \le 24, \\ \sum_{j=1}^{24} x_{ji} \ge 1, & \text{for } 1 \le i \le n, \\ v_{\min} \le \sum_{j=1}^{k} b_j \sum_{i=1}^{n} x_{ji} - \sum_{j=1}^{k} z_j + v_{prev} \le v_{\max}, & \text{for } 1 \le k \le 24 \end{array} \right\} \tag{2}$$

and the scalar product $\langle X, C \rangle = \sum_{j=1}^{24} \sum_{i=1}^{n} x_{ji} c_{ji}$ presents the total daily costs of pump operation during the filling of a tank.

The matrix $X \in \{0,1\}^{24 \times n}$ corresponds to the pump schedule, where $x_{ji} = 1$ means that the pump i operates over the period of $(j-1)^{00} - j^{00}$ for $1 \le j \le 24$, $1 \le i \le n$, whereas $x_{ji} = 0$ means that the pump is idle. The matrix $C \in \mathfrak{R}_{+}^{24 \times n}$ stands for the matrix of unitary pump operations costs, i.e. c_{ji}– pump operation cost i over the period $(j-1)^{00} - j^{00}$ and $c_{ji} = q_j p_i$ for $1 \le j \le 24, 1 \le i \le n$.

The system restrictions (as a definition of the set of acceptable solutions D) presented in (2) are as follows. The inequality $\sum_{i=1}^{n} x_{ji} \le n - 1$ for $1 \le j \le 24$ is a limitation and means that in over the period of $(j-1)^{00} - j^{00}$ the number of pumps in operations does not exceed $n - 1$. The inequality $\sum_{j=1}^{24} x_{ji} \ge 1$, for $1 \le i \le n$ means that each of the pumps

should operate for at least one hour per day. The value $\sum_{j=1}^{k} b_j \sum_{i=1}^{n} x_{ji}$ corresponds to the volume of water pumped into the tank starting from 0^{00} till k^{00}, but the value $\sum_{j=1}^{k} z_j$ stands for the volume of water taken from the tank and pumped into the water system. The value v_{prev} denotes the water volume at the end of the previous day. The last inequality in system restrictions (2) presents the constraints on the water level. The water level cannot exceed the excess required volume and should be above the required minimum volume (fire-fighting reserve) (i.e. the table of water in the tank should be between the minimal and maximal level for every $k = 1, 2,\ldots, 24$).

The above-mentioned task was solved with MATLAB software, as an linear integer programming problem. The linear integer programming task

$$\min_x f^T x \tag{3}$$

with the constraints

$$\begin{cases} x \in \mathrm{N}^m \\ Ax \le b \\ A_{eq}x = b_{eq} \\ l_b \le x \le u_b \end{cases}$$

in MATLAB is solved by using the defined function

$$\text{intlinprog}\left(f, \text{intcon}, A, b, A_{eq}, b_{eq}, l_b, u_b, options\right)$$

Devising the most unfavorable schedule, which would generate the highest costs of water intake pumps operation was an additional task. Hence, the following problem was solved as

$$\max_{X \in D} \langle X, C \rangle \tag{4}$$

where the set of acceptable solutions D assumes the form of system restrictions (2).

4 Results and Discussion

An optimal pump schedule – i.e. the solution to task (1) – was obtained by means of the defined function (3); see Fig. 4 left. Utilizing this schedule will enable to achieve minimal costs of electricity, while simultaneously meeting the above-mentioned requirements. The calculated minimal cost of electricity under such conditions amounts to 81.97 PLN.

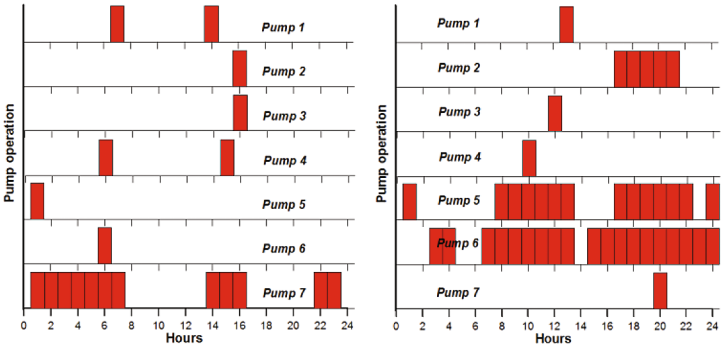


Fig. 4. Graphical representation of water intake pump schedule used to achieve minimal cost of electricity

In line with the adopted methodology, a schedule which generates the highest costs of electricity for water intake pump operation was prepared as well. The schedule was presented in Fig. 4 right. The maximum cost of electricity under these conditions equals 334.04 PLN.

The graph showing the volume of water supplied to the tank and its fill height were presented in Fig. 5. In both versions of the schedule, the requirements set for the pumps operating in the considered water intake were met. The assumed minimum and maximum fill height of the tank was not exceeded.

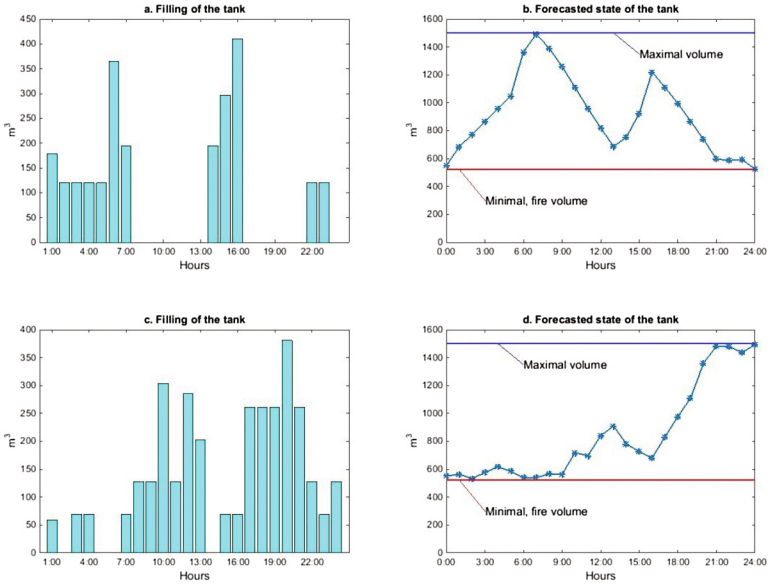


Fig. 5. Graphs showing the water volume pumped into the tank and its filling achieved by means of a schedule generating minimal (*upper part*) and maximal (*lower part*) costs of electricity

The conducted calculations enabled to determine the range of costs available for the operator. Depending on the decisions made, the cost may range from 81.97 to 334.04 PLN (which translates to the total of 29 920 to 121 925 PLN per year). The maximum value is over 4 times greater (4.08) than the minimum value.

5 Conclusions

The presented issue is relevant from the point of view of environment and economy of water companies. The current practice in small and medium-sized water companies in Poland indicates that the decision-making based on the experience of the operator does not guarantee a simultaneous meeting of all the requirements set for the operation of a water intake and minimization of electricity costs.

The calculated difference between the minimum and maximum costs is substantial. The maximum value is 4.08 times greater than the minimum value.

It should be noted that the presented tool may be easily modified when individual wells need to be shut down for repair. It can also constitute a part of a bigger system, controlling the pumps in the main pumping station. The necessity of integrating the proposed tool with a water demand prediction system should also be taken into account and investigated further. However, although the devised system generates an optimal operation schedule through automatic and autonomous processing of data, an operator should be able to interfere with the automatic control system when, for instance, incidental water intake irregularities occur (unforeseen by the prediction system). Conducting further studies aiming at increasing the functionality of the export system presents an opportunity to successfully eliminate such limitations.

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Competence-Based Performance Analysis of U-Shaped Assembly Lines

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Abstract. The paper presents a performance analysis of a u-shaped assembly line taking into account the competences of multi-skilled workers. This arrangement requires multi-skilled operators to serve on several different processes and machines. A multi-skilled worker can possess many skills at various levels. These competences translate into varying performances of individual operators and as a result on the performance of the whole line. In this paper we use a Hierarchical Competence Model to estimate the performance of a u-shaped assembly line knowing the required and possessed competences.

Keywords: U-shaped lines · Competences · Multi-skill · Performance evaluation

1 Introduction and Literature Review

U-shaped assembly lines (in short u-lines) are a popular special type of cellular manufacturing used in just-in-time and lean manufacturing. In the u-shaped line operators works inside the u-line and one operator supervises both the entrance and the exit. This kind of assembly line organization allows seamless control of production rates, maintaining a constant level of work-in-progress and a rapid response to external and internal disturbances in the materials flow. An operator working on the first and the last technological operation of the u-shaped line enforces the production pace. Miltenburg [11] reviewed the advantages and different variants of u-shaped line organization. Common reasons for establishing u-lines were to reduce WIP inventory, setup time, throughput time, material handling, and to improve quality.

Lean management principles emphasize the role of the human factor in industrial systems. Humans are the most valuable and vulnerable part of the system. Despite this, the majority of research remains focused on only the technical parts, completely omitting, or just superficially touching, the opportunities and consequences of proper workforce management. In this paper we demonstrate how operator competences affect the u-shaped assembly line. U-lines are an interesting case because operators are working as a team and are handling several technological operations. Required competences at these technological operations are usually interrelated, and mastering competences while performing one technological operation will have a positive influence on the performance of another somewhat similar operation.

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A classic task for u-lines is line balancing [10] where balance is determined by grouping tasks into stations by analyzing a precedence network of technological operations. A majority of works consider only the technological factors, like: stochastic completion times [5], simultaneous line balancing and sequencing [6], use of a specified set of equipment with cost [12], parallel layout of lines [7]. In such research the human factor is completely omitted. Gong et al. [4] proposed a training policy for a cross-trained workforce to improve the performance of u-shaped lines. In that work competences are used as a notion of the required skills, and operator experience is not taken into account. Manavizadeh et al. [9] considered a line-balancing problem and a labor assignment policy with permanent and temporary workers. Categorical skills are used, that is, operators either possess a skill or not. The dynamics of a system which included a model of fatigue engagement and its correlation with a resting schema was investigated in Fruggiero et al. [3].

The novelty of this present work lies in the performance analysis of u-shaped assembly lines, taking into account the dynamic nature of individual operator performance. Operator performance results from the accumulated experience in executing technological operations which have related required skills.

2 Competence Modelling

In this paper we apply a Hierarchical Competence Model (HCM) developed by Malachowski and Korytkowski [8]. The HCM assumes that skills have a hierarchical structure and could be represented by a simple weighted acyclic digraph $G(S, R, \Gamma)$, see Fig. 2. The nodes of this graph are skills $= \{s_i\}$ with assigned experience level $U_k = \{u_{i,k} \in [0, 1]\}$. External nodes are called elementary skills (independent of other skills, and have no prerequisite skills) and internal nodes are called compound skills (apart from its own unique abilities to apply knowledge, mind-set and thought patterns, also partly relies on other independently defined skills). Arcs of the graph are relations between skills $R = \{r_{i,j}\}$, where $r_{i,j} = (s_i, s_j)$ and weights are skill relation force $\Gamma = \{\gamma_{i,j} \in [0, 1]\}$.

The degree of excellence in the use of skill s_i by worker p_k is called competence strength $\alpha_{i,k} \in [0, 1]$. For a compound skill, $\alpha_{i,k}$ applies only to the new set of skills, excluding those skills inherited from the component skills. The value of competence strength is calculated using the learning curve approach [1]:

$$\alpha_{i,k} = f_i(u_{i,k}, B_i, d_k). \tag{1}$$

This means that the competence strength depends on learning curve shape $f_i()$ with parameters B_i, personal learning rate d_k and the number of executed task repetitions $u_{i,k}$. A technological operation duration time by operator p_k is denoted as $\tau_{n,k}$

$$\tau_{n,k} = \tau_{n,min} + \left(\tau_{n,max} - \tau_{n,min}\right) \cdot \left(1 - \beta_{i,k}\right), \tag{2}$$

where $\tau_{n,max}, \tau_{n,min}$ are respectively minimal and maximal duration of a technological operation at working station, and $\beta_{i,k}$ is the overall competence performance. To determine $\beta_{i,k}$ we have to find out which competence is assigned to the working station. While the performance of an elementary skill s_i is just equal to $\alpha_{i,k} \cdot \gamma_{i,i}$ in the case of a compound skill s_i it is:

$$\beta_{i,k} = \alpha_{i,k} \cdot \gamma_{i,i} + \sum\nolimits_{c_j \in C_i} \beta_{j,k} \cdot \gamma_{j,i}. \tag{3}$$

Substituting $\alpha_{i,k}$ we get:

$$\beta_{i,k} = f_i\left(u_{i,k}, B_i, d_k\right) \cdot \gamma_{i,i} + \sum\nolimits_{c_j \in C_i} \beta_{j,k} \cdot \gamma_{j,i}. \tag{4}$$

Here competence performance is a synonym for work performance. If the competence performance has a maximum value then the performance of the worker carrying out the task requiring that competence is the most efficient, i.e. it takes the minimum time. That model is valid when the structure of the skills does not change over time and skills are independent.

The HCM enables describing the current competences of a worker and the required competences at a working post. A match of possessed and required competences creates a situation where a worker is capable of working at a certain working post. Moreover HCM allows calculating the performance of a worker performing certain work taking into account his/her prior experience in executing the required competences at that working post.

3 Case Study – Modified Jackson's Problem

To demonstrate the idea of incorporating competences into performance analysis of u-shaped lines we have decided to use the classic Jackson line balancing problem [10] with $N = 11$, $C = 10$, i.e. a line consists of 11 technological operations and takt time equal to 10 (Fig. 1). In the optimal u-line configuration, 11 operations are assigned to five stations with one crossover station (with the first and the last operation). In the original problem processing times are constant, but in our case the actual processing times will depend on operator competences. Table 1 gives the assumed minimal and maximal duration of technological operations ($t_{\min}$ and $t_{\max}$). The actual durations of technological operations are calculated taking into account the competences (i.e. experience) of an operator using the HCM described above.

Technological operations performed on the example production line require five different skills from the assigned operators. Three skills are elementary and two are compound. They are all interrelated and form a hierarchical model, depicted in Fig. 2. Table 1 shows the required skills in each operation of the production process. If the required skill is compound, it means that all its child skills are also needed in order to successfully operate at the working post. For example, operation 1 requires compound skill s_3, which in the skills tree (Fig. 2) is the parent node for the two elementary skills

s_4 and s_5. In this case operating at this working post requires the joint use of all these three skills. In order to better illustrate this case, if we assume that operation 1 consists of assembling a particular electronic module, then the two elementary skills (s_4 and s_5) could be for example soldering and bonding, while the top compound skill s_3 could be mounting of the circuit board inside a chassis. The relational structure of these competences shows that the elementary competences can be used alone in some other cases, while the higher level compound skill cannot be used without its base component skills.

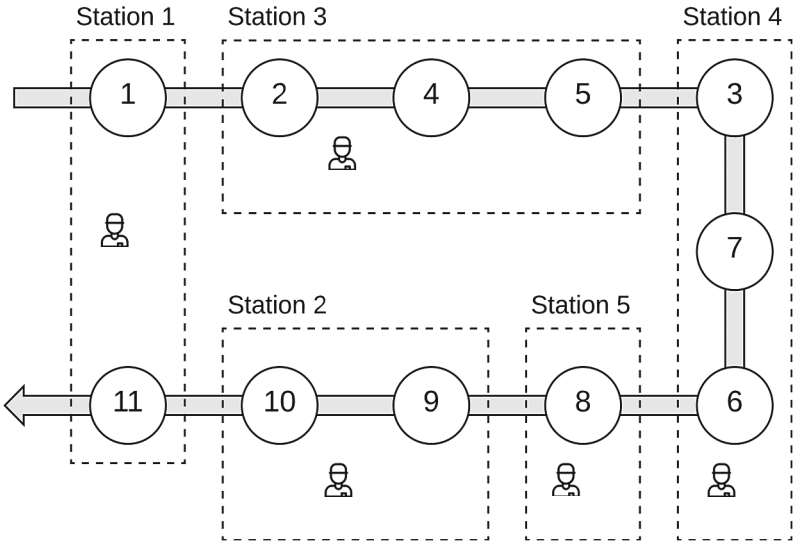


Fig. 1. U-shaped assembly line – Jackson's problem

Table 1. Parameters of technological operations

Technological operation	t_{min}	t_{max}	Required skill
1	6	12	s_3
2	2	4	s_4
3	5	10	s_3
4	7	14	s_5
5	1	2	s_3
6	2	4	s_4
7	3	6	s_2
8	6	12	s_1
9	5	10	s_3
10	5	10	s_3
11	4	8	s_5

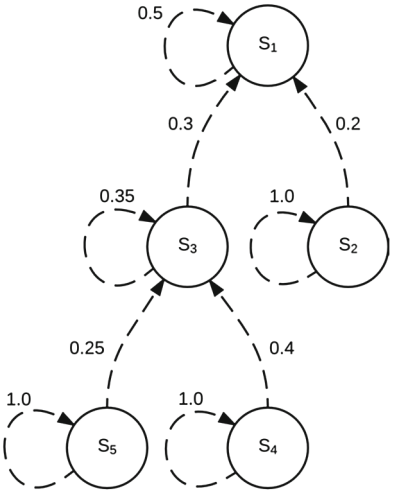


Fig. 2. Skills hierarchy

As was explained in the previous section, this model of production workers takes into account the effect of the performance increase which occurs with small increments with every item completed on the production line. Table 2 shows the learning curve functions used to model the skills in the example. The table also contains the shape parameters of these functions. The meaning of shape parameters and their influence on the shapes of various learning curve functions can be found in Anzanello and Fogliatto [1].

Table 2. Learning curve functions of skills

Skills	Learning curve function	Parameters
S_1	Generalized logistic function	$B = 0.5$, $M = 20$, $Q = 1$
S_2	Log-linear	$C = 1$
S_3	Generalized logistic function	$B = 0.4$, $M = 15$, $Q = 1$
S_4	DeJong	$C = 1$, $M = 0.3$
S_5	Log-linear	$C = 1$

Table 3. Characteristics of the workers

Worker	Learning rate	Skill
w_1	−0.30	s_3
w_2	−0.35	s_3
w_3	−0.25	s_3
w_4	−0.30	s_1
w_5	−0.40	s_1

Operators working in the example production line have their own performance characteristics. Even if two or more workers have the same skills, it is natural that their learning curves can be slightly different. This is reflected in individual learning rates assigned to workers, which influence the shapes of learning curve functions. The values of these rates are presented in Table 3.

4 Simulation Results

The above-described u-shaped assembly line was simulated using DESMO-J 2.4.2, which is a general purpose discrete-event simulation library for Java [2]. The DESMO-J library allows us to integrate the simulation model with HCM, which has also been developed in Java. Data collected from the simulation experiments are visualized on several subsequent charts. Figures 3 and 4 depict the evolution of competence strengths and performances for operator 1, who is alternately performing technological operations 1 and 11. Three skills (s_3, s_4 and s_5) are assigned to these operations. Experience in execution these skills have different characteristics as described by the distinct learning curves: generalized logistic function, DeJong function and log-linear function (see Table 2). Figure 3 shows changes in $\alpha_{3,1}$, $\alpha_{4,1}$ and $\alpha_{5,1}$. As the first saturates skill s_3, while skills s_4 and s_5 even after 24 h are at little more than 80%.

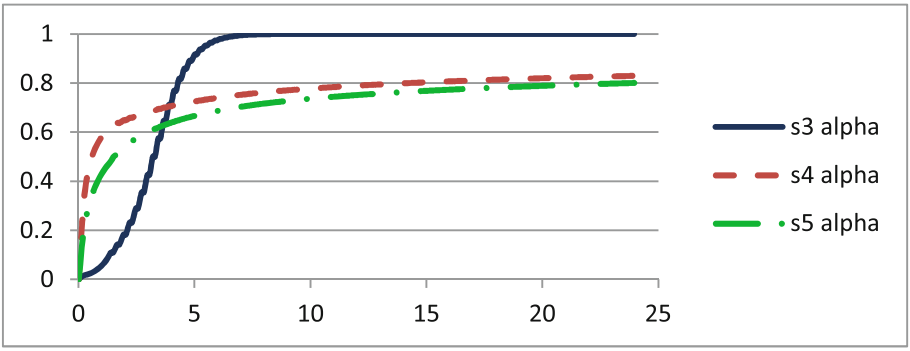


Fig. 3. Evolution of competences' strength in time for operator 1

In Fig. 4 we can observe the increase of operator 1 performance in executing technological operation 1 (skill s_3) and technological operation 11 (skill s_5). For operation 11 skill s_5 is elementary and thus no other skill strength influences it. In case of operation 1, assigned skill s_3 is compound, with skills s_4 and s_5 also making up the overall performance. The overall competence performance $\beta_{3,1}$ is a result of $\alpha_{3,1}$, $\alpha_{4,1}$ and $\alpha_{5,1}$ competence strengths according to Eq. 4. The same happens for all four other operators.

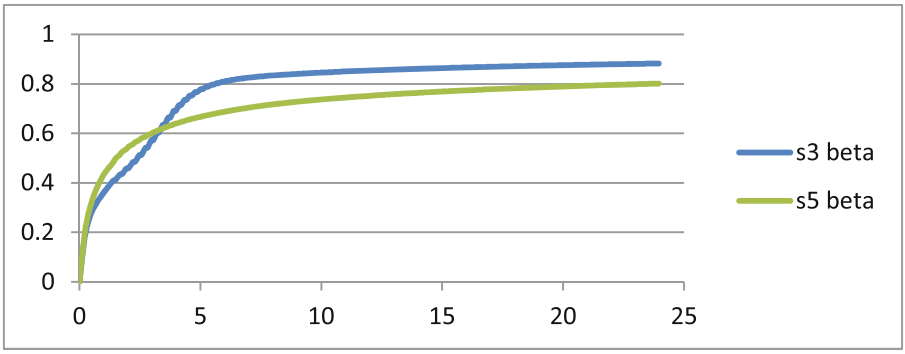


Fig. 4. Evolution of competence performances over time for operator 1

Figure 5 presents the cycle times for all five workstation. Cycle time here is calculated as the time duration between starting the first technological operation of the station again. It can be observed that for all five stations, cycles times are steadily decreasing (production capacity increases). Cycle time for a u-shaped assembly line determines the slowest operator, thus as is shown in Fig. 5 the cycle times are very close, and local changes in cycle time result from temporarily waiting for the next product to be processed.

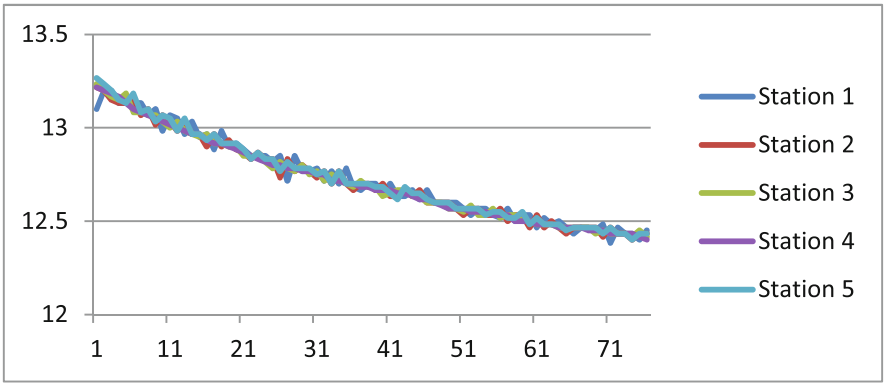


Fig. 5. Evolution of cycle time on workstations over time

5 Conclusions

This paper investigates the issue of performance evaluation of multi-skilled workers on a u-shaped assembly line. The proposed approach uses HCM, a graphic model of competences, to represent the capabilities of a single worker that are required to efficiently perform a task at a workplace. In the manufacturing domain, competences are easy to describe and measure. Often, competences are standardized at the company level. Competence (experience in using skills) is related to the execution time of repetitive

tasks on the production line. Thus, the collection of input data for competence analysis can be achieved easily by measuring the execution times of the repetitive tasks. This makes application of this method feasible and easy to use. Further, the presented approach could be used in line balancing and job sequencing algorithms to better assign operators and to schedule jobs for u-shaped assembly lines.

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Decision Support System for Rapid Production Order Planning in Production Network

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Abstract. Today the functioning of small and medium enterprises in production networks gives many opportunities for businesses, but also raises some concern and requires solutions to many problems. The process of forming the network of enterprises is dependent on the degree of preparation of these companies to share their resources, the possibility of estimating the related costs and the rapid planning jointly implemented projects. The aim of the article is to present a prototype decision support system for rapid production order planning in production network. The proposed tool can be helpful in the development of the concept of Industry 4.0. In particular, the article is presented the way the selection of partners to the network and load the productive resources to the needs of the timely implementation of the new order. The proposed approach and its computer implementation allow the permissible variations of network in condition of cost, resource and logistics system constraints to be determined.

Keywords: Production planning and scheduling · Production network · Rapid order planning

1 Introduction

Today the significant challenge for modern manufacturing companies is strong competition and variable, unpredictable environment. Consumers expect new products with high quality and low price. Therefore, the result of the growing needs of the customer is high specialization of companies involved in the manufacturing process, which ensures the high quality of products, high process capability and enables innovation and flexibility [1, 2]. Manufacturing companies are increasingly oriented on the new organizational forms of production and reducing the cost of production and delivery of products to the customer [3, 4].

A development of the companies' cooperation involved in joint production orders within the production networks due to the high requirements of manufacturers and the possibility of contemporary communication networks is observed. The idea of manufacturing in the network means a common production in the context of providing specialized production capacity which is at the disposal of enterprises offered by different companies, necessary for the production and distribution of the product in the context of providing, at the disposal of enterprises, specialized production capacity, offered by

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different companies necessary to manufacture and distribute of the products [5]. This solution enables the execution of production orders by a group of specialized companies in a situation where the implementation of an order exceeds the capabilities of each of them individually. The idea of the product manufacturing through a network of cooperating business entities is the essence of the increasingly popular concept of the Industry 4.0. The partnership which combines a professional competence and ability to exchange production capacity to better meet the expectations of the consumer becomes a new opportunity for development [6].

An important problem in manufacturing production network is too long time of a network forming [7]. In practice, there is a lack of methods and tools for rapid prototyping networks taking into account resource and logistics constraints of the production system. Therefore, there is a need to conduct research and implement methods and new IT solutions which allow the rapid generation of permissible variants of planned production order execution in condition of resource and logistics constraints [8, 9].

The article proposes a prototype of the decision support system for rapid production order planning in production networks. It is an example of a solution that helps in quick planning of production orders in the production network. This concept can also be used to schedule the execution of orders as part of a production platform created as a factory 4.0.

2 A Concept of the Proposed Solution

A computer system supported a prototyping of production network of companies which is presented in the paper allows an effective implementation of new production orders to be planned, which demands exceed the capabilities of individual enterprises. This system is a kind of a platform where unused enterprise's production capacity (machinery, equipment, employees) are made available and specialized tasks are commissioned. An efficient functioning of the system allows a level of the resource utilization of the cooperating companies and at the same time the level of their productivity to be increased. Due to the simple interface and the ability to make available through a Web-service, does not require high costs of implementation and use.

The important advantage of the proposed solution is the ability to create dynamic network of companies, which also may be involved in many different projects. The unused production capacity of enterprises is use to execute production orders in the network. The proposed system is a tool to support the exchange of information between the initiator of the joint execution of orders, providing the offer and companies which have unused production capacity to execute these tasks. A set of variants of a network capable of timely production order execution and a schedule showing the load of individual company resources in a particular variant to execute a new production order is generated based on information collected in the system. Each variant is characterized by a set of selected enterprises with an indication of the used resources, the cost of implementation and the start and the end date of a production order. This allows finally the variant to be chosen and planned to realize resources of individual companies in the system to be locked.

3 Production Order Planning in the Production Network - Case Study

In the presented case we are dealing with production order which is understood as a 5-tuple: P = (Z, To, Ts, Tk, K), where: Z = {Zj = (Oj, Lj, ZNj): j∈{1,..,n} ∧ if j = 1 then ZN1 = nil otherwise ZNj [1] nil} – a set of tasks belonging to the order P, To – the deadline for submission of offers, Ts – the date from which to begin execution of the order, Tk – the date by which the order must be executed, K – the maximum (permissible) cost of the order. For the description of the order, the following additional indications are set: Pred(Zj) – a set of predecessors (which deliver their results directly to Zj); Succ(Zj) – a successor - (which makes use of the results from Zj).

The task is a 3-tuple: Z = (O, L, ZN), where: O - the task description, L – the number of pallets required to transport the task outcome, ZN – an indicator on the another task that directly uses the result of task Z (if the next task for Z does not exist, then ZN = nil).

The initiator of a common network receives production order P consisting of the execution of specialized equipment for heat treatment of metals, which will form part of a production line. The equipment is required to carry out the operations shown in Table 1. Planned date of implementation Tk was determined as 03/28/2017 at 15.00. The maximum acceptable cost to the customer is K = 65500 PLN. It is assumed that production of full documentation of the product technology is included in the implementation of individual tasks.

Table 1. Table of tasks (operations) (own work).

J	Mark of tasks	Name of tasks	Pred(j)	Succ(j)	L(j)
1.	Task1	Assembly in client	–	{Task 1.1, Task 1.2, Task 1.3}	10
2.	Task 1.1	Heating chamber	Task 1	{Task 1.1.1}	8
3.	Task 1.3	Control (automation)	Task 1	∅	1
4.	Task 1.2	Heat exchanger	Task 1	{Task 1.2.1}	2
5.	Task 1.2.1	Heating element	Task 1.2	∅	1
6.	Task 1.1.1	Housing	Task 1.1	{Task 1.1.1.1}	5
7.	Task 1.1.1.1	Structure of a machine	Task 1.1.1	∅	3

The order of the tasks planned for implementation can be represented by a graph of the product sequence limitations, which is shown in Fig. 1.

The key question to be answered in deciding to pursue an order in a production network relates to the possibility of meeting the deadline and the cost-effectiveness of project implementation in a geographically dispersed, temporary organization. In contrast to previous approaches, scheduling and project management in the proposed approach includes the selection of companies based on the availability of resources necessary to implement the project, the cost of using resources and logistical constraints related to the dispersion of firms. In the proposed approach, in order to answer the question of the possibility of forming a network of companies capable of joint implementation of a production order due to the available capacity at the time and cost of use of

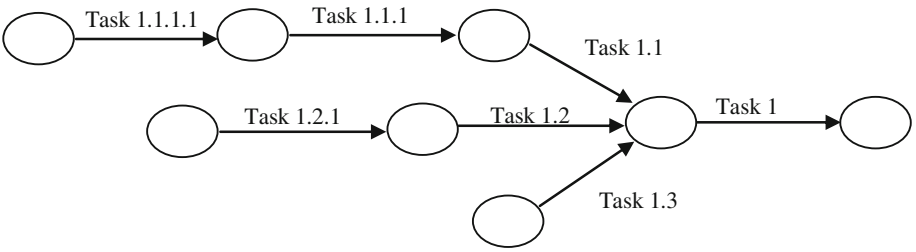


Fig. 1. The graph of precedence constraints of the production order (own work).

resources, ultimately sought is a subset of companies $\Omega = (F_1,\ldots,F_n)$ of set N - cluster enterprises $\{F_k|k = 1,\ldots,N\}$, which will implement the planned order in the network.

Companies bid for the proposed order tasks P. A company that wants to join the production network indicates a resource R that can be used by the newly created network to meet the needs of the new production order. The resource is understood as a particular machine or department of the company responsible for the task.

Offer for the task it means a 6-tuple: OZ = (Z, R, F, Tz, Kz), where:

Z - is a task, R - the resources needed to complete the task Z, F - company, where there is a resource R, Tz - the time required to complete task Z, Kz - the cost of realization of task Z (the cost includes the total cost of resource use and cost of materials used).

Additionally, the enterprise determines, for each resource covered by offer, the range of periods accessible to the cluster, of which there are three W = (R, T1,T2), where: R - the resource, [T1,T2] - time interval in which the resource R is available for the cluster.

The declared availability of production resources sufficient to the task allows a map of resource availability to be built a map of accessible of resources. The map shows the available time slots on the resources of companies that declare the execution of the j-th task in the planning period Tk (see Fig. 2).

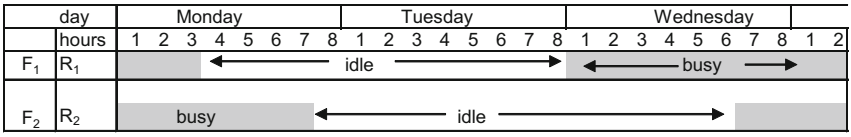


Fig. 2. The map of accessible of resources (own work).

For example to accomplish the task 1.1.1.1, two companies have come forward F1 and F2. These enterprises declared the availability of resources R1, R2, which is shown in Fig. 4.

Company F1 needs, for the realization of (task 1.1.1.1) - 10 h of resource R1 in "idle" time (13 h) as illustrated in Fig. 2. Estimated cost of the resource for task is 4500 PLN.

Company F1 needs, for the realization of (task 1.1.1.1) - 10 h of resource R1 in "idle" time (13 h) as illustrated in Fig. 2. Estimated cost of the resource for task is 4500 PLN.

Company F2 needs, for the realization of (task 1.1.1.1) - 13 h of resource R2. Availability of the resource is 15 h. Estimated cost of task realization (task 1.1.1.1) in this

case is 4800 PLN. So, the specified data is introduced into the proposed system for production network planning by the production managers of companies F1 and F2 and will be considered in the planned realization of a production order.

Similar offers are delivered for the other tasks of the planned production order by companies: F3, F4, F5, F6, F7. Based on the information provided about the realization time of the tasks required by the individual companies and information about the time required to carry out transport operations between the partners, the time range of tasks in a planned order is designated. Figure 3 shows the Gantt chart for the task deadlines.

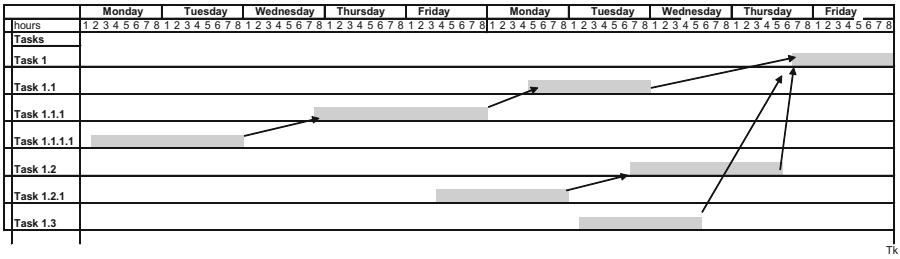


Fig. 3. The Gantt chart of the planned production order P (own work).

In the next stage, bids for specific tasks submitted by different companies are compared to the planned date of implementation of tasks. Enterprises in which the available resources do not guarantee the implementation of tasks within the deadline will be eliminated. Tenders sometimes allow overlapping operations in the selection of a group of companies that can ensure the joint implementation of the order because of the availability of productive resources. Figure 4 shows the allocation of tenders for the planned tasks of the order P.

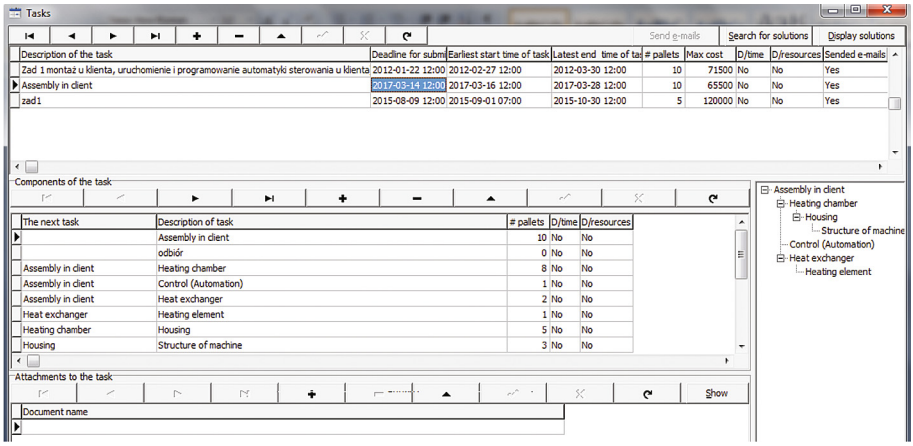


Fig. 4. Entering the data of the planned order (own work).

In the case under consideration, which has been simplified due to the complexity of the problem under consideration, the allocation of tenders to appoint a task allowed only two variations of the order execution due to the available capacity: Variant I: $\Omega 1 = \{F1, F4, F2, F1, F6, F5, F3\}$, Variant II: $\Omega 2 = \{F1, F5, F2, F1, F6, F5, F3\}$.

It should be noted that execution of the production order P (project) will take place with the participation of resources belonging to geographically dispersed companies. It is therefore not only necessary to take into account the times of resource use, but also the logistics cost and time of the project (transport and storage).

In view of the need to carry out transport operations, as a result of the assignment companies to tasks, the company F2 was rejected, which makes an offer to the task (task 1.1.1.1) does not guarantee the sequence of tasks due to the inability to carry out the transport operation. Similarly, the offer of company F7 for the task (task 1.2) has been rejected due to the inability to carry out the transport operation ensuring the timely start of the task at company F3. Transport costs is calculated as the product of the distance between the selected network companies and the rates per kilometers of the route travelled charged by the logistics operator. Thus, in the schedule shown in Fig. 4 the additional time and cost of logistics should be taken into account.

For a set of variants, the total cost of the order is determined, which is the sum of the costs claimed by enterprises for tasks execution, transportation costs and storage costs. Total cost of the order in variant I is - 62 700 PLN and in the second variant, variant II - 63 000 PLN. Since the maximum cost of the order was set at 65 500 PLN, both variants of the network are therefore admissible because of the costs. Ultimately, variant I would be selected as it offers the lowest cost of order execution.

4 A Prototype of the Computer System of Production Network Planning

A computer system for production network planning was designed to apply the proposed concept in practice. The functioning of this solution is described in this paragraph. The initiator of the network introduces data about production orders planned to implement in the network, what is presented in Fig. 4. Each order is divided into subtasks. The following data about planned production order to realize in the system is introduce:

- a deadline for the receipt of tenders for the planned task order;
- planned completion date of the order (required by the customer);
- the estimated number of pallets used in delivery to the customer;
- absolute cost of the order (the price proposed by the customer);
- full technological documentation, technical drawings.

Firstly, there is a process of an offer submitting to the specified order. Then, information about resources and periods of their availability are introduced to the IT system. A production manager defines an availability period for the network for each resource. An information about the availability of transport means is introduced in similar way (Fig. 5). The following parameters are defined for each vehicle: cost of vehicle using (e.g. rate per km) and the permissible capacity of each vehicle, expressed in units of

cargo, e.g. euro-pallets. Next, availability periods of vehicles which are in the disposal of the company are written to the IT system. Specified tasks belonged to the production order are offered. After all information about the deadline for submission of the offer and the date until which must be carried out the task, to ensure the implementation of the whole order according to customer expectations is introduced into the system (Fig. 5). In addition, information about the number of transport pallets planned to carry after the completion of the task, and information about the possibility of dividing the task into several periods in the available time intervals offered resource and information about the possibility of dividing the task into several resources offered by the company is made. A production manager shows an offered resource to execute the order, determines the planned number of hours of resource using and the total cost of the task, as shown in Fig. 6.

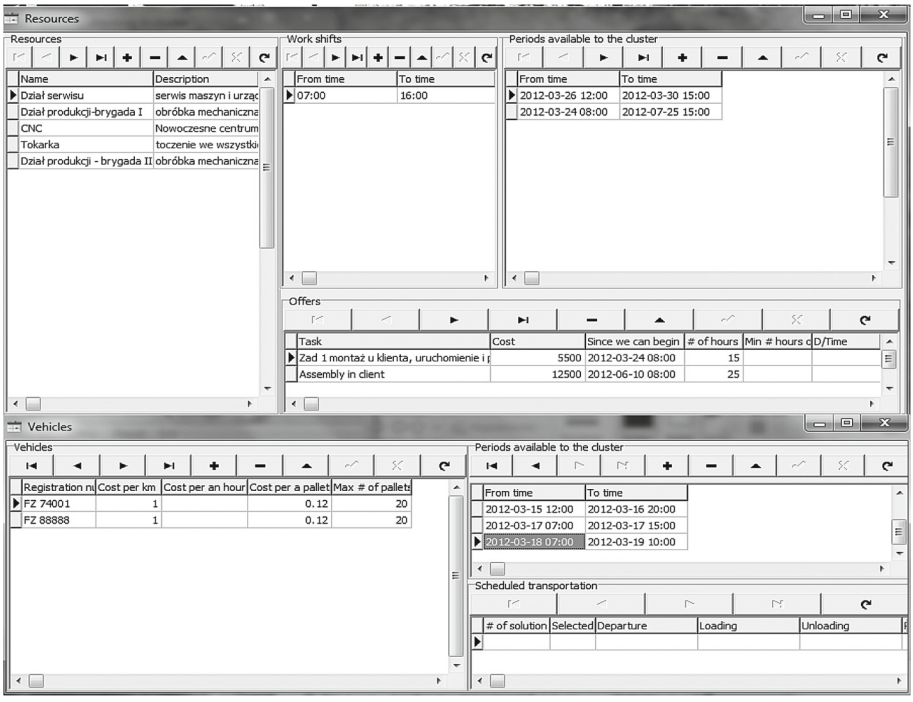


Fig. 5. Introduction production resources, transport means and time of their availability (own work).

After entering the specified tasks of the planned production order and all tenders of companies within a specified period, the initiator of a common network starts the procedure of appointment of a set of permissible network variants, which guarantee the execution of the order. As a result, a set of feasible solutions that ensure timely implementation by not exceeding the total cost specified by the client is received. Figure 7 shows a set of solutions generated for a sample order: variants of the enterprise network, a collection of selected businesses assigned to a specific task with information about the

selected company, used the resource defined in the system, the date of commencement and completion of the task, the deadline for the completion of the transport operation, the total cost of the task realized by the company and the cost of transportation for the specified task.

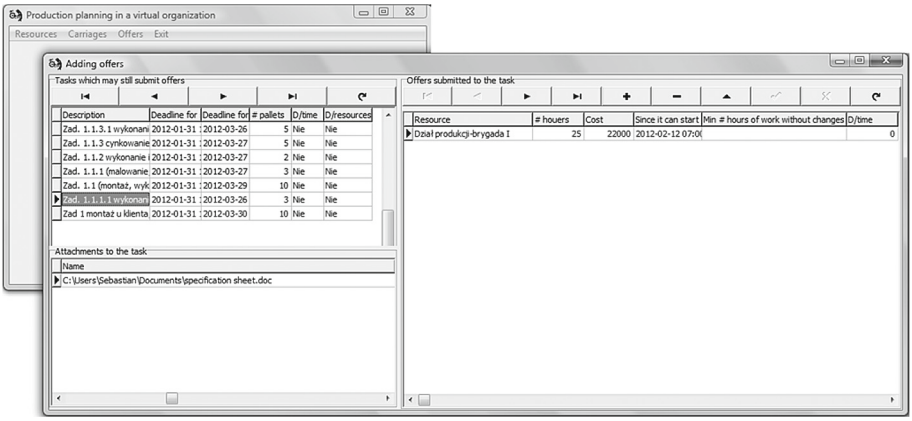


Fig. 6. Introduction the offer of the specified task of the planned production order (own work).

The initiator of business cooperation selects the variant to execute. He is responsible for the completion of tasks in the production network. For each variant is generated a schedule of production flow, which allows the efficient completion of all tasks in each enterprise, the coordination of ongoing production and transport operations, and control the progress of the planned order execution in the system.

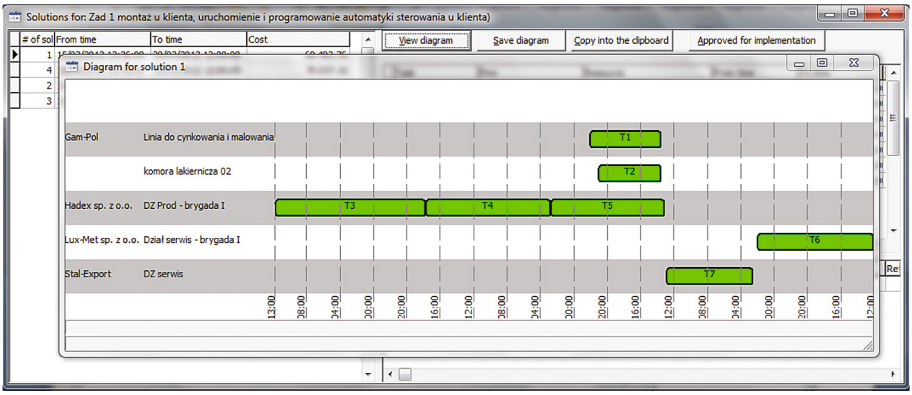


Fig. 7. A schedule of a load of resources for the specified variant of the production order execution in production network (own work).

5 Conclusion

Today, consumers expect a wide range of high quality products matching to their individual needs. For this reason, developing small and medium enterprises with a high degree of specialization is observed which professionally manufacture elements of the product. Therefore, there is a strong pressure on the cooperation of enterprises. A development of production networks is growing rapidly whose main task is to use available production capacity in order to implement a joint production order.

The main problem of this type of cooperation is the quick formation of a production network and planning joint production orders. Hence, a prototype of the decision support system for rapid production order planning in production network is proposed in the manuscript. This is an example of a solution that helps the selection of suitable partners for the newly designed production network and planning the production flow of new orders in the production network. The selection of the partners based on a procedure of offer submitting for a set of tasks necessary to complete a new order and selection of these partners whose offers included cost execution, available production capacity and logistical constraints associated with the location of the company guarantee the joint implementation of the order on time.

The system allows a set of acceptable solutions characterized by different configurations of enterprise networks that guarantee timely completion of orders at a maximum total cost of the order specified by the customer to be determined. This solution helps to establish cooperation in form of a production network on the level of coordination of information flows and physical between network partners primarily through telecommunication networks. This kind of tools can provide excellent support for the development of the idea of the Industry 4.0.

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Durability of Supply Chains as Non-renewable Systems

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Abstract. The article presents issue of survival of simulated supply chains. Authors focus on aspects of durability of supply chain as non-renewable systems. In order to study a survival of objects in supply chain, the simulation model was built. This model includes coordination aspects. By carrying out experiments for a hypothetical supply chain system, the cohort table was developed. Based on experiments was defined: (1) the assessment of the probability of termination of cooperation in the defined interval of time, (2) the estimated function of the simulated objects and (3) the assessment of the hazard function.

Keywords: Durability · Agent · Supply chain · Multimodal networks · Simulation

1 Introduction

Supply chains are complex systems, dynamic, dispersed and open; is a metastructure. A metastructure is an intermediate form between a single enterprise (microstructure) and global economy (macrostructure). The greater the supply chain grows, the less coherent and lacking close relationships it is [1, 2]. In turn, this results in a situation in which in such a metastructure's connections and dependencies may vary in permanence. Sustainable systems (supply chain system, production system, ergonomics system) [3–7] operate on the basis of strictly defined principles and are capable of maintaining specific reliability and quality parameters.

The aims of the study are to present the results of a simulation experiment conducted using the FlexSim application, and to perform an empirical analysis of the survival of simulated supply chains. The publication has the following structure. Chapter two outlines the background information related to the reliability and durability of non-renewable systems. Chapter three describes the simulation model used. Chapter four focuses on the analysis of survival performed on the basis of the conducted experiments. The results of the analysis are demonstrated and discussed. The final section contains a summary and conclusions.

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2 Basic Concepts Related to Non-renewable Systems

For the purpose of the study, the following definitions were adopted for the concepts of system, agent theory and durability. System is understood [8]: (1) an internally coordinated configuration of elements possessing a specific operational structure $\Longrightarrow$ a supply chain consisting of a series of cooperating enterprises, (2) a set of modes of action, performance of complex activities $\Longrightarrow$ procedures of action, (3) a set of organizational rules, a collection of norms, rules and standards, which are in force in a given field of activity, (4) a comprehensive and structured set of tasks interconnected with one another by specified logical relationships. Systems theory allows the transfer of research results from one field to another [9–13].

Agents representing various enterprises from particular tiers cooperate with one another, coordinate and negotiate conditions to achieve the common goal whereas every agent may try to attain the target of the individual user delegating it [14].

The system under analysis can be accommodated within the agent theory. The approach is justified because intelligent agents involved in the simulated system perform, on a continuous basis, the three tasks listed below: (1) perception of the dynamically changing environment conditions, (2) action to influence/alter these conditions, (3) reasoning so as to interpret the data being perceived and solve problems [15]. The simulated system can be broken down into the following constituents: Leader Agent represents the particular interests of cooperating companies and it is responsible for cooperation, communication, negotiation with the other agents representing companies outside the cooperation network. Leader Agent is able to manage complex business processes. It cooperates with groups of agents and creates multi-agent system, as followed: (1) Searching Agent (SA), (2) Offering Agent (OA), (3) Informing Agent (IA), (4) Negotiating Agent (NA) and (5) Verifying Agent (VA) [16].

For the purpose of the study, it was assumed that the simulated system (supply chain) is non-renewable. What this means is that in the event of a breakdown or low maintenance level (below 60%) in one of the links in the supply chain, the link is not subject to repair or replacement, and the system "dies". Consequently, if a non-renewable system is in the up state at time $t_o = 0$, and is damaged at time t_u, then the time interval $t_u - t_o = t_u$ represents the up period of the system. It also represents its durability [17–19]. It is stipulated that sustainable supply chains are created for standard products and assortments with high sales volumes, often mass-produced products. They are also created for strategic products and assortments, which play a very important role both for production and sales processes. They are geared towards the optimization rather than maximization of profit. The primary requirement they are expected to fulfil is high durability. The supply chain system stimulated for the purpose of the study has a serial structure (supplier, subcontractor, producer, recipient) The durability of such a system (T_s) can be determined with the formula given below:

$$T_s = \min T_i = \min\left(T_1, \ldots, T_i, \ldots, T_n\right)$$

where:

T_i – durability of the i-th element

Therefore, the durability of the supply chain T_s is defined by the durability of the weakest (i.e. least sustainable) link within that supply chain. Consequently, throughout its entire planned (design-specified) period of operation, the designed sustainable supply chain should meet the requirements that take into account its usability without a significant decrease in its suitability or excessive and unpredictable maintenance costs.

3 Simulation Model

A supply chain can be analyzed as a complex system, in which information and materials flows have to be realized. Moreover, the connection between these two aspects have to be considered. Proper sharing of information is one of the conditions of cooperation and a chance for success in today's rapidly changing and growing market. In the publication a complex system, which used mechanism of action coordination was analyzed. Authors focused on one mechanism of coordination – with using the Electronic Bulletin Board. This mechanism and simulation model representing this model was described detailed in [20, 21]. For the purposes of this article the simulation model with using the Electronic Bulletin Board (EBB) has been expanded. Authors decided to add a transportation part into this model. Moreover, they decided to analyze supply chain, which consists of few entities (contractors), exactly four. Each entity consists of decision and transportation parts. The decision part consists of 18 operations (basic operations for this part, which is described in detailed in [20, 21]). While, the number of operations in transportation part depends on number of entity in the chain. In every contractor in transportation part are these 2 operations:

- T1 – the operation of transport realization (Tt).
- T2 – the operation of determination of the satisfaction level (SL) of the implemented service.

In the last contractor (the fourth) is one additional operation:

- T3 – the operation of checking the service's satisfaction and making the decision of reject the object or re-admission to the circulation (the decision on further cooperation).

Some assumptions were made with regard to the simulation model with EBB with four contractors. Firstly, for every entity the decision part looks the same. The assumptions for activities T1 and T2 also are the same in every contractors. These information stay unchanged - they are described exactly in [23, 24]. The next change is: a share of positive decisions (expressed in %) in the two decision-making points (A5 and A13) defined as 80%. These operations belongs to the decision part of EBB. In A5 is making the decision about the possibility of realization the tasks, in A13 – the decision about the possibility of realization the subtasks. In simulation model, authors defined the % of positive decisions in these points.

Figure 1 presents the algorithm of flow in described model.

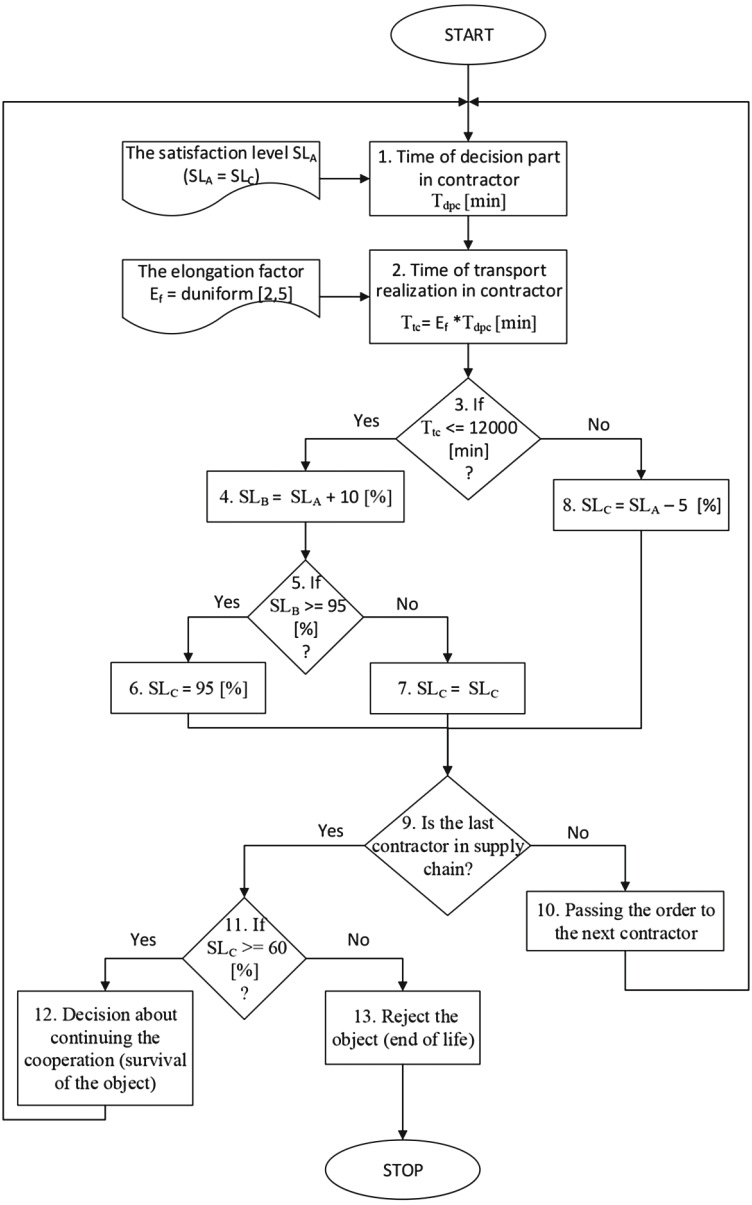


Fig. 1. The algorithm of flow in analyzed model. Source: own study.

In the transport part the following assumptions were made:

- T1 – the transportation time (Tt) is 2–5 times longer since the decision-making process (Tdpc1) which consists from time of steps A1 to A18. The elongation time is determined at random integer value with the same probability.

- T2 – the satisfaction level (SL) at the beginning is equal to the 50%. If the time of realization of decision and transportation activities in one contractor will be lower than 12000 min, this level is increasing 10%, if not is decreasing 5%. Simultaneously it was assumed that the level of satisfaction can be up to 95%.
- After performing the T2 activity at contractor 1, the order comes to the A1 activity at contractor 2, with an updated satisfaction level. For this activity (T2) at contractor 2 and 3 it looks the same. At the last contractor – the fourth, after activity T2 it is making the decision of reject the object or re-admission to the circulation (the decision on further cooperation). If the actual satisfaction level is greater than or equal to 60%, the order comes back to first activity at first contractor, with actual satisfaction level.

For presented model the experiments were performed. During these research authors focus on time of survival of complex system with an actions coordination mechanism (with the Electronic Bulletin Board). The observed values in experiments are:

(1) whole time in every contractor, which consist of decision and transportation part time,
(2) summarized time for four contractors,
(3) the satisfaction level of the implemented service after activity T1 in every contractor – using for verification the proper operation of the model.
(4) the satisfaction level at ending point in the loop – in fourth contractor,
(5) number of cycle for each object (order) – it shows how many times was undertaken the cooperation with this object. It depends on satisfaction level.

The decision-making processes can be mapped using agent-based approach (ABS). By using ABS the behavior of individual agents (objects) are presented and also the interaction between them. It is assumed that agents have a certain freedom of action and they can learn during the process – making the earlier decisions.

The number of agents depends on the assumed level of detail of the analysis for the described coordination model. For the presented supply chain, which consists of 4 contractors, two levels of detail can be distinguished:

- both processes: the decision-making and transport, in every contractor are presented with an individual agent – the total number of agents is 8 (Fig. 2).
- the decision-making process at contractors number 1–3 is represented by a six agents, whereas at the fourth contractor – with seven agents. Transport process at contractors 1–3 is mapped using one agent and at the last contractor by two agents. Total number of agents is 25 (Fig. 3).

Depending on the goal of analyzed model, a different level of detail will be established, which is associated with a different number of agents. The general level (case 1) will be appropriate for the analysis in the overall level – only analysis the time of decision making and transport process for every contractor. While, for the analysis of the particular steps for each contractor (for example: the process of dividing orders for tasks in a particular contractor or dividing task into subtasks) establishment a greater number of agents seems to be more appropriate (case 2). For this level of detail one more decisions should be taken: if all activities from transportation part should be included in the range

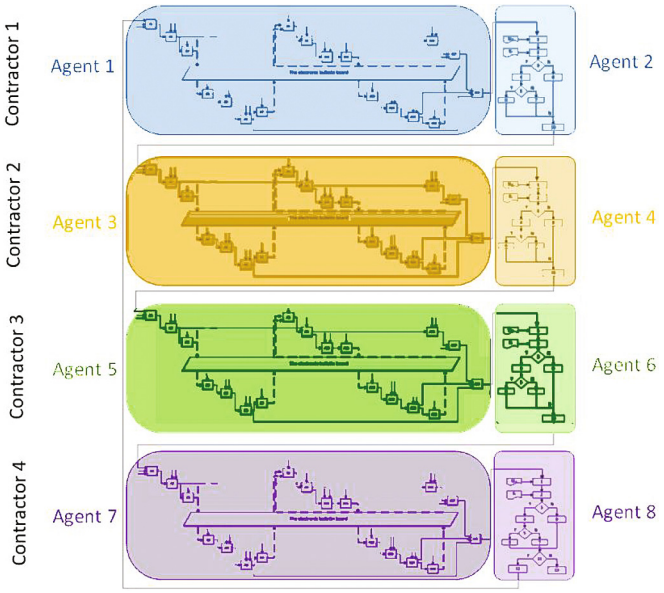


Fig. 2. The Electronic Bulletin Board–the number of agents in general level of detail. Source: own study.

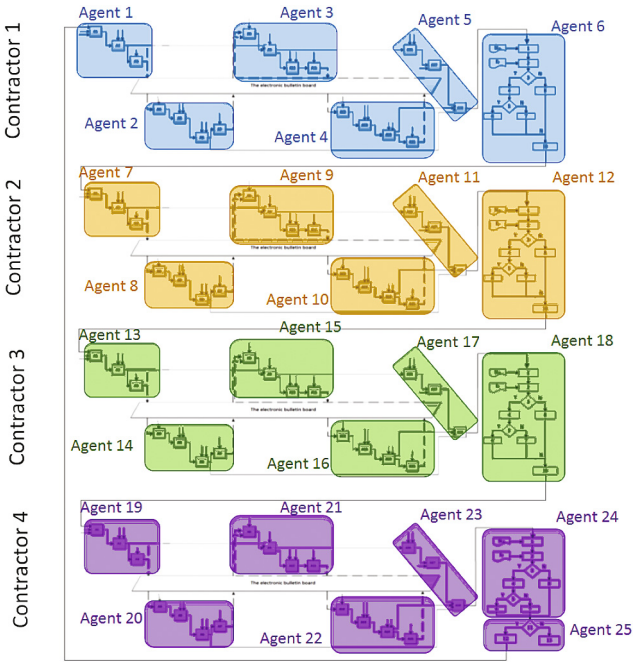


Fig. 3. The Electronic Bulletin Board–the number of agents in detailed analysis. Source: own study.

of action for one agent? Or the activity number 2 associated with the physical transportation should not be included?

A case, which is discussed in this article, refers to the general level of detail – only results (time) for decision-making and transportation parts are analyzed and the final satisfaction level.

4 Results of the Survival Analysis

The survival model is the probability distribution of a positive random variable. It takes the time elapsed since the initial moment into account until the occurrence of an event [22]. It is assumed that the observed object can experience an event ending only once in an observation. This event is the end point determining the "death".

On the basis of the initial and end point (event-free survival) survival time of the object examined can be determined. The time of observation of each object is individual. The individual survival time is calculated from the moment of its incorporation to the test until the occurrence of the end point or interruption of the observation due to the termination of the study. The study may incorporate cut observations. These are observations that do not specify the exact survival time. This is closely connected with the analysis of survival.

The survival analysis allows comparing the probability of survival/hazard between the different groups of objects. The survival function can be estimated using the estimator proposed by Kaplan and Meyer according to the formula [22]:

$$S(t) = \prod_{t_j \le t} \left(1 - \frac{m_t}{n_t}\right)$$

where:

S(t) – estimated survival function,

Π – symbol of the product,

m_t – number of objects in which end point occurred in the *t* period,

n_t – number of all objects exposed to occurrence of end point in the *t* period.

The analysis of survival of a simulated complex system takes the following assumptions into account: (1) the objects of observation are simulated complex systems; (2) were analysed 100 objects; (3) the survival time of the examined objects is the total operating time; (4) the data covers the period 6 months; (5) the initial event is the starting point of observation of a simulated process; (6) the final event for the object is the end point or the end of the study.

For the purpose of the work, the non-parametric, tabular model will be adopted. A cohort table of the simulated systems was developed (Table 1). It contained the results of the assessment of the probability of termination of cooperation in the interval of time ($\hat{f}_t$). The probability estimator on the termination of complex systems in the time interval can be described by the formula $\hat{f}_t$:

$$\hat{f}_t = \frac{m_t}{n_t}$$

Table 1. The cohort table of survival of simulated complex systems; own work

Intervals of duration time	Number of objects that survived	Number of objects, which have not survived	Number of objects, which have censored	Probability estimator on the termination of complex systems f(t)	Estimated survival function S(t)	Intensity function (hazard) Ht
(1)	(2)	(3)	(4)	(5)	(6)	(7)
					1.00	
0	100	0	0	0.000	1.00	0.000
1–10 days	100	0	0	0.000	1.00	0.000
11–20 days	100	0	0	0.000	1.00	0.000
21–30 days	100	0	0	0.000	1.00	0.000
31–40 days	100	0	0	0.000	1.00	0.000
41–50 days	100	0	0	0.000	1.00	0.000
51–60 days	100	1	0	0.010	0.99	0.010
61–70 days	99	38	41	0.384	0.61	0.480
71–80 days	20	10	9	0.500	0.31	1.092
81–90 days	1	0	0	0.000	0.31	0.000
91–100 days	1	0	0	0.000	0.31	0.000
above 111 days	1	0	1	0.000	0.31	0.000

Another parameter is the $S(t)$. $S(t)$ signifies unconditional probability that the event occurs after t moment, and hence that the cooperation will last at least until t moment. This function expresses the pattern of survival in the examined population. Evaluated survival function decreases with time. The speed with which it decreases, known as the intensity function (hazard) ($\hat{h}_t$) depends on the duration of the complex system. It can be described by the formula:

$$\hat{h}_t = \frac{\hat{f}_t}{(S_t + S_{t+1})/2}$$

The cohort table of survival of simulated supply chains is presented in Table 1. In the cohort survival table (Table 1), the first column contains intervals of duration time of the simulated supply chain (objects). Day periods of time were established.

The column shows the beginning of the interval, which is also the moment of observation. The second column indicates the number of simulated objects that survived to the designated point of observation. The output population of the analyzed cohort

amounted to 100 subjects. With time, this number is reduced by the number of objects, which have not survived (third column) and the censored (fourth column).

A total of 49 objects did not survive in the survey. Termination of the cooperation was associated with a lack of satisfaction with the implemented service. The level of satisfaction with the cooperation could not be lower than 60%. A total of 48 objects did not survive in the seven and eight periods from the start of the study.

Fifty one of the simulated objects were censored in the study. This means that these objects have survived until the last moment of observation, which is the end of the study. They represent 51% of the study cohort.

It is also worth noting that after the three months of the cooperation 99 objects have survived. After the two weeks later of the cooperation 20 objects have survived which accounts for 20% of the study sample.

Table 1 provides an assessment of the probability objects, which have not survived (column 5). The probability of termination of cooperation (not surviving of the simulated complex systems) in the eight period of time is the highest (0.5), little smaller is in the seven period (0.384). The Table 1 also presents the estimated function of the simulated objects. The survival function for all objects (Fig. 4) confirms the great psychological significance of the seventh and eighth stages of cooperation, which determine the continuance of the supply chains.

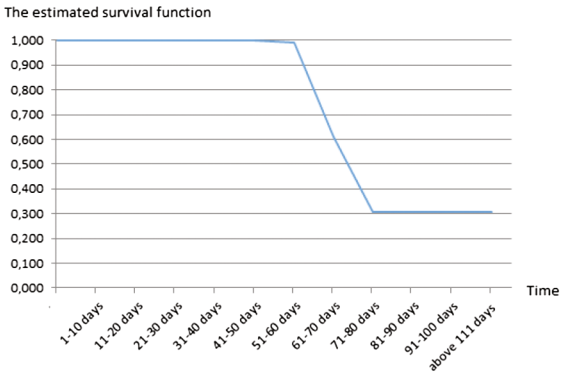


Fig. 4. The estimated survival function; own work

The final column of the table presents an assessment of the hazard function. This is a function of the intensity, which denotes the risk of termination of cooperation provided that it did not occur until the end of the study. The intensity function for the tested cohort of objects takes the shape reversed of the letter U, with a maximum in the time interval of 71–80 days (eighth period). Therefore, after exceeding this time interval the risk of termination of cooperation decreases again.

5 Conclusion

The survival analysis methods applied in this work are focused on assessing the durability of supply chains. Analysis can help with developing better interventions that can be deployed early during a cooperation and minimize risk of termination of cooperation. For the purpose of the article a simulation of 100 objects was performed, which were subsequently subjected to survival analysis. The results of the analysis indicate that the probability of the termination of the cooperation in the eighth period (71–80 days) is the highest.

Presented cooperation model has some assumptions and simplifications. There are plenty of possibilities for its development. First proposition applies inclusion a medium and large order size for analysis. Thanks to them it will be possible to analyze more complicated cases, which will be more real. The second step is changing a number of contractors in the chain and possibility of exchanging the contractor, which work is not corresponding to the requirements (for example: carrying out the process for too long) for the new contractor. An interesting direction for the development of this model seems to be the issue of making the decision about sending the order from the last contractor to the first contractor. It would be useful to analyze the possibility of continuing the cooperation, depending on the total time of the implementation of all activities for all contractors in combination with achieved satisfaction levels for each contractor.

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Dynamic Spaghetti Diagrams. A Case Study of Pilot RTLS Implementation

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Abstract. Spaghetti diagrams are widely used as improvement tools within lean manufacturing framework. Drawing spaghetti diagram is time-consuming. The diagram is static and does not reflect dynamics of logistics systems. Real time locating system was proposed to overcome this drawback. A case study of pilot implementation of the system was presented. It was proved that pilot system may operate reliably in industrial environment in terms of hardware and software applied. System features and some improvements based on dynamic spaghetti diagrams were listed.

Keywords: Real Time Locating System (RTLS) · Spaghetti diagram · Ultra Wide Band (UWB)

1 Introduction

American Society of Quality defines spaghetti diagram (SD) as "a visual representation using a continuous flow line tracing the path of an item or activity through a process. The continuous flow line enables process teams to identify redundancies in the work flow and opportunities to expedite process flow" [1]. It is used to graphically depict the movement of objects through a process and as a tool used within lean manufacturing framework. The strength of the tool is possibility to visualize a movement of almost any object (materials, work in process, semi-finished goods, transportation assets, documents, people etc.), so the area of its applicability is not limited to manufacturing environment. It depicts the flow, distances, speed and waiting times.

The process of drawing spaghetti diagram is following [2]:

1. Obtain an existing or create a facility layout diagram (drawing).
2. Obtain an existing routing sheet or create one using typical object going through facility.
3. Draw a continuous curve starting at the first location on the routing sheet to the remaining locations.
4. Calculate total travel distance.

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5. Estimate travel time using travel speed.
6. Study the spaghetti diagram and identify flows with high part's travel distances and areas in the facility that are rarely or never used.
7. Move the processes closer together or rearrange to reduce total travel distance.
8. Repeat steps 4–7 using new layouts and assumptions.

The movements has to be recorded in order to draw a diagram. It is invasive and usually influence workers behavior. The other drawback is that recording is time-consuming and the diagram being drawn only once is static in its nature.

Finally, improvement derived from an analysis of a static spaghetti diagram may not be addressing real process and problems. The way to overcome pointed drawbacks could be an application of real time locating system (RTLS) for dynamic spaghetti diagrams (DSDs).

2 Real Time Locating Systems

2.1 Definition

According to ISO standards "RTLS are wireless systems with the ability to locate the position of an item anywhere in a defined space (local/campus, wide area/regional, global) at a point in time that is, or is close to, real time. Position is derived by measurements of the physical properties of the radio link." [3] Above definition reflects RTLS as a specific use of radio frequencies, to achieve location data. However, systems employing other technologies, like infrared light (IR), ultrasound (US), and hybrid solutions (IR-RF, US-RF, IR-US-RF) exist. IR and US allows to eliminate some shortages of radio e.g. radio penetrates walls, therefore to precisely distinguish locations between adjacent rooms, US could be applied as well. Budak and Ustundag [4] listed Ultra-Wide Band (UWB), Radio Frequency Identification (RFID), Wi-Fi, ZigBee, Bluetooth (BT) and Infrared (IR) as commonly used RTLS technologies. However, the list is not exhaustive, nor systematic e.g. UWB could be treated as specific active RFID. RTLS could be treated as a specific use of a broader RFID group of technologies, that sometimes is hybrid of RFID and other technologies. An attempt to the typology of RFID systems, including RTLS, was presented in [5].

Practically, when production and logistics shop-floor, middle and top managers talk about RTLS they have in mind a kind of indoor positioning system, that could be called colloquially "an indoor GPS". Therefore, the definition of RTLS adopted in this paper is focused on the goal of the system (locating objects), rather than on standards and technologies applied. For the purpose of this paper, RTLS is the system that enables the process of locating objects in relative coordinates. Detailed RTLS infrastructure may differ depending on a specific technology. A general infrastructure is presented on Fig. 1.

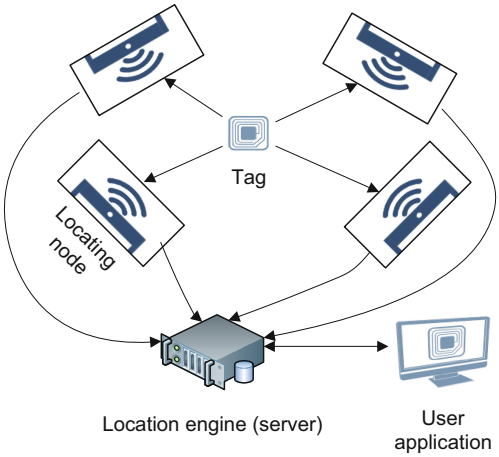


Fig. 1. General RTLS infrastructure

2.2 Applications

Applications of RTLS are almost unlimited. There is a broad literature on RTLS applications within healthcare [6], warehousing and manufacturing. RTLS applications in warehousing, manufacturing and logistics include, but are not limited to, controlling and reducing inventory through smoothing information handling [7], cooperating within supply chain [8], fighting maritime piracy [9], assets tracking in container terminals [10], improving mobile (transportation) assets utilization in manufacturing [11], assets tracking on a shop floor [12].

3 Pilot RTLS Implementation

3.1 Framework

Spaghetti diagrams are well established and widely used analysis tool in business practice. They are one of initial analysis tool used when implementing lean manufacturing/management. However, spaghetti diagrams are static in their nature. They also do not fully represent reality as employees, who are aware of being observed, tend to not behave in a typical way. One possible solution to overcome this problem is an idea of dynamic spaghetti diagrams, that are being drawn continuously, without awareness of employees whose work is a subject of an analysis.

Dynamic value stream mapping was presented in [13]. Presented approach is limited to chokepoint detection with passive RFID. Therefore, value stream map accuracy is limited to the department level. This approach does not enable drawing spaghetti diagrams, but only measuring lead times for departments, by identification of incoming and outgoing goods. Considering the process of drawing spaghetti diagram (see Sect. 1), steps 1–5 could be automated using RTLS. No papers were found regarding RTLS

application designed to draw DSD in industrial environment (warehousing, manufacturing, etc.). An idea of dynamic spaghetti diagrams is novel and may deliver substantial benefits to companies. Therefore, the main goal of this paper is to present a case study of DSD based on RTLS application, which is novel and not present in the literature. Such a solution consisted of three elements: organizational, software and hardware was not found in the literature. The other goal is to evidence usefulness of the idea of dynamic spaghetti diagrams for companies by its pilot verification in selected company. That was a company that realized themselves that flows are different that recorded using conventional approach to drawing spaghetti diagrams.

An approach to discussed pilot RTLS implementation is presented on Fig. 2. First step was the definition of needs, which was necessary to find criteria to assess and select specific RTLS technology. As RTLS is innovative and not known for everyone, the next step was a proof of the technology. It was necessary to convince a company, that considered solution is capable to operate reliably in the company-specific environment. After customer needs definition and proving technology, software engineering took place parallel with laboratory tests of RTLS. Last two phases were installation and pilot tests. Results of pilot tests are the main result of conducted research.

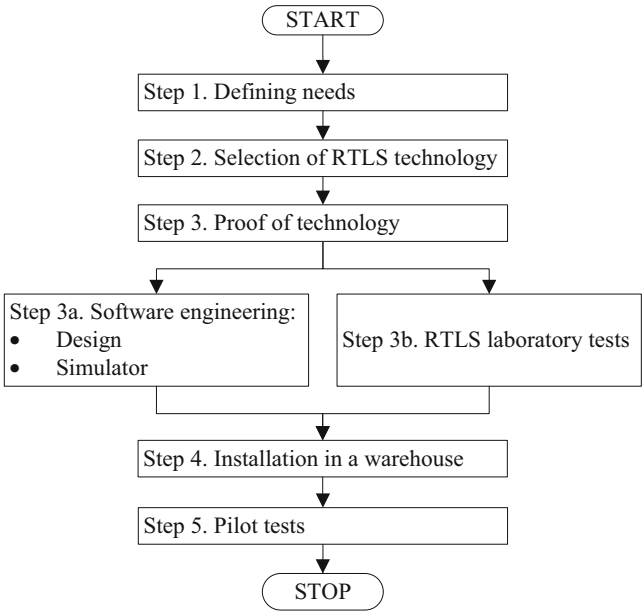


Fig. 2. Analysis, research and implementation algorithm

3.2 Definition of Needs

Presented case study is based on a cold chain warehouse. Cold chain is a type of supply chain where temperature must be controlled and preserved at a constant level. Cold chain logistics is focused on all areas of conventional logistics and additional issues related to

the control of a temperature. Analyzed warehouse deals with goods that should be stored within +2 °C to +6 °C range of temperature.

Objects that are going to be monitored are forklifts within a warehouse. Lean initiative is ongoing to improve processes. SDs are used to calculate real lengths of routes, lead times, cycle times, speed of flow, and therefore, to eliminate inefficiencies of unnecessary motion and transport and enable continuous flow. Diagrams are static and prepared occasionally and manually. Workers are aware of drawing diagrams, so they would not act in typical manner. Therefore, results and obtained diagrams are prone to be inaccurate, what limits further improvements.

Main features of considered RTLS implementation are four-fold:

- a diagnosis tool to support lean initiatives by elimination of unnecessary movement, transport, and waiting times, called dynamic spaghetti diagram,
- a controlling tool for a real-time monitoring of forklift routes and support for planning of picking operations, loading/unloading operations based on integration with Warehouse and Transport Management Systems,
- a controlling tool for a real-time monitoring of temperature by integration with wireless sensors installed on trucks,
- a controlling tool for calculation of key performance indicators of forklifts (average speed, overall equipment efficiency among others).

Considering features presented above, two main requirements were:

- high precision, at least 0.5 m, of RTLS positioning and
- high flexibility in terms of integration with existing software solutions.

On the other hand, considered warehouse is operating, so RTLS implementation should possibly do not interrupt warehousing processes. RTLS infrastructure should allow for easy dismantling and installation in other warehouses, as the idea is to circulate it between geographical locations.

3.3 Chosen System

Three alternative solutions were considered: passive RFID UHF (Ultra High Frequency), Wi-Fi, and UWB (Ultra Wide Band). Alternatives were assessed according to following criteria: financial, technical, organizational (including implementation). UWB system was chosen (see Fig. 3). Chosen RTLS is based on ultra-wide bandwidth and is not interfering with other radio systems. It operates in 3.5–6.8 GHz range of radio frequencies. Considered system requires only power cabling for location nodes. Network cabling is not necessary as location nodes form mesh network. UWB tags are relatively expensive, but can operate in two modes: tag and location node. Tags require own source of power, but power consumption is relatively low, if comparing to Wi-Fi tags. Battery life is not critical, as tags are supplied directly from forklift battery. In case of lack of power from forklift battery, UWB RTLS tags could work longer, than Wi-Fi RTLS tags.

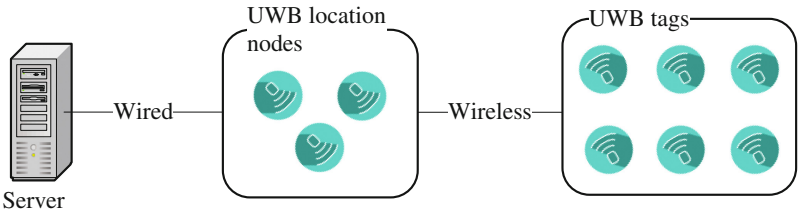


Fig. 3. UWB RTLS

3.4 Installation

Two areas were chosen for pilot implementation, which goal was to assess technology readiness level for a full scale implementation in a cold chain warehouse. Pilot areas were following:

- Dispatching: 60 × 60 m, 27 dock doors, pallets ready for shipping stocked directly on a floor,
- High-rack storage: 4 corridors, 3 × 44 m each.

6 location nodes were installed in the first area, and 12 in the second (3 per corridor). Location nodes formed mesh network and needed only power supply and no Ethernet. 5 forklifts were equipped with tags. Tags were powered directly from forklift batteries.

3.5 Software for Dynamic Spaghetti Diagrams

General architecture of the software component is presented on Fig. 4.

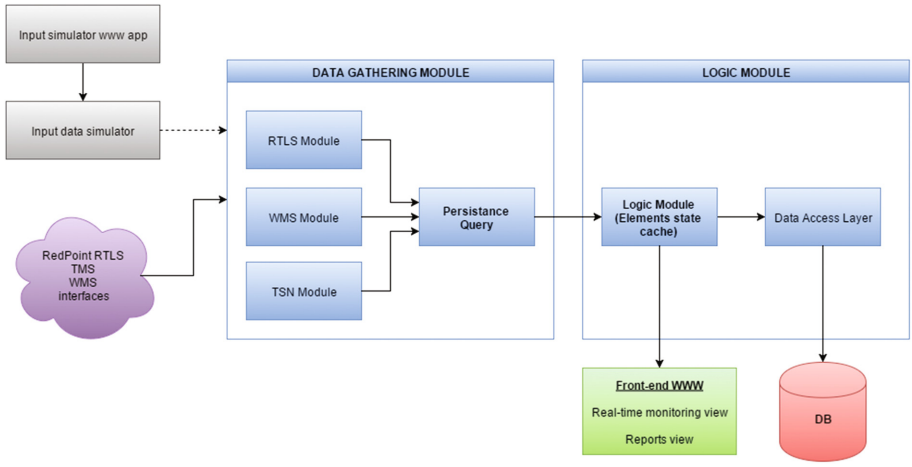


Fig. 4. General architecture of the software component

Main objects in the system and related parameters are presented in Table 1. Main events in the system and related parameters are presented in Table 2. Warehouse and transport management systems are tend to be the source of data about start and end of loading/unloading order including full data about order, start and end of picking order including full data about order. Integration with those systems was not a part of pilot tests. End user can access software via web browser.

Table 1. Main objects in the system (Source: HADATAP Ltd internal)

ID	Name	Parameters	
0	Forklift	• ID of forklift • ID of order	• ID of worker • ID of dock
1	Trailer	• ID of trailer • ID of dock • ID of order • Number of license plate	• Current temperature • Temperature alarm (OK, LOW, HIGH)
2	Order	• ID of order • Start of order • End of order • Type of order: 0 – loading; 1 – unloading; 2 – picking	• Total quantity of pallets in order • Current quantity of pallets served (progress of order)
3	Dock	• ID of dock • ID of trailer in dock • Occupation	• Zone of dock, series of X;Y coordinates
4	Position	• ID of forklift • ID of dock • Number of worker	• X coordinate • Y coordinate
5	Route	• ID of forklift • List of stoppages	• List of positions
6	Stoppage	• ID of forklift • End of stoppage	• Beginning of stoppage
7	Warehouse	• ID of warehouse • Current temperature	• Temperature alarm (OK, LOW, HIGH)

Table 2. Main events in the system (Source: HADATAP Ltd internal)

ID	Event	Parameters	
1	Trailer arrival	• ID of trailer • ID of dock	• Timestamp
2	Trailer departed	• ID of trailer	• Timestamp
3	Start of order	• ID of order • Type of order • ID of forklift	• Total quantity of pallets in order • Timestamp
4	Pallet served in order	• ID of order	• Timestamp
5	End of order	• ID of order	• Timestamp
6	Forklift enters dock area	• ID of dock • ID of forklift	• Timestamp
7	Forklift leaves dock area	• ID of dock • ID of forklift	• Timestamp
8	Change of forklift's position	• ID of forklift • Timestamp	• Position of forklift in X;Y coordinates
9	Change of temperature in trailer	• ID of trailer • Current temperature	• Timestamp

3.6 Results

Pilot test period was 3 months. Features that were successfully piloted were:

- Drawing spaghetti diagrams for a given period and chosen forklifts (see Fig. 5),
- Visualization of forklift/dock/warehouse changes of statuses and activities (moving/idle/out-of-reach) (see Fig. 5),
- Real time tracking of forklift movement,
- Identification of trailers at dock doors and visualization of dock doors statuses (see Fig. 5),
- Real time temperature monitoring in the warehouse (see Fig. 5),
- Reporting on forklifts utilization (see Fig. 6),
- Reporting on variations of a temperature in the emerging trailers and in the warehouse (see Fig. 6).

Figure 5a depicts exemplary spaghetti diagrams. One may notice that forklifts are moving diagonally through a warehouse floor. It is an alert that planning could be excelled or there is another assignable cause. In this case, the cause was repeatable failure of forklift, which needed service and had to move to a parking zone. An improvement action was proposed to eliminate this root cause. Figure 5b depicts incorporation of another lean management idea, which is visual management [14]. Processes are monitored continuously and colours are related to the state of equipment, what may be considered as a kind of andon sign [15]. Real time temperature monitoring (see Figs. 5b and 6b) is not only andon sign for process monitoring, but also serves as error-proofing (poka-yoke) tool [16], because it allows alerting when cold chain was broken, what is the most important quality requirement.

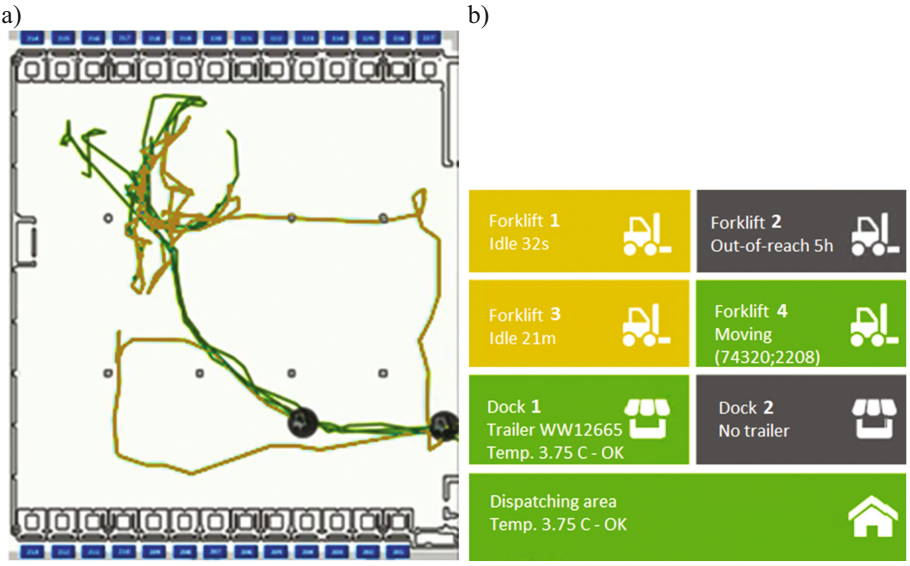


Fig. 5. (a) Exemplary spaghetti diagram for 2 forklifts; (b) Visualization of statuses of forklifts, doors, trailers and temperature

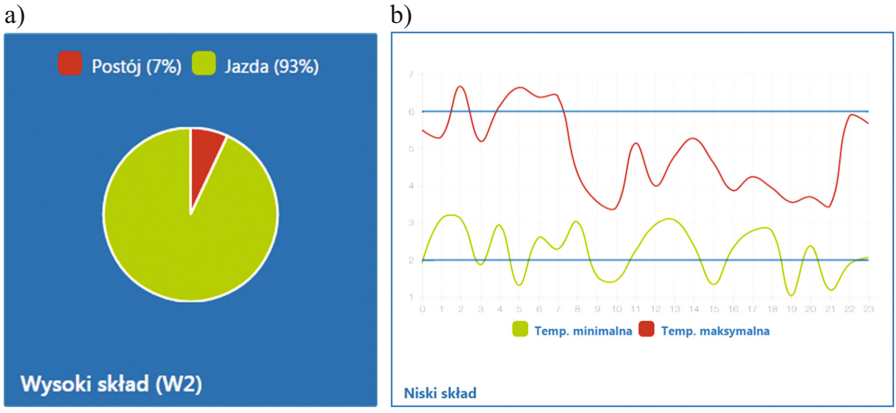


Fig. 6. Exemplary diagrams: (a) forklift utilization; (b) warehouse temperatures

4 Conclusions

Pilot implementation proved that RTLS can support lean initiatives by efficient and effective acquisition of data for:

- drawing dynamic spaghetti diagrams,
- availability and performance calculations for forklifts,
- temperature monitoring in an emerging trailers and a warehouse.

On that basis, the software component of the system could be extended to support:

- dynamic value stream mapping,
- support of calculations of performance indicators related to an equipment effectiveness e.g. OEE, TEEP,
- temperature monitoring along the whole supply chain (hardware component should be also extended).

Data recorded in RTLS database and used to draw SD, may serve to calculate idle time, average speed of movement and average cycle time of warehousing operation (if integrated with WMS). Therefore, it could support calculations of availability and performance parts of OEE factor [17].

Description of pilot RTLS implementation lacks more detailed information on the approach to selection of specific RTLS. This approach is the topic of the other paper and includes design analysis of a set of selection criteria, selection methodology, and multi criteria decision making approach.

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Information Management and Decision Making Supported by an Intelligence System in Kitchen Fronts Control Process

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Abstract. Measuring systems used for alternative control are the basis of the kitchen fronts acceptance. The assessment of such products is difficult. On the basis of the performed analysis, it can be said that different operators make different decisions that result in different problems in a case study manufacturing company. In the work, the authors propose a cyber-physical distributed computing infrastructure to implement performance metrics methods extended to manage the control system and to support the decisions concerning improvements in the control process. It will result in the minimization or avoidance of operators' mistakes concerning the wrong acceptance or rejection of the finished product.

Keywords: Cyber-physical information system · Intelligence system · Control process · Process effectiveness

1 Introduction

The paper presents the concept of a pervasive and distributed infrastructure for a cyber-physical system (a software solution), with humans in the loop, to be used for the management of the control system effectiveness, which can be integrated into the kitchen front control process. The main content of the paper is connected with development of a concept of a cyber-physical system (CPS), which will support a manager in decision making process. The overall control system relies on the extension of the semantics and quantification of a hierarchical set of key performance indicators, based on well-known performance metrics techniques. The technology adopted can be deployed in a distributed fashion to attain a lightweight information and communications technology (ICT) infrastructure that is lean enough to flawlessly interact with not specifically trained operators. The concept is to render the introduction of technology aids almost invisible and less invasive, while at the same time flexible enough to readapt quickly and to be reconfigured often. This approach suits manufacturing

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processes with high variability and customizability as well as in small lot sizes, where the reprogramming of ICT controllers is a rarely sustainable cost. Humans are a major component in this cyber-physical loop by design. Both the operators and managers are the main source of information that is analyzed in order to assess the effectiveness of the production control process. The information system is to ensure that in case of any problems in the control process, a manager will timely receive the specific and adequate information for corrective actions. Information is provided in intelligible, though quantitative form, by the semi-automated measurements of a context sensitive set of performance indicators. The proposed performance monitoring infrastructure is prone to its natural integration with planning and optimization tools, in the decision making process towards problem solving.

2 Cyber-Physical Systems for Performance Measurement

An ICT infrastructure can provide effective means to assist and enforce control policies with a view for the incoming 4.0 evolution in manufacturing. In the fourth industrial revolution, there is a search for holistic and unified approaches that render treatable the complexity of a factory seen as a cyber-physical system (CPS). The devices in CPS feature enhanced networking, distributed computing and intelligence capabilities. They can be assigned the role of distributed agents in multi agent systems for the control of complex production processes [1].

In the following, a well-known technique, used so far for the traditional equipment effectiveness measurement is adapted in order to extend it to "work stand cells", where actually the human "equipment" performs the main job. By doing so, we can leverage the results and the rather simple computing structure in [2] to solve the complex control problem at hand. The technique proposed here relies mainly on the establishment of the well-known performance metrics based on time, speed and quality measures, through a contextual extension of the semantics used in the overall equipment effectiveness (OEE), overall throughput effectiveness (OTE), and overall factory effectiveness (OFE). In [2, 6], OFE and OTE are recursively computed from the value of OEE at the lowest (atomic) level of process components. In the case presented in this paper, the manual work is analysed. Therefore, instead of OEE the authors propose to use the Overall Work stand Efficiency (OWE), which provides evidence of how well an operator and a workstation are prepared to perform the assigned tasks.

The main goal of OEE (OWE) adopting model is to have a key performance indicators (KPI) to assess the control process. However it is not so simple because the information must be exchanged between a cyber system (machine) and an operator (human or physical system). KPI is the value that is proposed to quantify the information to be exchanged. We parallel OEE with OWE by changing the semantics of the involved parameters whilst keeping the computing structure invariant. A work stand, which does not deliver sound information on time, is considered as a bottleneck. In [2], the relational database table *cells* hold the parameters (as relational attributes) to compute OEE at the bottom of the recursions in the OTE metrics. The very same computation can be conducted here for each of the work stands in this manufacturing

process. The adaptation of the input data depends on the interpretation (in a formal logic language semantic sense) of the OWE (1) [6]:

$$OWE = Aeff \times Peff \times Qeff \tag{1}$$

where typically:

Aeff – "availability efficiency", captures the deleterious effects due to breaks at work, delays, setups and adjustments,

Peff –"performance efficiency", captures productivity loss due to reduced speed, idling, and minor stoppages,

Qeff –"quality efficiency", captures loss due to defects, rework, and yield.

Noteworthy, this performance metrics method identifies and quantifies losses, enables actors to address their problems and improve the performance measurably. The modified OTE/OWE metric is able to automate the performance measurement and diagnostics. It identifies clearly the system to be improved, the quantum of improvement required to remove the bottleneck and the order in which the system must be improved. In association with the computing infrastructure [2], performance metrics enables generating a systematic and real-time performance control through bottleneck detection at different levels, from the bottom to the top of the system-of-systems tree. In [2], a recursive and tree-based approach is used in view of the distributed control of structured processes, where tiny embedded electronic devices can communicate and act as agents. Agents can receive percepts from the physical world, perform automation actions, and provide interfaces for input and output to human operators. ICT should be integrated into human-in-the-loop cyber-physical systems, and exploited in order to provide natural mappings for timely interactions with such systems [3]. The use of declarative languages, as the database languages, is the key concept and the technology that enables the transformation from stand-alone, monolithic systems to today's complex, distributed, interconnected, interoperable, adaptive and autonomous systems. Both software and people play an equally important part in the systems [4]. In this context, authors have been active in proposing the database centric infrastructure as a grounding framework for CPSs in smart manufacturing. In [5] the use of declarative language algorithms and their implementation on scalable tiny devices are discussed in some detail.

3 Description of the Problem

The manufacturing process of kitchen fronts consists of the steps presented in Fig. 1. In the frame of this work, the control process of the laminated fronts is analysed. The products are accepted to be sent to customers after the lamination process on the basis of the visual control results.

The quality of the visual control is performed by human operators and depends on the training and their own experience levels. They can identify different defects. A part of classification of possible defects, which can be identified on fronts after the process of lamination, are presented in Table 1. A problem appears when different assessments of the same products come from different operators.

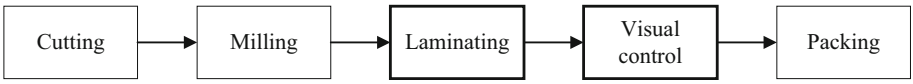


Fig. 1. A manufacturing process of fronts

Table 1. An existing classification of defects that can be identified after the lamination process – a fragment

Symbol of defect	Defect	Defect description
W01	Wrong colour	Wrong colour of laminate glued on the product
W02	Wrong profile	Wrong profile made on the product
W03	Wrong dimensions	A front has wrong dimensions
W04	Wrong graining	Wrong direction of graining
W05	Defect of basic material	A visible pit under the laminate
W06	Defect of milling	Defects in a profile shape
W08	Defect of laminate	A visible defect of material (laminate)
W09	Dots	Dots on laminate
W10	Detachment of the laminate	Laminate is detached from the product
W11	Too little laminate	Not enough laminate to cover the whole surface of the front
W12	Mechanical damage of the laminate	Visible mechanical damage of the laminate
W15	Wrinkles	Laminate is creased
W16	Water stains	Visible water stains on the laminate
W21	Crack of laminate	A visible crack of laminate
…	…	…

One product can be assessed as conforming by one operator, whereas the same product can be assessed as nonconforming by another operator. The problem was identified in a control system analysis. In order to assess the system, the simplified analyses of measuring systems used for the alternative control were performed. 20 products were chosen to be assessed by two operators and one expert. Apart from the operators' efficiency (OE), the frequency of false alarms (FFA) and the frequency of defects nonidentification (FDN) were calculated with the use of Eqs. (2)–(4). They are presented in Table 2.

On the base of the obtained results, it can be said that the control system is not acceptable. Operators are not able to identify defects. Operators assess conforming products as nonconforming. Assessing twice the same products the same operator undertakes different decisions and different operators identify different defects in the same product.

$$OE = \frac{Number\ of\ products\ for\ which\ the\ consistent\ decisions\ were\ made}{Number\ of\ inspected\ products} \cdot 100\% \quad (2)$$

$$FFA = \frac{Number\ of\ decisions\ to\ reject\ a\ product\ which\ should\ be\ accepted}{Number\ of\ decisions\ required\ acceptation} \cdot 100\% \quad (3)$$

$$FDN = \frac{Number\ of\ decisions\ to\ accept\ a\ product\ which\ should\ be\ rejected}{Number\ of\ decisions\ required\ rejection} \cdot 100\% \quad (4)$$

Table 2. Results of the measurement system assessment in comparison to value recommended in [9]

Parameter	The required value	The value obtained by operator 1	The value obtained by operator 2
Operators effectiveness (*OE*)	>90%	100%	90%
The frequency of false alarm (*FFA*) – false alarm rate	<5%	17%	8%
The frequency of defect nonidentification (*FDN*) – miss rate	<2%	100%	62%

Potential consequences of an improper control system can result in the situation when a front with a defect is assembled into a finished product (all assembly operations become non-value added), or a product with a defect is sent to a client (a client will submit a complaint). The costs generated by an improperly working control system can be connected with the costs of processes performed on non-conforming product, the

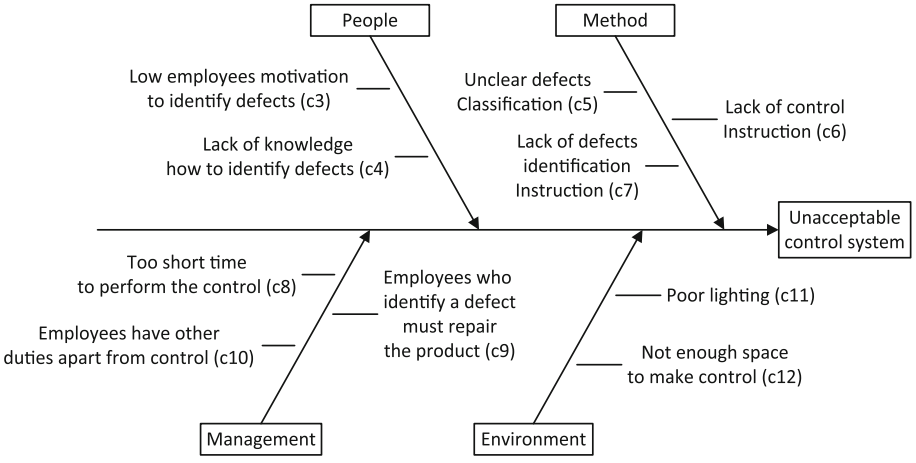


Fig. 2. Ishikawa diagram of unacceptable control system causes

costs of dealing with complaints, or the costs connected with the loss of a good image of the company.

Knowing that the work organization and workplace conditions can influence manual work and visual control [7, 8], the problem was analysed with the use of Ishikawa diagram, and the potential causes are presented in Fig. 2.

Based on the performed analysis, the following recommendations have been presented:

- The level of light intensity that is necessary in the control process should be analysed,
- The defects classification should be analysed and presented in a clear way – all defects should be presented in a graphic form,
- Operators should be trained and their ability to identify defects should be assessed from time to time,
- The adequate amount of time for the control process should be ensured,
- Operators have to be supported by a system which helps them in a fast decision making process.

The information presented in Fig. 2 was the bases for further analysis which are presented in the next chapters of this paper.

4 CPS-Oriented and Agent-Based Supervised Quality and Efficiency Control Structure and Methodology

The Ishikawa diagram of Fig. 2 is a direct graph diagram that connects causes and effects of inefficiencies in several classes of tasks and resources. A supervisor (a manager) should receive timely information about a loss occurring in any phase of the process as well as the information about the nature of the problem. In particular, when quality and operators are involved, the assessments explained in Table 2 provide suitable quantification for a performance metrics approach. With this information transferred to a supervisor (human and/or computing machine), the control can proceed with corrective actions at different levels of the structure. These actions will possibly be different. It is easy and obvious to associate a tree graph to the diagram of Fig. 2, where at different levels we find the nodes and sub-nodes pertaining increasingly to a specific place and actor as we go down the tree. In Fig. 3 the structure of the effectiveness control is shown.

Referring to that figure, the first level (the root) is the whole supervised control system. Below that, we distinguish the four major Ishikawa categories of People, Method, Management, and Environment. At the lowest level, we find the boxes representing the four Ishikawa categories and, inside them, the relative causes (c1, c2, etc.).

By defining such a structure, the flow of information can provide the answers to the problem causes based on the questions: where, who, how, why and when. In our case, the quality of information is relevant. Thus, the overall quality and effectiveness of the

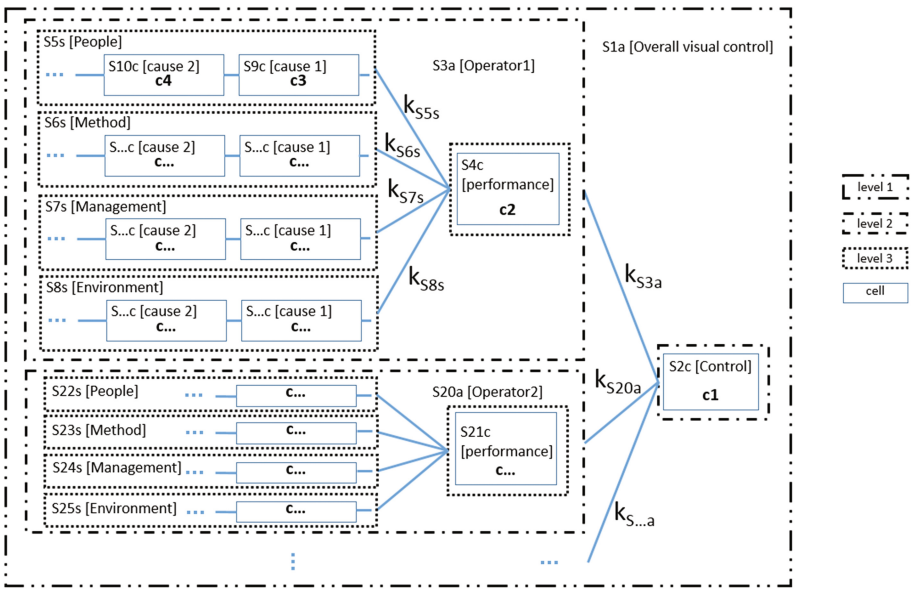


Fig. 3. The structure of the supervised control problem, following the technique in [2]

control must be measured as well. In return, the corrective action goes down the tree at the appropriate level in order to make focused intervention.

The Fig. 3 uses the notations in [2] to express 3 levels of the system-of-systems under performance control. A virtual *assembly* computing structure resides at the highest level (level 1), conveying information from the different operator. The assembly is virtual as it does not assemble physical product part but information flow. At level 2 the operators' virtual *assembly* system is considered. The assembly is still virtual as it assembles information from problems categories not a material flow, as in a typical work in process (WIP).

At level 2, the operators' systems are fed by the four main categories of causes of performance decrease presented in Fig. 2, namely People, Method, Management, and Environment. In turn, they constitute virtual *series* systems of the causes identified under these categories at level 3. This structure enables immediately the recursive computing implemented in [2] and allows the run-time detection of the point of weaknesses in systems performance at different levels in the system-of-systems – they are considered as bottlenecks also in this OWE context. The information quality flowing through is quantified by different effectiveness measurements obtained by the interpretation explained in the following Tables 3 and 4.

It should be noted that OWE/OTE/OFE are pure numbers, so any consistent physical meaning can be attributed to them. They yield a rate between 0 and 1 corresponding to 0 and 100%. The *Aeff*, *Peff* and *Qeff* are between 0 and 1 as well.

Table 3. Interpretation for the effectiveness measurements.

System/cell	OWE/OTE/OFE
S1a: factory level assembly	OFE: overall performance and quality of control
S2c/c1: head cell of the S1a assembly	OWE: effectiveness in collecting and assessing performance information from operators
S3a: operator's assembly system	OTE: performance index for the operator
S4c: head cell of the S3a assembly	OWE: capability of performing a tasks in a proper way with respect to skills and problems
S5 s/S6 s/S7 s/S8 s: series system for *People/Method/Management/Environment* category	OTE: capability of problem solving for *People/Method/Management/Environment*
S9c/c3: cell of cause 1 for people series	OWE: motivation to identify defects
S10c/c4: cell of cause 2 for people series	OWE: lack of knowledge on how to identify defects
S11c/c5: cell of cause 1 for method series	OWE: unclear defect classification
S12c/c6: cell of cause 2 for method series	OWE: lack of control instructions
S13c/c7: cell of cause 3 for method series	OWE: lack of defects identification instructions
S14c/c8: cell of cause 1 for management series	OWE: lack of time for control
S15c/c9: cell of cause 2 for management series	OWE: in-place repair by operators
S16c/c10: cell of cause 3 for management series	OWE: operator's resilience to other duties
S17c/c11: cell of cause 1 for environment series	OWE: operator's performance with regard to lighting level
S18c/c12: cell of cause 2 for environment series	OWE: operator's productivity with regard to space availability

Aeff, *Peff* and *Qeff* can be normalized and interpreted as probability measures in Bayesian sense, which is a useful feature in probabilistic artificial intelligence methods.

Due to the network enabled by the ICT devices, the parameters that make up these coefficients may derive from sensors measurement (e.g. lighting level) or measurements based on human assessments as well. For example, the requested lighting level in the environment (S17c in Table 3) might be the input from an operator (with his own eyes), while the factory standard maximum level is established by the controller (by a factory policy). Therefore, the OWE for c11 is a mixture of the data input from a user and a controller. Similarly, the time available for the quality check is another example: it could be declared by an operator (through the apt interface) and/or measured by a controller for comparison, through a simple web-based SCADA system, enabled by the database technology [5]. In the analyzed case, the information concerning quality comes from people.

Table 4. Interpretation for the OWE components.

System/cell	Aeff	Peff	Qeff
S4c	n/a	n/a	Values of: OE, FFA, FDN in scale (0-1)
S9c/c3	Awareness of the consequences of the defects non detection, assessment made by an operator (0 – not aware of consequences, 1 – aware of consequences)	Speed of transferring information about clients' complaints, assessment made by a manager (0 – vary late, 1 – immediately)	Motivation rate, assessment made by an operator (0 – not motivated, 1 – very motivated)
S10c/c4	Time of actual training received with respect to the time needed to complete training – assessment made by an operator or/and a manager (0 – too short training, 1 – enough long training)	Learning/improvement rate with respect to theoretical expectations – assessment made by an operator or/and a manager (0 – very slowly, 1 – very fast)	Quality of the knowledge received through training (0 – not everything was clear, 1 – everything was clear)
S11c/c5	Time needed to understand the defects classification, assessment made by an operator (0 – too long, 1 –short enough)	Speed of delivering modified defects classification, assessment made by a manager (0 – too slow, 1 –fast enough)	Quality of defects classification, assessment made by an operator (0 – not clear enough, 1 –clear enough)
S12c/c6	Time rate spent for control instructions understanding, assessment made by an operator (0 – too long, 1 –short enough)	Speed rate of incoming new control instructions, assessment made by a manager (0 – too slow, 1 –fast enough)	Quality of control instructions, assessment made by an operator (0 – not clear enough, 1 –clear enough)
S13c/c7:	Time rate spent for defects identification instructions understanding, assessment made by an operator (0 – too long, 1 –short enough)	Speed rate of incoming new defects identification instructions, assessment made by a manager (0 – too slow, 1 –fast enough)	Quality of defects identification instructions, assessment made by an operator (0 – not clear enough, 1 –clear enough)
S14c/c8	Time assigned for control, assessment made by an operator (0 – too little time, 1 –time enough)	Speed rate of delivering of new time standards in case of changes, assessment made by an operator (0 – too slow, 1 –fast enough)	n/a

(*continued*)

Table 4. (*continued*)

System/cell	Aeff	Peff	Qeff
S15c/c9	Time spent on repairing, assessment made by an operator (0 – too long, 1 –short enough to not disturb the control process)	Speed rate of delivering help for an operator in repairing of products, assessment made by an operator (0 – too slow, 1 –fast enough)	Quality of repairing, assessment made by a manager (0 – bad, 1 – good)
S16c/c10	Time rate spent on other duties, assessment made by a manager (0 – too much time, 1 – not too much time)	Speed rate of exchanging an operator when it is necessary, assessment made by a manager (0 – too slow, 1 –fast enough)	Quality of accomplishing the control in case of having other duties, assessment made by a manager (0 – bad, 1 – good)
…	…	…	…

5 Conclusions

The proposed performance-metrics approach possesses the feasibility, flexibility, scalability and low cost required in the CPS vision. It can be implemented and integrated into common ICT infrastructures, through the universality of the database language interfaces used for human and machines input and output [5]. Moreover, it is a barrier breaking (entry-level) solution for SMEs or production where ICT has never been implemented. It can be adapted to any lightweight networking infrastructure and it combines flawlessly a human and a machine in the cyber control loop.

The presented concept of the information management and decision making supported by an intelligence system in the control process can improve performance of the control system and help in the elimination of problems which can influence the process. An operator who identified a problem while performing the tasks on the work stand can transfer the information concerning the process at any time. Human intelligence is used in collaboration with computer systems that may support the distributed or centralized decision-making processes across the heterogeneous manufacturing echelons.

In the future work an architecture as well an interface of the system will be developed with the collaboration with the companies employees. Future work will also address the dynamics of information bottlenecks on the base of data collected from the kitchen front control process. After the implementation of corrective actions, the bottlenecks evolution can be followed through simple optimization of control policies and heuristics, due to the self-similarity features of the problem.

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Integer Linear Programming in Optimization of Waste After Cutting in the Furniture Manufacturing

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Abstract. The study was an attempt to develop the model of a decision controller allowing for simultaneous optimisation of the stock of semi-finished product generated during cutting and cut-out waste. The proposed decision controller was designed to select a suitable cut-out programme to account for such factors as: production orders, current stock of semi-finished product, minimum stock limits, the set limit of rejects. The elaboration concerns application of integer linear programming in multicriteria optimisation in constraint.

Keywords: Simulation · Optimization · Linear programming · Manufacturing system

1 Introduction

Integer linear programming (ILP) is a frequently applied method in optimisation [1, 2]. The method is implemented in a number of research studies, as well as in industrial applications. An example of such an application is optimisation of irregular-shaped item packaging. Certain mathematical models enable optimisation of 3D packaging through combination of two 2D models, in which case the first model optimises packaging of items in the horizontal plane and the latter in the vertical plane [3].

Integer programming is also found in the process of investment portfolio optimisation. Risk and return on investment over a given time horizon can both be subjected to optimisation [4, 5]. Furthermore, among problems of investment process optimisation there are examples of hybrid solutions, which constitute a combination of linear programming and fuzzy logic [6, 7].

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Linear integer programming is successfully applied as a supply chain management alternative to traditional ERP systems. Developed mathematical models enable optimisation of all supply chain resources, including subcontractors realising delivery orders in a multi-level structure [8–10].

High applicability of ILP is furthermore confirmed by the results of a study devoted to scheduling in a river transportation system model [11] or to scheduling of freight transport by rail [12]. Moreover, integer linear programming is also used in the development of sequential algorithms carrying out packaging optimisation tasks [6, 13, 14].

What is more, ILP was successfully employed in optimisation of Intensity-Modulated Radiotherapy (IMRT). Since the problem is NP-hard, there exists no simplified method that would enable solving it, and therefore an iterative method must be applied [15].

Another field where integer linear programming is put to use is the study of stock optimisation by means of cut-out programme adjustment [16]. The solution proposed in this paper is aimed at reduction of semi-finished product after cutting in the furniture manufacturing. The priority defined in the study was to optimise (reduce) the amount of waste produced during cutting furniture boards, at the expense of controlled increase of work-in-process stock, which would account for maximum work-in-process stock limits and defects in production.

The proposed solution employed the PLC method. The mathematical model of the decision controller was developed and its efficiency verified by means of computer simulation.

2 The Problem Presentation and Discussion

Small and medium-sized enterprises with semi-automated production face various problems of technical, functional and social nature [17–23]. Having analysed the given case the management was able to pinpoint the problem that is, according to them, imperative to the competitiveness of the enterprise.

The analysed medium-sized company produces approximately 40 different models of furniture (in six colours) for a large, international sales network. Taking into account two types of fronts (left and right), 480 various elements can be treated as an offer of the company. The company produces approximately 55 thousand of furniture sets a year. Orders for specific types and quantities of products are received every day. Products are also delivered to customers every day. The customer receives products in a dismantled form (packed in a paperboard boxes).

The basic material for production process are laminated chipboards in size $2800 \times 2070 \times 18$. In the first technological operation, the chipboards are cut using the CNC, highly-automated saw - model Holzma HP250. After entering data including dimensions of output elements and number of furniture elements to be cut out – the machine is able to optimize placement of elements to minimize the chipboard waste. However, very often the waste of the cut chipboard is so large that it can be used for producing other elements for future orders. Therefore the main objective – being the aim of the paper – is optimisation is of the cut-out process to minimize both of chipboard

and work-in-process stock, achieved through introduction of cut-out templates for particular furniture elements. As a result the defined task has the character of multicriteria optimization in constraints.

After analysing the whole strategy of production it is worth to notice that for the time being, the enterprise functions in a pull system, i.e. the products are solely "made-to-order." In theory, the advantage of this system is minimisation of inventory of produced goods; however, this frequently involves a longer waiting time for the product. A further investigation into the detailed tissue of the analysed production process reveals the underlying problem, which are divergent aims.

It was observed that when the panel saw carries out cutting programmes that realize only current orders, the percentage amount of waste is higher than when the programme includes the cut-out of cupboard elements not yet in order at the time, which are however added to the programme based on the analysis of previously placed orders, as furniture elements that will be soon necessary in production. The method for the optimization of cut-out waste performed on panel saw consists in controlled, yet entirely predictable increase of semi-finished product stock. The unpredictability of semi-finished product stock increase results from the uncertainty as to when the extra cupboard components will be used.

In the studied case, decisions regarding inclusion of additional cupboard elements from beyond the current order, with a view to reducing the amount of cut-out waste, are taken by an experienced worker. The worker must employ his professional experience, knowledge, the knowledge of the market and hard data on current stock levels of particular semi-finished products (cut-out boards), estimated size and diversity of future orders. Due to the number of factors to account for in solving such a problem, to provide the optimum solution is particularly complicated, as the probability of human error is significantly high.

The purpose of the study is to develop a decision controller based on integer linear programming. The aim of the study was thus simulation modelling of the decision controller that will include the linear objective function and problem constraints, i.e. work-in-process stock limits and established levels of defects in production of particular furniture elements.

3 Problem Cases Formulation and Methodology

The aim of our work is to provide the solution to the problem of cutting furniture boards that would consider the stock limit of cut-out boards and established levels of defects in production. The initial stage of wooden cabinet production consists in process of board cut-out. As mentioned, any cut-out procedure demands specifying the cutting method. The numerically-controlled panel saw comes equipped with pre-installed specialist software for cut-out programme optimisation of currently produced furniture.

Let N denote the set of natural numbers. We are considering the production of $z \in N^n$ of finished products, composed of $y \in N^k$ elements. The value $y = Bz$, where the matrix $B \in N^{k \times n}$ denotes the matrix of average use of cut-out boards, *i.e.* $b_{ij} \in N$, $1 \leq i \leq k$, $1 \leq j \leq n$ denotes the number of type i elements used in the production of one piece of

finished product j. The initial stage of cut-out elements is denoted by $x \in N^k$. Assume that there exist m methods for board cut-out, the matrix $A \in N^{k \times m}$ denotes the matrix of cut-out methods, and $u \in N^m$ denotes the vector of cuts.

Let (Ω, F, P) denote the feasible region and the random vector $\xi = (\xi_1, \ldots, \xi_k) : \Omega \to N^k$ represent defects in production (elements which cannot be used). Let us assume that the random variables $\xi_1, \ldots, \xi_k$ and for $1 \leq i \leq k$ the variable ξ_i is a Poisson random variable with intensity parameter $\lambda_i > 0$.

Presented below are two planning problem cases, which will be used in the simulation. Random integer generator will generate numbers using the uniform distribution, which will represent orders, and defects will be generated by a Poisson random-number generator.

3.1 Problem Case 1

Given the current stock of finished elements, we must determine the optimal vector of cut-out $u \in N^m$ necessary to produce $z \in N^n$ finished products, however, for each element used in production the probability of not performing the task does not exceed the level $\alpha > 0$; therefore, the probability of not completing the order is similarly equal to α. Here follows the stochastic programming problem, which becomes:

$$\min_u \sum_{i=1}^{m} u_i \tag{1}$$

$$\text{subject to: } \begin{cases} u \in N^m, \\ P\left([Au]_i + x_i - \xi_i \geq [Bz]_i\right) \geq 1 - \alpha \text{ dla } 1 \leq i \leq k, \end{cases}$$

where $[Au]_i, [Bz]_i$ denote $i-$ dimensional vectors of Au and Bz respectively.

Given that $p_i = F_i^{-1}(1-\alpha)$ for $1 \leq i \leq k$, where $F_i()$ denotes distribution of a Poisson random variable ξ_i with intensity parameter λ_i, and $p = (p_1, \ldots, p_k)$. Therefore, as an integer programme the stochastic programming problem (1) can be specified as follows:

$$\min_u \sum_{i=1}^{m} u_i \tag{2}$$

$$\text{subject to } \begin{cases} u \in N^m, \\ Au + x - p \geq Bz. \end{cases}$$

3.2 Problem Case 2

The main assumptions are identical as in problem case 1. In addition, given that all elements produced in the future will be good, we include the constraint that the stock levels will not exceed the value of $g \in N^k$. In this case the probability of not exceeding the maximum stock level is not considered. The stochastic programming problem becomes:

$$\min_{u} \sum_{i=1}^{m} u_i \tag{3}$$

$$\text{subject to} \begin{cases} u \in N^m, \\ P\left([Au]_i + x_i - \xi_i \geq [Bz]_i\right) \geq 1 - \alpha \text{ dla } 1 \leq i \leq k, \\ Au + x \leq Bz + g. \end{cases}$$

As an integer program the stochastic programming problem (3) can be specified as follows:

$$\min_{u} \sum_{i=1}^{m} u_i \tag{4}$$

$$\text{subject to} \begin{cases} u \in N^m, \\ Au + x - p \geq Bz, \\ Au + x \leq Bz + g. \end{cases}$$

In Matlab the integer linear programming problem

$$\text{subject to} \begin{cases} x \in N^m \\ Ax \leq b \\ A_{eq}x = b_{eq} \\ lb \leq x \leq ub \end{cases} \tag{5}$$

is solved with the defined function:

$$intlinprog\left(f, intcon, A, b, A_{eq}, b_{eq}, lb, ub, options\right) \tag{6}$$

where *intcon* denotes the vector of integers.

To solve problems (2) and (4) we must first define the vector:

$$f = (1, 1, \ldots, 1) \in N^m, \; g = (50, 50, \ldots, 50) \in N^k,$$

$$lb = (0, 0, \ldots, 0) \in N^m, \; ub = (Inf, Inf, \ldots, Inf) \in N^m.$$

Problem (2) is solved with the function:

$$intlinprog(f, 1{:}m, -A, x - p - Bz, [], [], lb, ub).$$

Problem (4) is solved with the function:

$$intlinprog\left(f, 1{:}m, [-A;A], \left[x - p - Bz; Bz - x + g\right], [], [], lb, ub\right).$$

As seen in the above description, the simulation study was performed with the use of a mathematical model through a parameterised function.

In the simulation the following assumptions were introduced:

1. The matrix of all acceptable cut-out methods is presented in Table 1. As seen above, the total of 40 cut-out methods were included.
2. Each cabinet consists of 4 elements (cut-out boards).
3. There are 2 types of cabinets.
4. The initial number of particular element types in stock is equal to: [12; 40; 2; 30; 10; 0; 1; 22].
5. The vector of constraints g denoting maximum stock levels of each of 8 elements is equal to 50 pieces.
6. The vector of defects occurrence intensity takes the following values: $\lambda = [0.05; 0.02; 0.001; 0.001; 0.03; 0.02; 0.04; 0.06]$
7. The simulation covers 100 consecutive days in the functioning of the production department.
8. The simulation time covers 100 work days of the production system. It is assumed that each day one order is submitted.

Table 1. The matrix of cut-out methods $A \in N^{8\times40}$

Type of element	Cut-out method													
	1	2	3	4	5	6	7	8	9	10	11	12	…	40
Type 1	6	1	1	3	0	2	4	7	5	3	0	0	…	3
Type 2	5	7	7	1	2	3	5	0	2	9	3	6	…	5
Type 3	2	3	0	1	5	0	8	7	6	7	7	4	…	7
Type 4	4	1	0	7	2	0	1	8	5	0	3	0	…	1
Type 5	8	4	4	7	3	3	3	7	5	3	5	1	…	2
Type 6	3	5	0	0	7	4	3	6	0	1	5	8	…	0
Type 7	5	8	8	1	1	2	0	1	2	5	0	8	…	8
Type 8	6	1	0	0	0	5	1	0	3	3	7	0	…	2

4 Results and Discussion

Two simulation experiments were conducted, one for each analysed problem case. Both experiments covered the period of 100 work days of the production system. Each day consisted in performing standard cut-out operations in the number corresponding to the number of orders modelled with the random integer generator.

Presented below are stock levels on the penultimate day of the simulation (day 99). Table 2 shows the stock of particular elements for problem case (1), where no maximum stock limit was set, whereas Table 3 shows stock levels for problem case (2) with the stock limit imposed and set to 50 pieces, with assumed defect levels for particular cut-out boards.

Table 2. Stock of cut-out boards. Day 99. Problem case 1.

No.	Initial stock	Requirement	Restock	Defects	Final stock
(1)	(2)	(3)	(4)	(5)	(6)
1	57	3	7	0	61
2	10	6	20	0	24
3	1	6	6	1	0
4	51	3	5	0	53
5	7	10	4	0	1
6	2	20	20	0	2
7	2	20	21	0	3
8	1	10	10	0	1

Table 3. Stock of cut-out boards. Day 99. Problem case 2.

No.	Initial stock	Requirement	Restock	Defects	Final stock
(1)	(2)	(3)	(4)	(5)	(6)
1	45	3	6	0	48
2	8	6	19	0	21
3	5	6	3	1	1
4	37	3	5	0	39
5	20	10	0	0	10
6	1	20	23	0	4
7	5	20	20	0	5
8	2	10	10	0	2

On day 99 the following orders were placed: for cabinet 1 in the amount of 3 pieces, and for cabinet 2 in the amount of 10 pieces. In the case when stock limit was not imposed on the decision controller, the controller proposed using three boards. One board was cut out according to method 17, and the other two boards according to method 29 (Table 1). Table 2 shows stock levels on day 99 of 100 of simulation.

Rows in the table show particular elements of two cabinets (2 cabinets $\times$ 4 elements per cabinet = 8 elements). The final stock level is obtained from subtraction of required number of boards (current orders) and defects (non-repairable elements) from initial stock, to which made-to-stock elements are added. Considering the numbers of columns, the method for calculation of final stock becomes as follows: (6) = (2) − (3) + (4) − (5). Analysis of Table 2, which shows the solution for problem case 1, shows that elements 1 and 4 exceed the number of 50 pieces. Storing excessive amounts of finished elements is not rational. It can be seen that without setting the limit on the stock, the production process would not be optimal.

Table 3 shows problem case 2 (stock limit set), the decision controller suggested 3 cut out methods for 3 boards numbered 2, 17 and 29 (Table 1). The final stock (column 6) does not exceed the level of 50 boards. In element 3 one defective piece occurred. The controller did not allow for the final stock level to drop below 0, which would in

practice lead to disturbing the continuity of production on account of insufficient numbers of cut-out semi-finished product.

Figures 1 and 2 show the stock of all eight types of semi-finished product (cut-out boards) over the period of 100 days, in two variants, with and without stock level limit of 50 pieces. The red line represents the changes in stock levels with stock limit set (case 2), whereas the blue line shows changes in stock levels with no stock limit set (case 1).

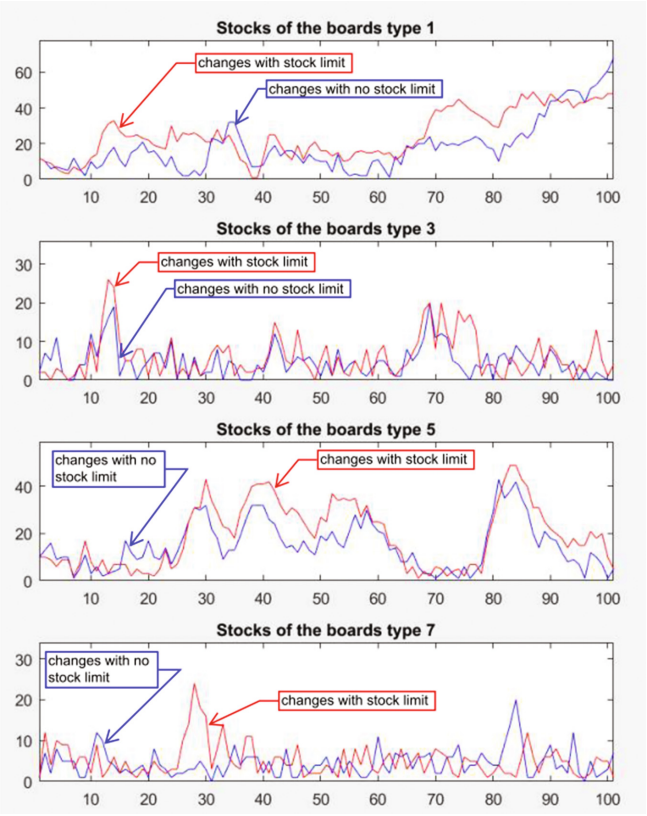


Fig. 1. Stock of cut-out boards over simulated 100 work days of the production system

The diagram clearly shows that when no stock limit was set, the maximum level of stock for elements 1, 2 and 4 exceeded 50 pieces.

What is more, when the decision controller was set to comply with the maximum stock level limit of 50 pieces, none of eight elements exceeded the set limit over the period of 100 work days, which becomes even more interesting given the constraint regarding production rejects, included in the model.

This is particularly visible in the case of elements 1, 2 and 4. When maximum stock limits are inactive, the stock levels at the end of experiment do exceed 50. The limit causes that the stock levels of all eight elements of cabinets was within 0 to 50 pieces.

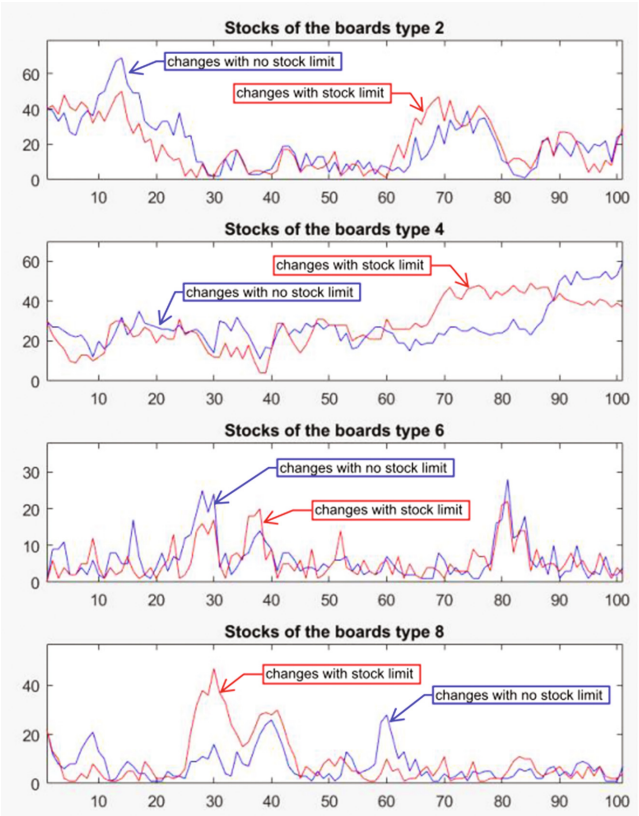


Fig. 2. Stock of cut-out boards over simulated 100 work days of the production system

It can be observed that in the case of numerous elements, the courses of their lines in charts are comparable.

5 Summary and Conclusions

As stated in the introduction, our main objective was to present the concept of waste optimization in the production of furniture at the expense of controlled increase of work-in-process stock limits. The waste is produced during the cut out of furniture boards. The mathematical simulation employed integer linear programming and accounted for the limit of rejects. The mathematical model of the decision support system was developed to carry out multicriteria optimization, i.e. minimization of the stock of semi-finished product created during cut-out of furniture boards and minimization of cut-out waste, including rejects occurring in the production process. Computer simulation was applied in conducting two experiments, which simulated 100 work days of the decision controller.

The first experiment consisted in carrying out a simulation of a cut-out process with no maximum board stock level defined. The second experiment had the maximum board stock level set at 50 pieces, for each cut-out board template. The experimental simulation confirmed the efficiency of the analyzed method. The controller was able to adjust the cut-out programmes according to the maximum stock level and production defects.

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Kanban System in the Flow Control Subassemblies as a Component of Lean Manufacturing

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Abstract. The paper analyses the Kanban system introduced at a company manufacturing multiple types of rotors for electricity-powered engines. The system comprises two loops of Kanban cards: the production card loop and transport card loop. The main assumptions for the system is the capacity minimisation for buffers between operations and streamlining the information flow between individual production cells. The analyses use the 7M, 5S and SMED methods, as well as a combination of the ABC and XYZ classification methods for materials. The introduction of the Kanban system significantly reduced warehouse stocks and improved communication between individual production lines.

Keywords: Logistics production · Lean toolbox · Kanban system · Buffers

1 Introduction

The strategies known as "lean" have been used with growing frequency in management. Depending on the area of application of such strategies, we may speak of lean management, lean office, lean administration etc. J. Womack and D. Jones, known for their research in the area, have even proposed "lean thinking" [1] as a way, a method to eliminate waste and create value at various types of enterprises.

Throughout the paper, however, the notion of lean manufacturing will be used purposefully to emphasise that the analyses performed primarily relate to a company's production functions. Nevertheless, treating an enterprise as a system, the introduction of lean management should be striven at, with lean manufacturing considered a subsystem of enterprise management only, with all the consequences of interrelations among subsystems identified at the enterprise.

Manufacture makes up the main material stream of the production process flow through the company's individual production cells (positions). This flow depends on many factors, of which the structure of the production system has the most definite effect [2].

The common element that combines different approaches to production logistics is property flows. Hence, new concepts and tasks of production logistics arise. As a way to eliminate waste *(muda)* J. P. Womack and D. T. Jones recommend the lean approach (*lean thinking*) by creating a stream of values in the enterprise. In the lean approach, one has to go outside the company in order to look at all the actions that make up the process

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of developing and producing a particular product. Lean may be defined most simply as a process of continuous elimination of waste. Access to large spaces leads to the accumulation of large stocks, which leads to the generation of excess manufacturing in the course of WIP (*Work in Process*). In the terms proposed by M. Rother and J. Harris [3–5], the most important task in manufacturing systems is the maintenance of continuity in the flow of materials, as well as the constant improvement (*kaizen*) of continuity. In relation to supply chains, P. Nyhuis and H. P. Wiendhal [6] state that the primary purpose of production logistics can be determined by the ability to increase supply and the reliability of supply at the lowest possible cost of logistics and production. Currently, there are many methods and techniques that can be used in the production-related activities of the enterprise [7–10]. Hence, proper selection of these (for the enterprise or process) is difficult at times [11–14]. An extensive array of various tools, techniques, methods assisting the *lean* concept was published by J. Bicheno and M. Holweg [15].

It is obvious that from a logistic point of view the appropriate control of the flow of materials within the production system is among the most basic logistical tasks [16–18]. Here, 'appropriate control' means control that guarantees the continuity of the manufacturing processes in accordance with the 7R rules of logistics. In this regard, it is important to properly understand the production process. All customised solutions that contribute to improving the productivity of manufacturing processes may be of help here [19, 20].

The analysis of the specific task of creating a continuous flow considered herein has led the author to propose that the Kanban system should be applied to control the flow of specified subassemblies included in the ready product.

The main idea of the Kanban system [21, 22] consists in the direct control of the flow of materials and control of production process. The method is designed to shorten processing time and reduce stocks, while simultaneously execute the production task in a timely manner. It includes matching the quantities of the products manufactured with number of orders and quality control at each phase of the production process. This is known as a pull-flow and it supports totally eliminating or minimising the use of warehouses between such operations or production lines which depend on one another.

Logistics and production cards are frequently used to discriminate between what is called the sides of the Kanban system. The main objective of those cards is furnishing information on the flow of materials during the production process. A Kanban card displays the identifier of a material reference. It also bears other data, such as the number of parts in a container, reference name, flow path (from where and where to), as well as other data, as needed. Actually, a Kanban card identifies a given batch x of material or product.

Recently, Kanban card circulation has with growing frequency been supported by IT systems, with use of Automated Identification tools (e.g., bar codes or radio tags). The Kanban system should operate according to clearly defined rules:

– each consecutive line in the production process has to initiate the flow from the preceding stand (for this reason, such a system is known as a pull-flow system);
– a product which is not covered by an order in the form of a Kanban card is neither manufactured, nor transported;

– one card only may be assigned to a given product container and the container should contain a fixed number of products, as specified in the card;
– card flow is executed in accordance with the FIFO principle;
– any card has to include unanimous information on the product production venue, destination and storage place.

In the Kanban system, the information flow starts only with a customer's order placement. The direction of that information is opposite to the direction of materials flow in the production process. The signal triggering a production order is sent not to the start but to the end point of a line. The employee operating at the last stand along the line receives a production order for a batch of a given product. The materials necessary for production are then taken (sucked) from the previous stands, where the materials needed there are taken from stands which are closer still to the beginning of the line and so on, thus replenishing the stocks of products forwarded to the next stand. Such a solution enables the flow of materials to be synchronised with the work rhythm at the last stand.

The implementation of the Kanban system requires that, after the mapping of the value flow at the discussed production facility of an enterprise, the following actions should be performed:

– 7M and 5S analysis, SMED implementation (if there is any changeover problem),
– classification of subassemblies used to manufacture the products with: ABC and XYZ methods (classification of order regularity by variability ratio),
– selection of subassemblies to which the JiT will be applied (based on the results of classification combining the ABC and XYZ methods).

Additionally, all parameters necessary to characterise the Kanban system (loops, cards, stocks and operation durations) should be computed.

2 Research Object and Tasks to Be Executed

The object of the research is a production line (at an automotive company), where electric engines and drivers are manufactured for central locks, sunroofs, safety belt stretchers, windscreen wipers, as well as for photocopiers, coffee expresses, hospital beds etc. These engines and drivers are mainly produced on manual or semi-automatic lines. All components used in the production are supplied by external suppliers.

The company also manufactures ready subassemblies, used later to assemble an engine. These subassemblies include rotors, rotor casings and transmission casings. The semi-products are used internally to manufacture engines or sold to external customers. The company's products are assembled in cars of such makes as VW, Ford, Fiat, Land Rover and Mercedes.

The engine production process comprises numerous operations, both manual and automated ones. Production planning for the production line in question is a complicated task. The process requires high precision in the manufacture of both individual subassemblies and the final product. The process is very difficult, as any allowable deviation from the engine predefined dimensions or functional parameters is very little. Therefore,

each product has to be checked frequently. The final operations are engine balancing and testing. Thus it is of utmost importance that rotors be stored for as short a time as possible, because it sometimes happens that workmanship errors are revealed only on the ready engine production line.

The initial analysis of materials flow in the engine production processes has led to the conclusion that the rotor line (ROT_LIN) is among the company's most important strategic units. Basic data concerning the ROT_LIN line is as follows:

– broad range of products (50 variations, known as "references"),
– large number of production orders (several dozen thousands per month),
– frequent changeovers during a single production shift,
– long changeover duration (around 60 min).

The ROT_LIN line products (rotors) are delivered to four ready engine production lines in line with the predefined relations, that is, each production line supports the manufacture of specified engine references.

Problems relating to the execution of production tasks result in:

– frequent shutdowns of all lines (rotor and engine lines),
– generation of excess stocks,

from this in turn there follows: need to modify the system.

For these reasons, the rotor line was selected for optimising materials flow through the implementation of the Kanban system.

This is outlined in Fig. 1.

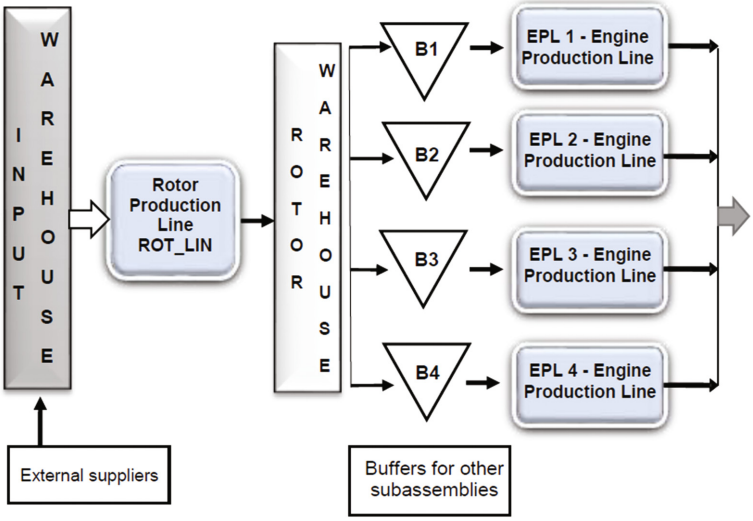


Fig. 1. Chart of the system discussed

The outcome of the implemented measures should include:

- implementation of the Kanban system for these references which should be manufactured according to the Just in Time principle,
- minimisation of stocks at the ROT_LIN warehouse.

A team composed of several people, appointed to execute the project, performed the following tasks:

- Initial tasks (5S, 7M, SMED methods, analysis of references classification with the ABC and XYZ methods for all engine references - data was sourced from the company's database – supported by the SAP system),
- Supplementary tasks (full identification of materials flow – value stream map, computation of parameters necessary to introduce the Kanban system),
- System implementation to the production and control of flow between the rotor line and four engine production lines.

It was further assumed that for references controlled with use of the Just in Time principle an interoperation warehouse may be established to act as a buffer (referred to as the "little warehouse" or M1), while for the other references the previous system may be maintained with the buffer M2.

Figure 2 outlines the suggested system with the references Ri assigned to individual production lines EPLj (j = 1, …, 4).

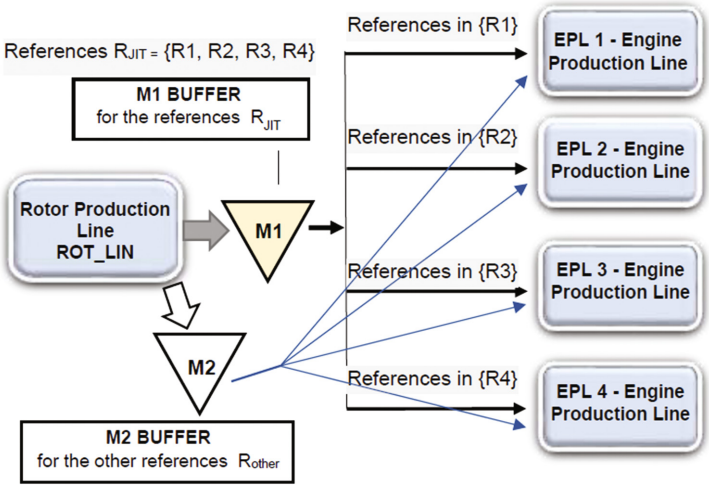


Fig. 2. Assignment of references to individual production lines

The study omits the description of loss analyses, organisation and arrangement with the 5S method, as well as changeover streamlining with the SMED method (the use of external changeover process enabled the line downtime to be shortened from 60 to 15 min).

3 Analysis of Initial Tasks

A very important action along the path to the implementation of the Kanban technique is the preparation of the materials ABC and XYZ analyses supporting the selection of products for which the use of the Kanban system is reasonable. Data necessary for the preparation was sourced from the data base of the company's SAP IT system. The analysis was performed for all 50 products going through the ROT_LIN line. The analysis results (obtained based on the data made available by the company's supplies department) are arranged in tables (ABC analysis results and XYZ analysis results).

The analyses having been performed, a combination matrix for the ABC and XYZ methods was built. The matrix reflects the entire range of the rotors produced (Table 1). The specification set forth in Table 1 was the source of accurate information on the selection of product types for which it would be reasonable to apply the Kanban system. The fields including subassemblies (rotors) which are marked with the combinations AX, AY and BX sourced from the matrix and for which the application of the Just in Time principle is reasonable are highlighted in yellow in the table.

Table 1. Combination of the ABC and XYZ methods.

Forecast accuracy	Subassembly reference					
	A		B		C	
X	473-067	473-755	475-879	472-138	474-175	478-014
	475-451	470-397	476-455	474-252	484-426	
	477-555	480-396	471-171	485-251	480-619	
Y	470-607	474-923	474-923		471-995	
			469-939		474-192	
			475-873		470-345	
Z	476-454		476-454	475-878		
	474-176		479-778	474-987		
			485-885	477-123		

The results of the analysis also supported a further subdivision of the nineteen selected references, such a subdivision designed to synchronise the references with the production process. The ROT_LIN line puts out rotors for four other production lines: EPL1, EPL2, EPL3 and EPL4. Consequently, each product included in the AX, AY and BX groups has to be assigned to a specific line.

Table 2. Assignment of individual subassembly types to receiving lines.

EPLj line	Product (number)
EPL1	477–555, 477–627, 470–607, 474–923, 469–940, 474–252
EPL2	475–451, 475–879, 476–455, 471–171, 472–138, 485–251
EPL3	470–397, 480–396, 470–685
EPL4	473–067, 477–215, 475–382, 473–755

Table 2 sets forth the assignment of products (rotors) disclosed in Table 1 and manufactured on the LIN_WIR line to the engine production lines to which the rotors are supplied.

Following the analyses, a specific solution for the Kanban system was suggested. It was assumed that the production on the ROT_LIN line will be exclusively controlled by Kanban cards:

– production cards – between subassembly little warehouse and the producer line,
– logistics cards – between the customer line and rotor warehouse.

The circulation of production cards is effected in the following way:

– each box has to bear its own card and to be stored together with the card in the buffer at the production line,
– if a given box is collected by a logistics employee, the Kanban card is detached and inserted in a special card holder.

Figure 3 presents the chart of the suggested Kanban solution.

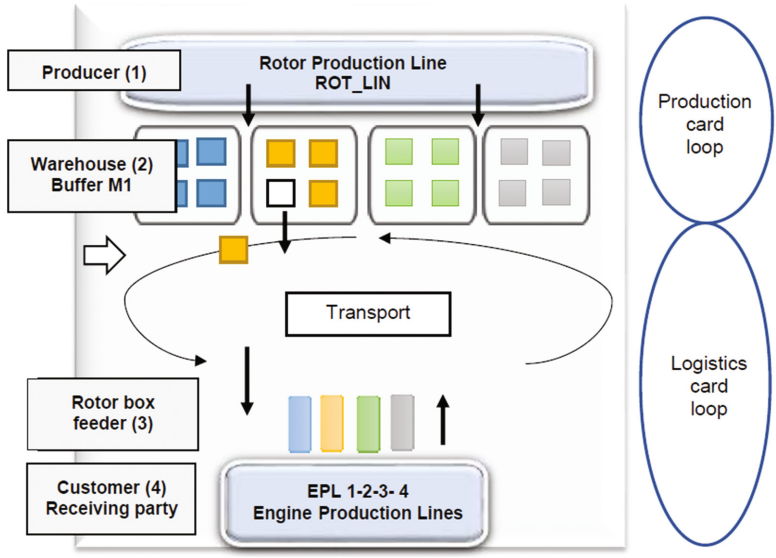


Fig. 3. Suggested solution for the Kanban system

The top part of the figure depicts the semi-product producer (1), that is the ROT_LIN line. Below, the little warehouse (2) is located, called the M1 buffer, between the producer line and the subassembly receiving party (the four EPLj lines). In the bottom part of the figure, there are depicted the rotor box feeder (3) and the customer (4), receiving semi-products manufactured on the ROT_LIN line. This is the last link of the system, where the engine manufacture completes. Appropriate levels and numbers of boxes supplied to the customer (receiving party) lines through placing them on the feeder were determined by computation.

The two card circulation loops are also depicted in the figure:

- production card loop – between the semi-product buffer M1 and the producer line (ROT_LIN),
- logistics card loop – between the customer lines (EPL1, EPL2, EPL3 and EPL4) and the semi-product buffer M1.

4 Efficiency Analysis for the Producer Line

Data necessary for the analysis primarily include:

- efficiency measurements for each of ready product production lines (EPL1, EPL2, EPL3 and EPL4) and the rotor production line (ROT_LIN),
- breakdown ratio measurements for each of production lines, necessary for the determination of emergency stocks.

Stock levels refer to Kanban storages, where semi-products are stored temporarily before being collected by a logistics employee and delivered to the customer line.

Based on the historical breakdown data, the average TRP values (a machine usage rates) are computed. The ratio (TRP) reflects the rate of production equipment usage (effective production) relative to the entire time planned for production.

Based on breakdown data, the average TRP values (a machine usage rates) are computed. Table 3 sets forth measurement results and information on the projected production volumes, as well as on the number of shifts for individual lines.

Table 3. Data necessary to perform analysis.

Line	TRP [%]	TT [s]	Number of pieces per shift	Number of shifts
ROT_LIN	85	17	1,296	3
EPL1	79	74	350	3
EPL2	81	74	350	3
EPL3	77	65	400	3
EPL4	87	96	270	2

The next phase of the analysis required logistics data to be collected, including:

- time of rotor delivery from the ROT_LIN line to the production lines EPLj,
- number of rotors in a single Kanban container.

Based on the analysis, it was decided to store rotors in boxes housing 44 pieces each. The mass of a box with rotors is too large for the box to be stored on the racks used at the company. Therefore, it was suggested that semi-products be stored on special trucks with a capacity sufficient for storing five boxes on a single truck. The trucks are arranged in appropriate driveways. The driveways are marked with relevant numbers identifying the type of product stored and appropriate warehouse area.

The computation of parameters governing the M1 buffer (little warehouse) requires the following data:

- TT times (Tact Times) for each production line: TT_{EPLj},
- TT time for the rotor line: TT_{ROT_LIN},
- number of rotors per box: p,
- changeover time for the ROT_LIN time: $T_{pz,}$
- machine usage rates TRP for the ROT_LIN line: TRP_{ROT_LIN},
- emergency stock for each production line: Z_p,
- number of reference changes on the ROT_LIN during a single production shift: I_z,
- planned production time during a single shift: T_p,
- number of receiving lines: L,
- number of shifts per week for receiving lines: Z_{EPLj}.

The following computations were also performed:

- loss time T_s during reference change on the ROT_LIN line,
- time scheduled for the production of a single batch, based on the efficiency of the ROT_LIN line,
- volume of the production batch P (pieces),
- time T_{deliv} after which the delivery of rotors to the last line commences,
- emergency time for the production using one box for each of *j* receiving lines: T_{emerg_EPLj},
- checking computation correctness against the weekly demand of receiving lines, number of reference changes and the efficiency of the ROT_LIN line,
- aggregate number of rotors which the ROT_LIN line should manufacture within a week for all four receiving lines,
- number of rotors which the ROT_LIN line is able to manufacture within a week in the three-shift work regime; the shift duration has been reduced by the machine changeover time: S_{ROT_LIN}.

Table 4. Capacity of the M1 buffer behind the rotor production line.

Number of reference changes	Production line	Computed capacity [pcs.]	Capacity rounded up to the nearest full truck [pcs.]	Number of trucks
$I_z = 2$	EPL1	644	660	3
	EPL2	644	660	3
	EPL3	729	880	4
	EPL4	508	440	2
$I_z = 3$	EPL1	451	660	3
	EPL2	451	660	3
	EPL3	509	660	3
	EPL4	359	440	2

Tables 4 and 5 set forth the results of computations for different numbers of reference changes I_z ($I_z = 2$, $I_z = 3$ and $I_z = 4$) during a single production shift (assuming 44 rotors per box and 5 boxes per truck, that is a total of 220 rotors per truck).

Table 5. Balance of rotor supply and demand (for one week).

Number of reference changes I_z	Demand for rotors $\sum_{j=1}^{4} S_j$	Output of rotors S_{ROT_LIN}	Balance $S_{ROT_LIN} - \sum_{j=1}^{4} S_j$
2	19 200	21 248	+ 2 048
3	19 200	20 488	+ 1 288
4	19 200	19 694	+ 494

Result analysis was based on identifying the difference between the required demand for rotors from the four receiving lines EPLj and the actual rotor output from the semi-product line ROT_LIN, for different numbers of changeover changes on the ROT_LIN line.

The information triggering the production on the ROT_LIN line is a change in the capacity of the Kanban buffer by a number larger than one production batch. The signal itself is the number of Kanban cards which are to be delivered from the customer lines (EPLj) to the producer.

Table 6 sets forth the parameters governing the M1 buffer, based on the computations performed.

Table 6. Parameters of the designed Kanban buffer.

Number of trucks	Warehouse length [mm]	Number of rotors [pcs.]	Receiving lines			
			EPL1	EPL2	EPL3	EPL4
1	400	220	220	220	220	220
2	800	440	440	440	440	440
3	1200	660	660	660	660	660
4	1600	880				
5	2000	1100				

The quantity of a production batch was computed assuming three reference changes during a single production shift. The computations included:

– the number of production cards in the warehouse circulation for individual lines K_{EPLj},
– the level Kp of signal triggering the production of a given product.

The computations performer lead to a conclusion that it is three reference changes during a single production shift that ensure the best production. For such arrangement, the buffer (warehouse capacity) between the production line ROT_LIN and semi-product receiving party EPLj is the least. In order to harmonise the customer's (receiving party's) line and logistics loops better, additional computation was performed including:

– maximum number P of boxes required during a single shift by each semi-product customer EPLj,
– level Ml (number of boxes) of the buffer at a line depending on the number of logistics loops,
– number Q_i of rotors required by a line during a single logistics loop, according to the TT time,
– number Q_{Ri} of rotors supplied to a line during a single logistics loop.

Table 7 sets forth the results of computations for various numbers of logistics loops during a single production shift.

Table 7. Results of computations for various numbers of loops.

Number of loops	Production line	Level Ml	Output Q_R [pieces]	Demand Q [pieces]	Security level (stock)
3	EPL1	3	132	117	15
	EPL2	3	132	117	15
	EPL3	4	176	133	43
	EPL4	3	132	90	42
4	EPL1	2	88	88	0
	EPL2	2	88	88	0
	EPL3	3	132	100	32
	EPL4	2	88	68	21

The results presented lead to a conclusion that the best solution is to use three logistics loops (during a single production shift). The computations are actually very simple, which might tempt one to conclude that Kanban cards are superfluous. It would suffice to determine the types and appropriate numbers of logistics loops. The cards are very useful, though, for instance in the event of a failure of the customer's line. The established production regime is then corrupted and without Kanban cards the supply of semi-products would continue, unnecessarily crowding the warehouse.

The use of cards supports system self-regulation. If there does occur a shutdown of the customer's line, the logistics employee does not receive a signal in the form of a card which also serves as a production order, thus he discontinues supply of components and the production of a given component on the semi-product producer's line is not triggered. This is of utmost importance if the JiT principle is to be followed (here applied to nineteen references).

5 Conclusions

The paper describes the application of the Kanban system to controlling the flow of semi-products (rotors) during the production of specified products (engines for windscreen wipers). The object analysed comprised the rotor production system (ROT_LIN line) and four engine production lines EPLj (customers, receiving parties). The main

assumption for the system was to minimise the capacities of inter-operation buffers and simplification of the information flow between individual production units.

The implementation of the system enabled rotor stock to be reduced significantly (by 34%). A number of factors contribute to buffer minimisation: from production capacities of the lines involved in the production process for a given product, to data on failures, to the number of changeovers during a shift. The computations performed lead to a conclusion that the greater the number of changeovers per shift, the lower is the level of stock in an interoperation warehouse. However, changeover time is a loss, as it shortens the time of actual production. For this reason, the introduction of the Kanban system had been preceded by the implementation of the SMED method, which reduced the changeover time from 60 min to 15 min. The feedback between the Kanban and SMED methods contributes to the system efficiency significantly.

The computations and analyses performed also support a conclusion that the size of the buffer at a production line may be reduced if a larger number of logistics loops are implemented. Owing to this, subassemblies are collected from the warehouse only if they are actually needed and not to build a stock for, e.g., an entire business day. The implementation of the principle providing for the collection of a given component from the warehouse only if it is actually needed (according to the JiT principle) enhances the capabilities of logistics procedures in the scope of reducing the capacities of raw material and semi-product warehouses.

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Modeling and Analyzing Performance of a Production Unit Using Dynamic Bayesian Networks

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Abstract. The aim of this paper is to formulate a quantitative integrated model of how quality and productivity performances of a production system are interrelated. Indeed, productivity and quality, some of most important objectives of a production system have been studied separately since decades whereas studies are demonstrating a close interaction between them nowadays. Such an integrated model will be beneficial to engineers during design and/or operation stages of the system because it can be used to set up or to assess overall performance measures such as: total production rate, effective production rate, machines availability, inspection policies performance, etc. Dynamic Bayesian network will be used as the underlying mathematical tool to describe the dynamics of the state of the system as they are well suited for the representation of stochastic processes (machine failures, quality failures, etc.).

Keywords: Productivity · Quality · Production system design/Operations · Dynamic Bayesian networks

1 Introduction and Statement of the Problem

1.1 General Consideration and Literature Review

Designing and operating production (or manufacturing) systems is a subject of constant evolution due to issues such as technology changes, social and societal concerns (ergonomic and no danger working environment for employees, labor law changes, sustainable development issues, etc.) as well as business considerations (optimization of production resources capabilities and satisfaction of high quality performance for the products). In general, for industrial engineers in charge of designing and operating such systems, business concerns are the privileged issues though they are, more and more, required to understand the impact of a wide range of processes from row material extraction to disassembly of the obsolete manufacturing resources such as machines. In what concerns business issues, manufacturers must satisfy high productivity and high quality at the same time to maintain their competitiveness, see [4]. Notice that by ensuring high quality and high productivity, manufacturers are participating at the same time to societal and social concerns of manufacturing processes as they minimize waste

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and energy consumption. If the productivity has been for a long time the principal objective of all manufacturing industries, practices in what concerns quality have been spurred by success in automotive industry; but there is little studies that relate productivity and quality [4]. Practices such as jidoka (stop production automatically or manually as soon as something abnormal has been detected, see [13], are argued to improve quality and increase productivity; but this is not true if defects are due to common quality failures as observed in [4]. There are two main kinds of quality failures: common failures and assignable failures [8]. For common quality, failures are independent and are not due to a permanent change in a machine; they can be due to defective row material for instance; as stated in [4], for these failures there is no reason to stop a machine that produces a defective part because the subsequent parts will not necessarily be defective. Most of quantitative literature on inspection allocation assumes these kinds of failures [12]. Assignable quality failures depend on a change in machine so that once a bad part is produced, there is a great chance for subsequent parts to be bad until the machine is repaired, so stopping the machine as soon as a defective part is detected will be profitable. Here, quantitative models for statistical quality control are concerned by finding efficient inspection policies (sampling interval, sample size, control limits, etc. see [16]). A similar problem has been considered in [4] for a two machines production line through a complex mathematical model using Markov chains; here we are more interested by the simplicity and the compactness of the model. In this paper we will be concerned with these kinds of failures and mostly with their impact on the effective production rate of the system. In the following paragraph, we will describe the problem under consideration and its performance measures we will deal with.

1.2 Problem Statement

A manufacturing system transforms row material to products or semi products (that may constitute row material for downstream manufacturing systems in a production line for instance) by using some resources (machines, energy, information, human operators, etc.). A typically manufacturing system (or a production unit) that we will consider in this paper is shown by Fig. 1.

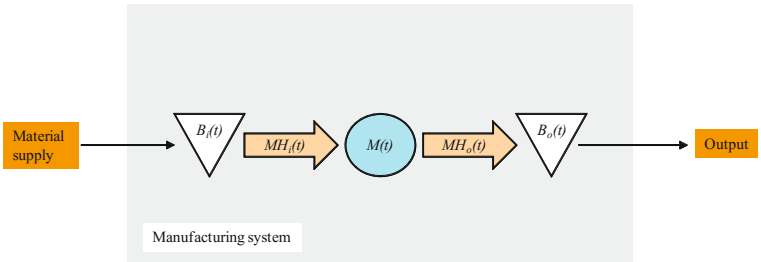


Fig. 1. A typical production unit

The meaning of the components $B_i(t)$, $MH_i(t)$, $M(t)$, $MH_o(t)$, and $B_o(t)$ of this figure that are functions of a discrete time t are given in the following items.

- $B_i(t)$ represents the state of the upstream buffer (buffer where row materials are stocked); it has an influence on the system productivity because the lack of row material will starve the machines and on the quality because defective row material will lead to defective products.
- $MH_i(t)$ is the state of the upstream material handling system (system used to supply machines with row material); the unavailability of this component will block the machine even if this one is ready to operate and there is enough row material.
- $M(t)$ is the state of the machine(s); this is the main component of the system; it has an influence on the productivity and on the quality of products because a possible change in its operation conditions and/or capabilities may lead to defective products.
- $MH_o(t)$ represents the state of downstream handling material system (system used to evacuate manufactured products from the machines); it has the same role and can, most of the time, be the same physical entity as $MH_i(t)$.
- $B_o(t)$ represents the state of the downstream buffer (buffer where manufactured products are stocked); it can block the machine when it is full and so have an influence on the productivity; it is shown also that it has an influence on the quality as it acts as a row material buffer when engaged in a line production system, see for instance [4].

The overall performance of such a system will depend on each of the components described above as well as on what may happen around the system that is its environment and logistic. In this paper, we will focus our attention on the role of main physical resources, namely machines, buffers, material handling systems and inspection process, on the performance of the system. The main component widely studied in the literature in terms of performances of a manufacturing system is the machine (its reliability, its availability, its maintainability and its safety) associated some time with its buffers (see [4]). The principal performance measure considered in this paper is the so called effective production rate (EPR) that is the fraction of non defective produced parts and its relationship with former presented components of a production line.

In this paper, adopting a similar description of the machine state as in [4] we will develop a less complex quantitative model based on dynamic Bayesian network that integrate also material handling systems and inspection operation.

The remainder of this paper is organized as following: in the second section we will present dynamic Bayesian networks (only the concepts that are relevant to our purpose will be presented; for more formal presentation, the reader is invited to consult specialized literature such as [9]); the third section presents the main contribution of this paper in terms of a quantitative integrated model of the problem described previously with an illustrative application in the last paragraph; finally section four concludes the paper.

2 Dynamic Bayesian Networks

Dynamic Bayesian networks [9] derive from an extension of Bayesian networks (see [3, 11] and references therein) that describe probabilistic relationships between variables of a knowledge domain in order to take into account time behavior. Dynamic Bayesian networks (DBNs) are directed graphical models of stochastic processes, see [9], and they generalize Hidden Markov Models (HMMs) and Linear Dynamical Systems (LDSs) by representing the hidden and observed state in terms of state variables, which can have complex interdependencies. The graphical structure provides an easy way to specify these conditional interdependencies, and hence to provide a compact parameterization of the model. A dynamic Bayesian networks is completely defined by two components: its structure that is a directed acyclic graph (DAG) where nodes represent variables and directed arcs represents influential relationships between these variables and its parameters that represent conditional probability density (CPD) functions in the case of a continuous variable (the allowed values of the variable belong to a continuous set) or conditional probability table (CPT) in the case of a discrete variable (the allowed values of the variable belong to a discrete set that will be in general a finite set). A dynamic Bayesian network structure consists of an intra slices directed acyclic graph and an inter slices directed graph; slices represent time instants to describe dynamic behavior of the system. Intra slice graph models the instantaneous relationships of nodes (a Bayesian network) and the inter slice graph represents the dynamics of the nodes. Intra slice parameters are conditional probability density functions and/or conditional probability tables of the corresponding Bayesian network and inter slice parameters represent the dynamics of variables on one hand and their relationships with the variables that influence their behavior on the other hand. The advantage of the Bayesian network model over the Markov chain representation for instance, besides the fact that the model is more compact and/or the possibility to consider the influence of the history up to some complexity, is that the transition matrix P can be learnt (estimated) from the expert knowledge and/or experimental data. BN and DBN have been widely used to assist decision making processes in domains such as: dependability, product heath management and maintenance, see for instance [5–7, 14, 15] and references therein.

In the following section, we will use dynamic Bayesian networks to establish an integrated model of a manufacturing system to be used to assess and to analyze its performance measures or to be used as a support for (reactive) decision making.

3 Production Unit Performance Model Formulation

The purpose of this section is to use dynamic Bayesian networks as underlying modeling tool to establish an integrated productivity and quality model of the manufacturing system described in the introduction section for supporting design and operation decision making. To this end, the components $(B_i(t), MH_i(t), M(t), MH_o(t), B_o(t))$ of Fig. 1. as functions of time t must be more precisely described; we consider discrete time with constant interval $(t-1,\ t)$ so that the meanings of these variables are given by the following items.

- $M(t)$ is the state of the machine at the end of period $(t-1,\ t)$ or the beginning of period $(t,\ t+1)$;
- $B_i(t)$ and $B_o(t)$ are the upstream buffer and downstream buffer levels at the end of period $(t-1,\ t)$ or the beginning of period $(t,\ t+1)$ respectively;
- $MH_i(t)$ and $MH_o(t)$ are the states of the material handling systems at the time instant t.

Each of these components will be considered separately and a model of its behavior in terms of dynamic Bayesian networks established progressively in the subsequent paragraphs until the global model is obtained.

3.1 Model of the Machine

We will consider, as in [4], that the machine at each instant will be either producing good parts, producing defective parts or will be not operating so that its state *M(t)* can take only (exclusively) one of the following modalities.

GP (Good Production): the machine is producing non-defective part.

DP (Defective Production): the machine is producing defective parts but the operator is not aware of that.

NO (Not Operating): the machine is not operating, it is being repaired, waiting for row material or waiting for evacuation of finished product.

The transition to the state NO from states GP and DP has a number of causes: the operational failure of the machine; the starvation of the machine because there is no sufficient material in the upstream buffer or/and the upstream material handling system fails to supply material; the blocking of the machine because the downstream buffer is full or that the downstream material handling system fails to evacuate finished products; the machine is stopped by the operator because defective products have been detected. The transition to GP from NO is due to the reparation of any faults (defective production or/and operational failure) and the transition from GP to DP is due to the loss of quality because of a persistent or assignable quality failures. The dynamics are transitions between time slices, of the machine are then functions of the states of other components: buffers and material handling system (starvation or blocking) and inspection process. The structure of its behavior model over time in terms of dynamic Bayesian network, with Markovian assumption (two time slices), is given by Fig. 2.

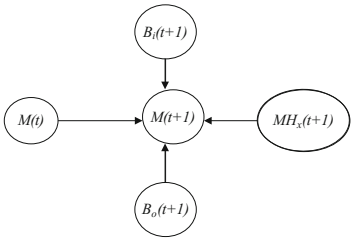


Fig. 2. Dynamic Bayesian network structure of machine dynamics

To completely define the model, we must specify its parameters, namely, the conditional probability table that is the following transition matrix (1)

$$P^M = \Pr\{M(t+1)/M(t),\ B_i(t+1),\ B_0(t+1),\ MH_i(t+1),\ MH_o(t+1)\} \quad (1)$$

Given the states of variables $B_i(t)$, $MH_i(t)$, $M(t)$, $MH_o(t)$, and $B_o(t)$ this matrix will depend on the following parameters:

- λ transition rate of operational failures, the rate of the transition from GP to NO where $\frac{1}{\lambda} = MTBF$ is the mean time between operational failures in the case of constant rate;
- μ transition rate of reparation, the rate of the transition from NO to GP where $\frac{1}{\mu} = MTTR$ is the mean time to repair if the transition rate is constant;
- $\phi = \lambda + \eta$ transitions rate from DP to NO where $\frac{1}{\eta} = MTTD$ is the mean time to get to defective production state;
- γ transition rate from GP to DP where $\frac{1}{\gamma} = MTQF$ is the mean time to quality failure.

We will also consider that the machine produces at the rate ρ. The behavior of the machine is completely characterized when these parameters are supplied by experts or/and by a learning process if one disposes of enough experimental data.

3.2 Model of the Buffers

For the sake of simplicity, we will consider that the sizes of buffers are commensurate to a discrete value so that the upstream buffer level $B_i(t)$ belongs to a discrete set (2)

$$B_i(t) \in \{0,\ \beta,\ 2\beta,\ \ldots,\ n_i\beta\} \quad (2)$$

where β is the required material quantity in order for the machine to operate and the level of the downstream buffer is given by (3)

$$B_o(t) \in \{0,\ \rho,\ 2\rho,\ \ldots,\ n_o\rho\} \quad (3)$$

where $n_o\rho$ corresponds to its capacity. Buffers' dynamics depend on the state of the machine, the state of material handling systems and the logistics. The model of these dynamics in terms of dynamic Bayesian network is given by Fig. 3 where $q_\times(t)$ represents either the quantity of material supplied ($q_i(t)$) or the quantity of finished products demanded ($q_o(t)$) during time period $(t,\ \ t+1)$; $q_i(t)$ and $q_o(t)$ are considered to be commensurate to β and ρ respectively.

The conditional probability tables of these networks are determined by Eq. (4) where $\times$ stands for i or o.

$$\Pr\{B_\times(t+1)/B_\times(t),\ M(t),\ q_\times(t),\ MH_\times(t+1)\} \quad (4)$$

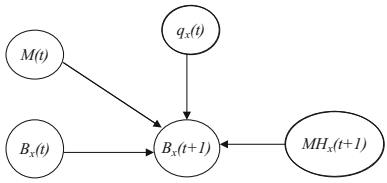


Fig. 3. Dynamic Bayesian network model of buffers dynamics

3.3 Models of the Material Handling Systems

We consider that at each time instant t the material handling systems are either operational (ON) or not operational (OFF), see Eq. (5)

$$MH_i(t),\ MH_o(t) \in \{ON,\ OFF\} \tag{5}$$

with the failure rate and reparation rate given by $\lambda_{MH_\times}$ and $\mu_{MH_\times}$ respectively where $\times$ stands for i or o. Notice that we do not consider the unavailability of material handling systems due to sharing with other manufacturing systems for instance. In terms of dynamic Bayesian networks, the behavior of a material handling system is given by Fig. 4 and its parameter (the transition matrix) given by Eq. (6)

$$P^{MH_\times} = \exp(A_{MH_\times}) \quad A_{MH_\times} = \begin{bmatrix} -\lambda_{MH_\times} & \lambda_{MH_\times} \\ \mu_{MH_\times} & -\mu_{MH_\times} \end{bmatrix} \tag{6}$$

in the case of constant rates. We are now ready to establish, the overall integrated model, this is done in the following paragraph.

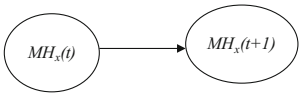


Fig. 4. Dynamic Bayesian network representation of material handling systems behavior

3.4 Model of the Production Unit and Performance Measures

To establish the overall model structure, we just aggregate models established previously for each component; this structure is given by Fig. 5.

Its parameters are those established individually for each component. The main interest of this model is to be used to support activities such as the following ones.

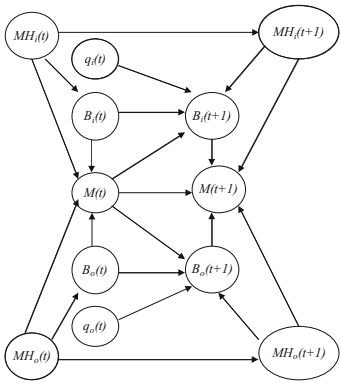


Fig. 5. Dynamic Bayesian network model of the manufacturing system behavior

- Operational management: the model can be used to propagate a change in the system operations conditions (a problem with the row material supply or demand for instance) so to prognostic what will happen in the future in order to react appropriately.
- Design of manufacturing system: by simulating the model some performances measures can be calculated and then be used as performance indicators to choose the appropriate inspection policy, the optimal maintenance policy or the buffers size.

As stated in the introduction section, we will be concerned mainly with the effective production rate (EPR) that is the fraction of good parts that are produced, and the availability of the machine, that is the fraction of the time it will be producing. To calculate these measures, let us denote by (7)

$$\pi_i^M(t) = \Pr\{M(t) = i\} \text{ and } \pi_i^M(\infty) = \lim_{t\to\infty}\left\{\pi_i^M(t)\right\} \tag{7}$$

the probability for the machine state *M(t)* to take its modality *i* at time *t* and the asymptotic value of this probability respectively. Performance indicators namely, total production rate (TPR), non defective production rate (NDPR) on one hand and effective production rate (EPR), and the machine availability (A_∞) on other hand in steady state are therefore given by Eqs. (8) and (9) respectively

$$TPR = \rho\left(\pi_{GP}^M(\infty) + \pi_{DP}^M(\infty)\right) \text{ and } NDPR = \rho\pi_{GP}^M(\infty) \tag{8}$$

$$EPR = \frac{NDPR}{TPR} = \frac{\pi_{GP}^M(\infty)}{\pi_{GP}^M(\infty) + \pi_{DP}^M(\infty)} \text{ and } A_\infty = \pi_{GP}^M(\infty) + \pi_{DP}^M(\infty) \tag{9}$$

By simulating the established model, one can relate these performance measures to operational and design parameters of the manufacturing system such as buffers

capacities, operational failures rate, quality failures rate, inspection process, the effect of material handling systems availability, the effect of logistics,…etc. In the following section, we will consider an example to show the application potentialities of the approach derived in this paper.

3.5 Discussion About the Model and Modeling Tool

States of components considered to take their modalities in a discrete set may be not realistic in practice; for instance a machine may be functioning in a continuously degraded mode instead of being down at once. In terms of size and in theory, modeling process presented in this paper is not limited in the number of components; but in practice and for simulation purpose, one can be confronted to some limitations. In this perspective, authors of this paper and their colleagues are actually developing a framework to deal with large scale systems based on object oriented paradigm and mainly on the object oriented Bayesian paradigm [5–7]. Roughly, in this paradigm, each component (input buffer, machine, output buffer, material handling system) described in the production unit, may constitute a class that can be instantiated to represent a particular corresponding component in a large scale system in practice.

In terms of drawbacks related to modeling tool, obviously Dynamic Bayesian networks convey those common to any modeling tool that necessitate learning and/or expertise. Indeed, in general registered data are not enough nor expert knowledgeable enough to perform model and/or parameters derivation with sufficient confidence.

Nevertheless, dynamic Bayesian networks, because of their capacity to represent compactly a large scale system constitute a very interesting modeling when one is confronted to deal with large scale and uncertain system; uncertainty which is pervasive in practical situations. The modeling approach adopted in this paper at a production unit level, is to clearly consider main components and to establish their behavior models in terms of dynamic Bayesian networks with the underlying idea that if one component not considered is added at any time in the production unit, this will not change drastically the established model. In such situation, modeling task is reduced to modeling separately each component of a system and establishing the interface or interactions among components; in terms of dynamic Bayesian networks this task of interactions is mainly related to parameters or conditional probability tables or probability density functions specification. In terms of possible implementation into an intelligent system supporting the manufacturing company, different possibilities can be envisaged: developing one's own intelligent decision support software based on the developed model; implementation of the model in an existing platform; Implementing the developed model using existing software such as Netica [10], Hugin Expert [2], or Bayesia Lab [1] to name few and interfacing them with one own intelligent decision or design platform.

3.6 Illustrative Application

To illustrate the modeling approach considered in this paper, let us consider a manufacturing system that is constituted by a machine, a material handling robot that supply material to the machine and evacuate the finished parts from the machine to convey it

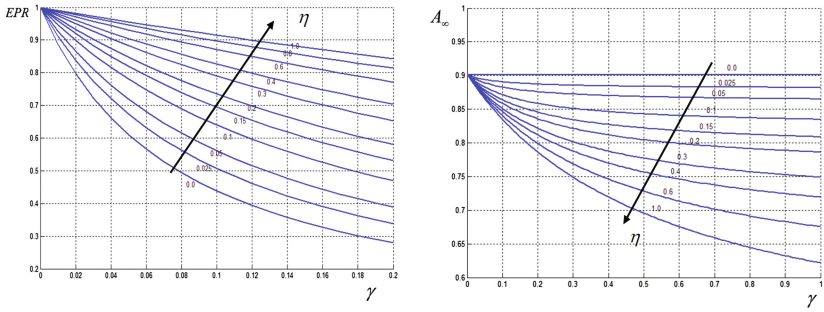


Fig. 6. Effective production rate (EPR) and machine availability (A_∞) versus η and γ for the considered application with $\lambda = 0.03$, $\mu = 1$, $\lambda_R = 0.01$ (robot failure rate) and $\mu_R = 0.2$ (robot reparation rate).

to the inspection post. Because of the lack of space, we will not enter into details and give results only in the case of infinite buffer size that is the machine is never stopped because of lack of row material or because of lack of place for a finished product. The key indicators EPR and A_∞ are presented on Fig. 6. for some configurations of parameters.

Figure 6 shows the behavior of the effective production rate and machine availability with regard to the parameters η and γ. We notice that the effective production rate increases when η increases meaning that when the detection rate is high, almost all what is produced will be non defective as the machine will be stopped as soon as it undergoes defective production; given a detection rate, the effective production rate decreases when the quality failure rate γ increases, which is normal because the machine will be transiting to defective production state without detection. Conversely the availability rate of the machine A_∞ decreases when η increases because when the detection rate is high, the machine will be stopped frequently reducing by the way its availability. This Fig. 6. can be used to design a manufacturing system to ensure some effective production rate and some availability by making a trade-off between the qualification of the inspection operator whose skills will influence the detection rate η and the features of the manufacturing system that impact the quality failure rate γ. This model can also be used to derive some operating policies in the case where there is no continuously inspection, that is $\eta = 0$; knowing that the machine will inevitably undergoes the defective production state, one can decide to periodically stop the machine for inspection and the question will be how long should one let the machine operate before stopping it. This time period can be determined by simulation by considering that the machine must be stopped whenever the probability $\pi_{DP}^{M}(t)$ for the machine to be in the state DP exceeds some threshold.

4 Conclusion

An integrated model that relates quality and productivity performance measures of a manufacturing system was presented in this paper. The novelty is that, by using dynamic Bayesian networks as the underlying mathematical tool, the interactions between different components and processes (material handling system, machines and inspection process) of a manufacturing system are compactly and graphically represented. Furthermore, the use of dynamic Bayesian networks facilitates the inference process that permits to calculate steady state performance measures such as the effective production rate, the availability of the machine. The established model can be used as a decision support tool for the purpose of design and/or operations management for a production unit because it relates attributes related to the quality (detection rate of defective part, quality failure rate, etc.) and those related to the productivity (operating failure rate of the machine and material handling system). The established model can also be used to support reactive decision process by simulating and analyzing the transient response of the system with regard to a change in its operating environment.

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Modelling and Forecasting the Sludge Bulking in Biological Reactors of Wastewater Treatment Plants by Means of Data Mining Methods

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Abstract. The bulking of active sludge in treatment plant bioreactors occurs very often in communal wastewater works what leads to worsening the abilities of sludge sedimentation and the efficiency of works operation. Because of that there is useful and suitable to model and predict the sludge bulking events in order to take some counteractions. In the paper the data mining methods of Support Vector Machines (SVM), Boosted Trees, Random Forests and Multivariate Adaptive Regression Splines (MARS) have been used for modelling and forecasting the sludge bulking events. By the calculation the measurement data series from 4 years concerning the physical and chemical parameters of wastewater flowing into the treatment plant investigated and the technological parameters of the plant bioreactor were used. The calculation results show that the best sludge bulking model containing the best prediction ability has been received by the MARS method and on another side the worst models have been generated by the Random Forests method.

Keywords: Mathematical modelling · Data mining methods · Sewage treatment processes

1 Introduction

One of the most used sewage treatment technologies is the active sludge method in which the elimination of biogenic compounds from the wastewater occurs on the surface and inside of the sludge flakes as a result of biochemical processes of assimilation and hydrolysis. After that the wastewater is directed into the secondary clarifies of the plant in which the sludge flakes are separated from the clarified sewage in the wake of sedimentation. But often this separation process is disturbed by action of filamentous bacteria contained in the sludge or by irrelevant process operation and then the sludge bulking effect arises [1–5]. The sewage bulking extends the sewage sedimentation time, causes an increase of concentration of suspended matter and Carbon compounds in the

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sewage outflow and creates problems by the processing of surplus sewage. The troubles resulted of the wrong sewage sedimentation make difficult the operation of treatment works and because of that several research works are done in order to explain the phenomenon of sewage bulking and to model it and forecast in case of real objects [6–11]. The ability of sewage sedimentation is estimated by calculating the Volume Sewage Index (SVI) which is the relations between the volume of sewage compressed by 30 min in Imhoff funnel and the dry mass resulted from it. The active sewage sediments well when its SVI does not exceed the value of 150 ml/g [12].

To forecast the Volume Sewage Index the auto-regression models and neural networks of MLP (Multi-Layer Perceptron) type are commonly used [13] although hierarchical and probabilistic ANN are applied sometimes either [14, 15]. The models received while using the MLP methods are not satisfied for the obtained coefficients of correlation between the model outputs and measurements data are relatively low. The SVI value is also calculated with the use of variables concerning the sewage amount Q and its quality (described by BOD_5, COD, pH, concentrations of total Nitrogen, Ammonium and Phosphorus, by temperature and concentration of dissolved Oxygen) as well as the bioreactor parameters (activated sludge concentration and the substrate load). Then the hybrid models are used being the connection of the self-organizing neural networks and the probalistic ones [14]. In this case the calculated correlation value is rather high on the level of 0,90 but the possibility of models calculation is restricted by the lack of available data. An example of a hybrid model of SVI is given in [16] in which a genetic algorithm to calculate the weight coefficients in the neural network of RBF type (with Radial Basic Functions) have been used. The use of the algorithm improved essentially the estimation of the network parameters compared to the classical MLP networks what resulted in better prediction features of the models received.

But there is a trouble in creation of more complicated neural hybrid models to predict the Volume Sewage Index for complicated numerical algorithms must be also used to do it and their exploitation in practical applications is difficult. Then there is more practicable and useful to look for statistical method of modeling which would be effective and relatively simple and could be easy by the works technologist.

An overview of literature shows that the methods of Support Vector Machines, Boosted Trees, Random Forests and Multivariate Adaptive Regression Splines have not been used until now to model the sludge bulking although they were already used for modelling processes occurring in the treatment plant technological objects like forecasting energy or biogas consumption, concentration of global suspension, reduction of biogenic compounds etc. [17–20].

In the paper the above mentioned data mining methods have been applied to model and forecast the Volume Sewage Index. To calculate the models the data concerning the amount and quality of sewage inflowing the treatment works, the temperature, pH and sewage concentration in biological reactor have been used. The data were gained in the communal works in the time period 2012–2016.

2 Object of Investigation

The object investigated is the communal wastewater treatment plant owns by the community of Sitkowka-Nowiny and located in East-South of Poland. The sanitary wastewater is coming to the plant from the distribution wastewater network operating the city Kielce and the neighbour communities Sitkowka-Nowiny and Maslow. The nominal efficiency of the works equals to 72.000 m^3/day by the ENI (Equivalent Number of Inhabitants) value being equal to 275.000.

The raw wastewater is mechanically pre-cleaned on the stairs grids and in the ventilated sand traps with separated fat removal. Then the wastewater is pressed into 4 preliminary clarifiers from which the separated sediment is directed into the pump works of secondary sediment. In the following the wastewater flows from the mechanical plant part into the biological one. Firstly it reaches the chambers of preliminary denitrification into which the active sludge is recirculated. There a partially removal of Nitrogen compounds from the wastewater occurs. Then the wastewater is directed into the dephosphatation chambers where the phosphorus compounds are eliminated. The key element of the treatment works is the biological reactor with separated chambers of nitrification and denitrification in which the final elimination of contaminations from the wastewater is realized. Afterwards the sewage with the sludge together flow into 4 secondary clarifies where the sludge falls down and the wastewater clarified goes into the river Bobrza being the final sewage receiver.

On the treatment works a monitoring system is installed that records from 2012 weekly measurements concerning COD (Chemical Oxygen Demand), BOD_5 (Chemical Oxygen Demand), TN (Total Nitrogen), NH_4 (Ammonium), TSS (Total Suspended Solids), TP (Total Phosphorus), IO (Volume Sewage Index) and daily measurements concerning Q (raw wastewater inflow), pH, sludge temperature (T_{sl}) and sludge concentration (MLSS) in the bioreactor and the Oxygen concentration (DO) in its nitrification chamber as well as the amount of coagulant PIX that is handed out to the wastewater.

3 Description of the Modeling Methods Used

For modeling the Volume Sewage Index SVI the methods of Support Vector Machines (SVM), Boosted Trees (BT), Random Forests (RF) and Multivariate Adaptive Regression Splines (MARS) have been used. The calculations were done using the measurements of Q (sewage inflow), of COD, BOD_5, NH_4, TN, TSS and TP (physical and chemical parameters of sewage inflowing), of pH, T_{sl}, MLSS and DO (parameters of biological reactor) and also of PIX.

The sludge parameters T_{sl} and pH create an environment that determines the speed of biochemical processes occurring in the wastewater. The temperature influences the growth of bacteria, among them of filamentous bacteria creating the sludge flakes in the sewage suspension. An optimal range of pH values in the chambers of activated sludge is between 7,0 and 7,5 and if pH values are under 6,0 then fungus organisms develop in the sewage which cause the sludge filiform bulking. The variables COD/BOD_5, NH_4^+/TN, TP are sources of Carbon, Nitrogen and Phosphorus for the sludge

microorganisms and they decide about the sludge growth and condition. A big content of carbohydrates and low concentration of nutrients in the wastewater give rise to the sludge bulking. The sludge amount in the bioreactor chambers is determined also by TSS and MLSS parameters and their values are influenced essentially by the value of sewage inflow Q [21, 22]. At last the introduction of PIX into the works chambers influences either the process of sludge sedimentation [12] and because of that PIX as well as the above mentioned parameters have been taken as inputs data by preparing the SVI models and predictions.

By the models calculation the available data sets have been divided into teaching and testing subsets in the percent proportions 75:25. All data have been also normalized using the formula [23]:

$$\bar{A}_i = \frac{A_i - \min A}{\max A \; - \; \min A} \tag{1}$$

where: $\bar{A}_i$ – normalized value of *i-th* element in data set A, A_i – measured value of *i-th* element in A, max A – maximal value of all elements in A, min A – minimal value of elements in A.

The SVM method belongs to the methods developed by Vapnik [24] initially for classification tasks only and in the following also for the regression ones. The relations occurring between the model output and its input variables are often nonlinear and because of that in the method a nonlinear transformation from the N-dimensional features space into K-dimensional one is conducted in which $K > N$. In the paper to forecast the SVI variable the SVM method regression oriented have been used containing the radial kernel function whose aim is to minimize the following functional:

$$\sum_{i=1}^{m} \frac{c}{m} \left| y_i - f(x_i) \right|_{\varepsilon} + \frac{1}{2} \cdot ||f||_k^2 \tag{2}$$

where: $|y_i - f(x_i)|_\varepsilon = \max\{0, |y_i - f(x_i)| - \varepsilon\}$, ε – admissible error value, $||f||$ - norm of function f in Hilbert space, c – constant defined experimentally depending of ε, m – number of elements in the teaching data set, $f(x_i)$ – value of function $f(x)$ in x_i where f has got the form:

$$f(x) = \sum_{i=1}^{N_{sv}} \left(\alpha_i - \alpha_i^{'} \right) K(x, x_i) + w_0 \tag{3}$$

in which: w_0 – constant term; N_{sv} – number of support vectors depending of c and ε; α_i, $\alpha_i^{'}$ –Lagrange multipliers; $K(x,x_i)$ – kernel function with radial basic functions [18].

The BT method is an implementation of stochastic method of gradient boosting commonly used while solving classification and regression tasks [25]. The main idea of the method consists in generation of series of decision trees in such the way that each following tree is used to determine the rests produced by the earlier one. The calculations performed show that by the solution of many estimation and prediction problems the

forecasts received by means of Boosted Trees are better than these ones obtained by using only individual trees.

The RF method has been proposed by [26] and it is a development of the bootstrap method [27]. On the first stage of RF method the training set consisting of n elements is sampled k times with the admission of repetitions (the training set elements mean the records containing p values of input variables and 1 value of the model output in time $i = 1,\ldots,n$). The sampled k subsets consist of the same vectors as the teaching set and a standard recommendation while solving regression problems is drawing the number of p/3 records to determine each subset. In the following regression trees are created basing on k sets received. As a result a random forest consisted of k trees is determined and for each tree a prediction of the variable modelled is calculated. The closing prediction of the variable being the result of the whole model is calculated as the arithmetical mean of all individual predictions of the single trees. The process of creation of following k subsets from the earlier ones and of calculation of new individual and closing predictions is continued until the error coefficients defined for the modelling reach their stated value.

The MARS method is one of numerous numerical tools used for solving regression problems [28]. It is an extension of the classical approach applied in previously methods for proceeding the input data during calculation of mathematical models. In the classical approach the independent input variables are treated uniformly and in the MARS method the value ranges of the predictors are divided into subranges in which independent variables have got different impacts on the phenomena investigated. The boundaries of subranges are defined using the threshold values (t). The predictor values are divided into the values that are lower and higher than the threshold values t_i. This is performed by means of a basic function which has the following form:

$$h(X) = \alpha_i \cdot (\max(0, X - t)) \tag{4}$$

where: $h(X)$ – vector of the basic functions for individual variables (x_i) for which the following condition is satisfied:

$$x_i - t_i = \begin{cases} x_i - t_i;\ dla\ x_i > t_i \\ 0;\ dla\ x_i \le t_i \end{cases} \tag{5}$$

In the MARS method, the regression relation is described by a spline function obtained from a linear combination of the product of the basic functions and appropriate weight coefficients. The function can be written as follows:

$$f(X) = \alpha_0 + \sum_{m=1}^{M} \alpha_m \cdot h_m(X) \tag{6}$$

where: $X = [x_1, x_2, \ldots, x_i]$ – vector of input data, α_m –weight coefficients, h_m – basis functions.

To calculate the values of the model parameters, Friedman [30] developed a special algorithm that allows the search of observations to establish threshold values. To assess the prediction ability of the calculated SVI models the following coefficients have been applied:

– average unconditional error:

$$MAE = \frac{1}{n} \cdot \sum_{i=1}^{n} \left| y_{i,obs} - y_{i,pred} \right| \tag{7}$$

– average conditional error:

$$MAPE = \frac{1}{n} \cdot \sum_{i=1}^{n} \left| \frac{y_{i,obs} - y_{i,pred}}{y_{i,obs}} \right| \cdot 100\% \tag{8}$$

– correlation coefficient:

$$R = \frac{\sum_{t=1}^{n} (y_{i,obs} - \bar{y}_{obs})(y_{i,pred} - \bar{y}_{pred})}{\sqrt{\sum_{t=1}^{n} (y_{i,obs} - \bar{y}_{obs})^2} \cdot \sqrt{\sum_{t=1}^{n} (y_{i,pred} - \bar{y}_{pred})^2}} \tag{9}$$

where: n – number of elements in the data set, $y_{obs,\,obl}$ – measured or calculated value of SVI, $\bar{y}_{obs,pred}$ – average value of the measured or calculated SVI.

4 Modelling results

On the first step of modelling for the data sets available their variability ranges, i.e. the average, minimal and maximal values of the parameters characterizing the quality of the wastewater inflowing and the operation of the biological reactor have been determined.

From Table 1 results, that in the time period investigated 2012–2016 the parameters concerning the sewage inflow quality, i.e. the concentrations of sewage inflow contaminations (BOD_5, COD, TN, NH_4^+, TP), the values of sewage inflow Q, of its temperature T_{sl} and of pH have been changed in big ranges. As a result also the parameters characterizing the bioreactor work, like MLSS, TSS, DO were changing essentially. This guided to a big variability of SVI values and the analysis of the whole data series shows that with the time passing the sedimentation ability of activated sludge was gradually deteriorated and there arose a tendency to the sludge bulking. Using the data mentioned mathematical models of Volume Sewage Index (SVI) by means of the MARS, SVM, RT and BT methods have been calculated (see Table 2). Analysing the results obtained one can say that SVI model calculated by SVM method is much more better than the models received by RF and BT methods and this is to notice while using the teaching data series as well as by the testing data.

Table 1. Ranges of variability of parameters describing the quality of the sewage inflow and of bioreactor work.

Variable	Minimum	Average	Maximum
Q, m^3/d	32.564	40.698	86.592
T_{sl}, °C	10	15.9	23
pH	7	7,6	8,1
MLSS, kg/m^3	1,97	4,26	6,59
BOD_5, mg/dm^3	127	309	557
COD, mg/dm^3	384	791	1250
TSS, mg/dm^3	126	329	572
TN, mg/dm^3	39,9	77,7	124,1
NH_4^+, mg/dm^3	24,4	49,31	65,9
TP, mg/dm^3	4,3	7,8	12,6
DO, mg/l	0,55	2,56	4,25
SVI, ml/g	95	170	331

Table 2. Results of modelling SVI index by means of the MARS, SVM, RT and BT methods.

Method	Model teaching			Model testing		
	MAE, ml/g	MAPE, %	R	MAE, ml/g	MAPE, %	R
MARS	6,61	3,72	0,980	6,33	3,69	0,970
SVM	8,69	4,50	0,972	8,75	5,00	0,919
RF	25,64	15,00	0,781	24,79	13,62	0,754
BT	17,42	9,60	0,854	16,27	9,44	0,840

In case of the SVM model the MAE and MAPE error values calculated for testing data are 5% and 8,75 ml/g respectively and the correlation coefficient R is equal to 0,919 and there is to emphasize that the results got for this kind of data describe the model quality better than the results received for teaching data set.

There is also to see from Table 2 that the best modelling results have been got for MARS model although they are only slightly better than by the SVM model (MAE = 3,69%, MAPE = 6,33 ml/g, R = 0,97). This means that these both models are comparatively good and they are much better than the RF and BT models for which the calculated values of MAE, MAPE and R are equal to 24,79%, 13,62 ml/g, 0,754 and 16,27%, 9,44 ml/g, 0,840, respectively.

The modelling results presented here for the MARS method are similar (R = 0,97) to the results received by Bagherii et al. [16]. To model the Volume Sewage Index (SVI) those authors have been applied the ANN method and as the input variables they used the data series of COD, TN, DO, TSS, MLSSV, pH and T_{sl}. Slightly better results (R = 0,99) they got using an ANN structure modified by means of a genetic algorithm of optimization. A worse fitting of the SVI model to the measurements (R = 0,95) was

reached by Luo and Zhao [22] who in their calculations applied also neural networks and as the model inputs they used the following parameters BOD_5, COD, TN, NH_4, TP and MLSS, pH, T_{sl} describing the sewage quality and the activated sludge chambers operation, respectively. The modelling results obtained in this paper are similar (regarding the MAPE error equal to 5%) to the results got by Han and Qiao [14] who using a modified ANN method have been considered only the following input variables Q, BOD_5, COD, TN, DO and pH.

The graphical visualization of the SVI modelling results received by the MARS, SVM, BT and RF method is shown in Fig. 1.

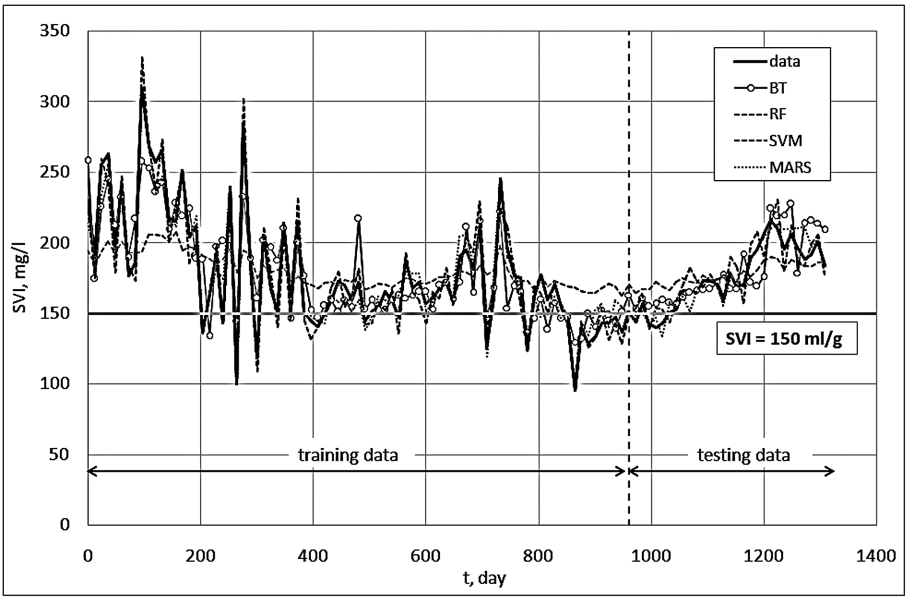


Fig. 1. Measurements and calculation results of SVI modelling done by means of BT, RF, SVM and MARS methods.

From Fig. 1 follows that in the analysed time period the values of the investigated SVI parameter had fallen many times below the accessible level of SVI = 150 ml/g what shows on the worsening of ability of sludge sedimentation what led to the sludge bulking. This phenomenon is of strong nonlinear character and this nonlinearity justifies the usefulness of application of the presented data mining methods for modelling and forecasting Volume Sewage Index (SVI).

5 Conclusions

The bulking of activated sludge occurs often in the sewage treatment processes and it weakens the sludge sedimentation. As a result the worsening of the sewage clarification process follows and also some problems with the activated sludge processing arise. The

indicator showing the event occurrence is the Volume Sewage Index (SVI) and because of that modelling, simulation and prediction of this variable is important for the operators of sewage treatment plants making possible undertaking of counteractions improving their management and exploitation.

The conducted investigations show that for modelling the Volume Sewage Index while using as the model inputs the wastewater inflow Q, the parameters of the sewage quality COD, BOD_5, NH_4, TN, TSS, TP and of the bioreactor operation MLSS, pH, T_{sl}, DO and also the added PIX coagulant, the parametric methods MARS, SVM, BT and RF can be successfully applied. The results of calculations show that the best features of SVI forecasting have got the models computed by the MARS method and on the opposite side the worst forecasting results have been received by means of the RF models.

There is also to underline that the modelling results got here by MARS and SVM methods are comparable with the results receiving by other authors by means of ANN methods. Those other results have been obtained for other treatment works and using neural networks with structures appropriately modified what resulted in minimizing the prediction errors [14, 16]. One can say then that the parametric methods of Multivariate Adaptive Regression Splines (MARS) and of Support Vector Machines (SVM) can be used to model and forecast the Volume Sewage Index (SVI) alternatively to modified neural networks and their advantage against the ANN methods is their relative simplicity and facility of use.

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Modelling and Recycling-Oriented Assessment of Household Appliances

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Abstract. The paper looks at the recycling-oriented analysis of selected household appliances in the CAD 3D environment, carried out on the basis of recycling-oriented product models, as a form of briefly-discussed eco-design. The recycling-oriented product model (RmW) and measures of recycling-oriented product assessment are explained. A software tool facilitating the creation of recycling-oriented models for selected products and calculation of assessment measures for the analysis are presented. Two examples of recycling-oriented product assessment with the use of the developed method and tools are shown.

Keywords: Eco-design · Product modelling · Agent technology

1 Eco-Design

Engineering design is a process which uses scientific methods, technical data and creativity of the designer to define the mechanical structure of a device or system to ensure the most economic and efficient performance of the predefined functions [1]. According to Tarnowski [2], the design process is an advanced sequence of actions which requires a substantial investment of money and time and expensive equipment, and lasts in time. Bąbiński [3] says that the design process is carried out by a design system, defined as a team of designers and the tools used [3]. The design system converts the input (data, assumptions) into the output (products of the design process). For a new product, the input is provided in the form of the requirements to be met by the product. The output is the design documentation. For updating product designs, the input is the data on the existing product (e.g. the design documentation), whilst the output is, as in the case of new designs, the (updated) product design documentation. According to the above definitions, the design process is complex and has a significant place in the product life cycle. The investment made at the stage of preparation of a product for manufacturing forms a material part of the total product costs and is a strong determinant of the costs of manufacturing [4]. Research [5] shows that leveraging new technologies brings the best results when they are implemented at early phases of product development, i.e. at

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the design phase. Therefore, early incorporation of environmental aspects into the design process is becoming important nowadays. The concept is referred to as eco-design.

As a new approach to the design process, eco-design is based on identification of the environmental impact of the designed product and taking it into consideration at an early stage of product development. Eco-design is also referred to as design for the environment or sustainable design. Terms such as eco-design, DfE (Design for the Environment), environmental design, ecological design, sustainable product design, and green design can be found in the literature of the subject. Eco-design introduces an additional dimension to the traditional design process [6]. There are two types of approach to sustainable product design. One is focused on the development of eco-innovative products which meet the criteria of eco-innovation. In practice, the designed product not only meets environmental standards, but is also made of materials which are fully recyclable or biodegradable. Moreover, the related manufacturing process meets the highest standards of environmentally friendly manufacturing. The other approach is based on the

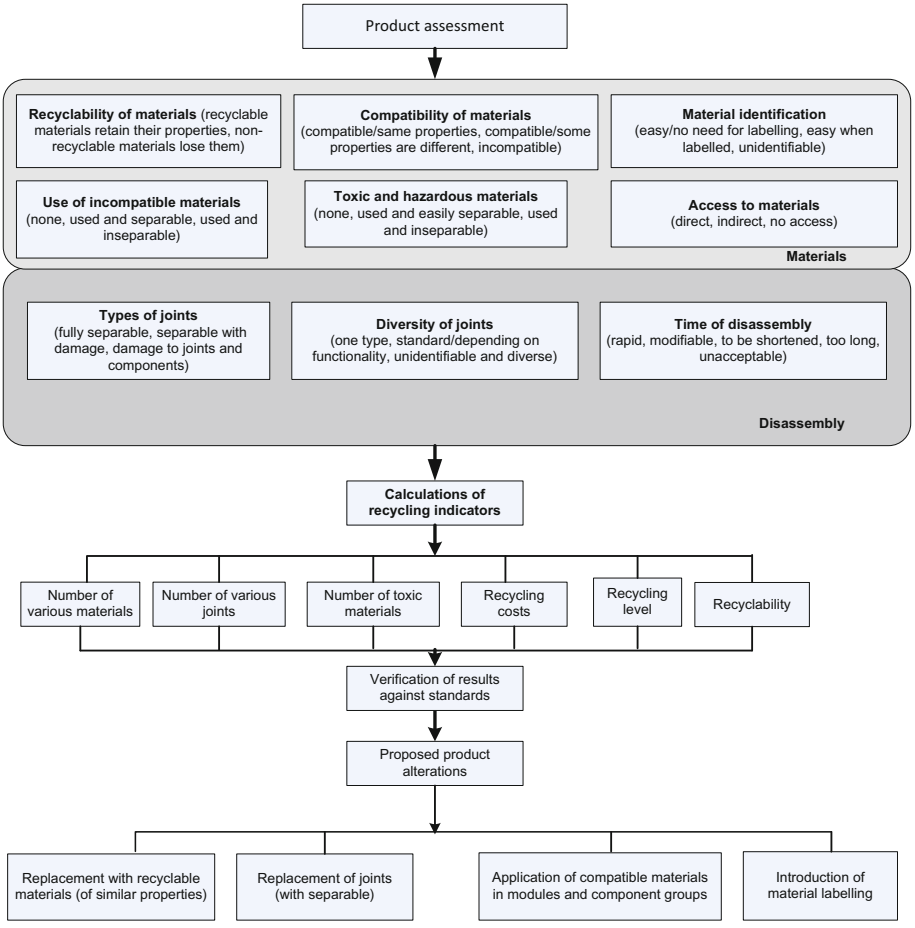


Fig. 1. Recycling-oriented aspects of eco-design [10]

incorporation of eco-design principles into the traditional design process in order to improve the product's environmental parameters, without changing its fundamental concept [7]. Such a product will use a smaller amount of materials compared to the previous model or an equivalent. Eco-design can be also considered as part of Industry 4.0 Concept, where all stages of product lifecycle are taken into account [8], and one of important aspects of maintenance management [9]. Eco-design is also based on the concept of using recyclable, compatible or renewable materials to design products which are easy to disassemble. Labelling the product components facilitates their recycling. Figure 1 presents recycling-oriented aspects of eco-design. Ideally, the designed product will be fully recyclable. This is rather unattainable, as products must meet other criteria, e.g. provide certain functionalities, and must be sold at competitive prices. These requirements often mutually exclude one another.

2 Eco-Design in Corporate Environment

Companies which design products with improved recyclability (e.g. household appliances) often appoint special eco-design teams. Eco-design teams, as well as designers and design engineers, seek to develop optimal solutions which meet the requirements shown in Fig. 1.

Eco-design teams are most often composed of environmental protection, law and quality management experts. Supporting designers as well as design and process engineers, they co-participate in the development of an action plan and verify the designed product in terms of its compatibility with the applicable standards, laws, etc. [11].

The collaboration enables flexibility and early response to the changing requirements of the market.

The task of definition and verification of assumptions for sustainable product design is sometimes assigned to employees of quality management departments. It follows from the fact that the environmental footprint of products falls within the scope of product quality. Dedicated teams or departments responsible for green design ensure that the designed products not only meet the expectations of customers, but also comply with the requirements of environmental protection.

Eco-design is a complex process. State-of-the-art IT solutions and technologies support designers at each stage of the process. In the recent years, a number of software tools have been developed to support the selection of materials and joints between product components. The software presented in this paper is one of the modern eco-design support tools.

As it has been mentioned above, taking into consideration the requirements concerning product recyclability at early stages of product design is of crucial importance. To make it possible, eco-design support tools should be integrated into other software tools used in the design process. The modelling and analysis discussed in this paper are based on a proprietary solution of a CAD 3D system overlay and an agent-based software tool compatible with a CAD system.

3 Product Modelling and Recycling-Oriented Analysis in CAD 3D System

The recycling-oriented analysis was performed with the use of a proprietary tool compatible with CAD 3D systems (the tool prototype is dedicated to Catia). The new software tool fills the gap existing in the standard CAD 3D systems, which lack the functionality of modelling product data required for a recycling-oriented analysis. The missing data includes data on joints, materials and their compatibility, recycling costs, tools applied for product disassembly, and product groups.

The development of the software tool (recycling product assessment module running in CAD 3D environment) was preceded by the creation of the recycling-oriented product model (RmW) [12, 13]) which includes the data mentioned above, and the recycling-oriented product assessment measures.

The assessment measures have been built on the basis of certain ratios determined in compliance with the applicable directives and laws [12, 13]. The following recyclability ratios are applied in the recycling-oriented product assessment [12, 13]:

- the weighting ratio of diversity of materials (WM),
- the weighting ratio of diversity of joints (WP),
- the weighting ratio of recyclability level (WPR),
- the number of toxic materials (WT),
- the recyclability ratio (WR).

In compliance with the applicable standards and directives, the recycling-oriented assessment takes into consideration the costs of recycling and the related costs of product disassembly.

The assessment measures are calculated on the basis of the data included in the recycling-oriented product model (RmW). The model includes data on [12, 13]:

- product composition,
- joints between product components,
- advanced material attributes,
- disassembly process,
- recycling costs,
- product group.

The product composition in the recycling-oriented product model (RmW) results from the standard 3D product. Considering the strong impact of joints between product components on product recyclability and the fact standard 3D product models lack an explicit representation of joints as a design feature, the recycling-oriented product model has been extended by detailed data on joints. The data describe the kind of joint (separable, non-separable), type of joint (threaded, glued, welded, etc.) and the components (parts or support) of which a joint is made. In the process of product design, the designer complements 3D assembly model, defining joints and their attributes, corresponding to their types. These activities are conducted using appropriate user interface in recycling product assessment module (Fig. 2).

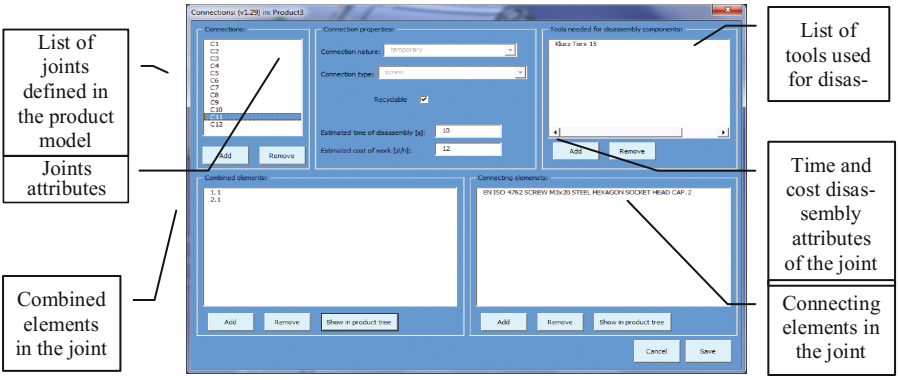


Fig. 2. User interface of recycling product assessment module – joints definition [12]

The recycling-oriented product model (RmW) also contains data on materials used in the product (advanced material attributes), which specify toxicity, group materials into categories and define compatibility of categories. In order to use these types of data in the model, they have to be previously defined. The definition of advanced material attributes is possible using appropriate user interfaces, developed for this purpose as another part of recycling product assessment module (Fig. 3).

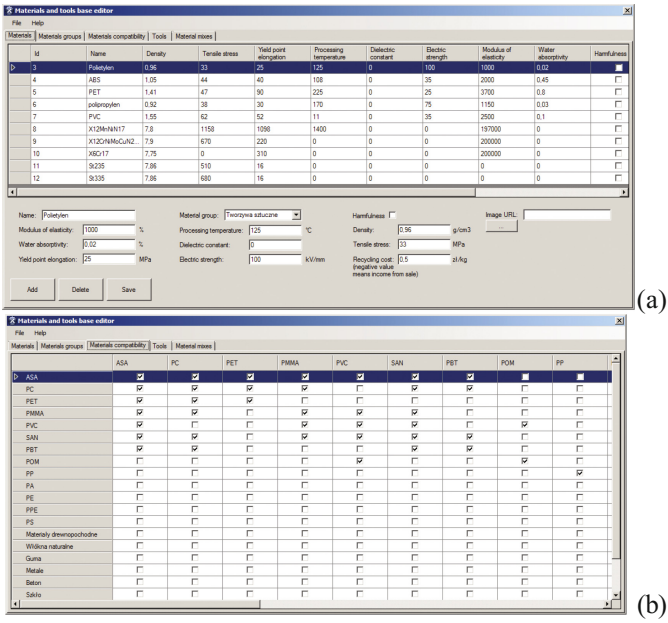


Fig. 3. User interface of recycling product assessment module – advanced material attributes definition: (a) extended material attributes, (b) compatibility of material groups [12]

The agent-based technology facilitates the recycling-oriented analysis of products designed in a distributed environment, where several designers work on the same project in various locations [15, 16]. The method and software tools have been developed as an extension to the previous solution, which was run independently of a CAD 3D system [17]. It is also planned to implement the existing solution in the VR environment in order to conduct the design and analysis in fully virtual space [18].

4 Recycling-Oriented Assessment of Selected Household Appliances

The proposed way of recycling assessment will be presented on examples of two household appliances: sandwich toaster and hairdryer.

At the first stage of the analysis, a CAD 3D model of the sandwich toaster was created (Fig. 4).

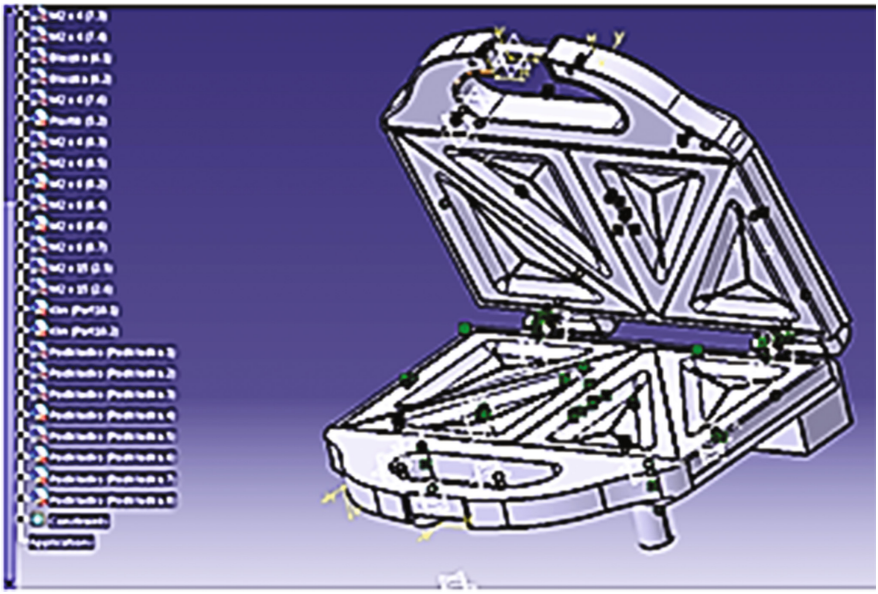
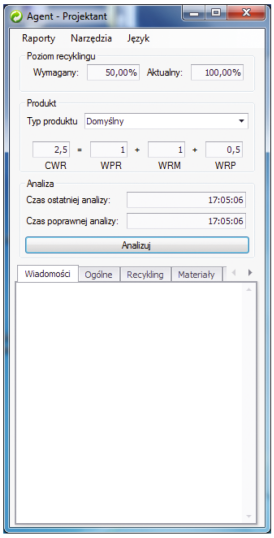


Fig. 4. A CAD 3D model of a sandwich toaster [19]

Next, a recycling-oriented product model was created, i.e. the joints, extended material attributes, hourly rate of the worker carrying out the disassembly and tools necessary for the disassembly were defined. The product was also assigned to a specified group, according to the applicable laws. The main results of the recycling-oriented analysis are presented in Fig. 5.



(a)

Recycling level			
Required	50.00%	Achieved	100.00%

General information	
Recovery level	100.00%
Mass	3.79
Disassembly time	00:00:40
Recycling cost	1.94
Number of materials	3
Number of tools	2

(b)

Fig. 5. Results of the recycling-oriented analysis of the sandwich toaster: (a) recycling-oriented analysis window, (b) final assessment report [18]

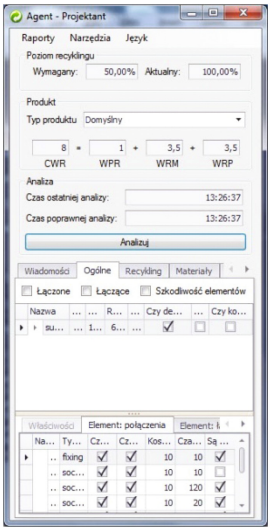
The results of the analysis show that the sandwich toaster is easily recyclable. The obtained product recyclability is 100%, and the total recyclability indicator (CWR) equals 2.5. The diversity of materials is very low (only three types of materials are used – ASA, general use steel and nickel-chromium steel). The joints used are also simple – 90% of them are highly recyclable threaded joints. The appliance can be disassembled with standard tools – a Pozidriv 2–3 mm (Pz1) screwdriver and pliers. The estimated time of disassembly is two minutes, the recycling cost – 1.94 PLN.

An identical analysis was carried out for a hair dryer (Fig. 6).



Fig. 6. A CAD 3D model of the hairdryer [18]

The sequence of the analysis was identical as for the sandwich toaster. The main results of the recycling-oriented analysis are shown in Fig. 7.



(a)

Recycling level			
Required	50.00%	Achieved	100.00%

General information	
Recovery level	100.00%
Mass	0.437
Disassembly time	00:01:55
Recycling cost	0.23
Number of materials	5
Number of tools	3

(b)

Fig. 7. Results of the recycling-oriented analysis of the hairdryer: (a) recycling-oriented analysis window, (b) final assessment report [18]

The recyclability level equals 100%, thus the WPR ratio has the best possible value, i.e. 1.0. However, other ratios are lower. The WRM equals 3.5 due to the higher diversity of materials. Here, the profit is only 30.77%. The joint diversity ratio (WRP) equals 3.5, due to a high diversity of materials, and generates a profit of 37.5%. The value of the total recyclability ratio (CWR) is unsatisfactory, considering the small number of components and materials used.

5 Summary

The products under analysis are small household appliances. It results from the recycling-oriented analysis that they are fully recyclable, owing to the reusable materials of which they are made. The sandwich toaster is made mostly of metals, which have higher recyclability than the plastics used for the hairdryer. The analysis of the sandwich toaster produces better assessment results, owing to the similar nut joints used in the appliance, which can be dismantled with a single tool. The hairdryer has more diverse joints, thus the WRP ratio is higher.

The solution presented in this paper is a support tool for the recycling-oriented analysis at early stages of the design process. It eliminates the necessity to compile the parameters required for the analysis from other systems. The solution can be integrated, as a separate module, into a CAD 3D system forming part of a PLM solution.

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Multi-agent Meta-model of a Non-cooperative Game in a Virtual Manufacturing Network

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Abstract. This paper presents the analysis of an approach to the issue of dynamic manufacturing networks scheduling. These aspects are closely connected with the concept of Virtual Enterprises (VE) and Virtual Manufacturing Network (VMN) in which integrated infrastructure of flexible resources is created. In the proposed paper it is analyzed the problem of scheduling tasks in such systems using the methods of game theory and multi-agent approach. The agents play an active role in the game theory approach to obtain access to resources that are needed in the process which is realized by them. Obtain results allow stating that this approach bring significant benefits to small and medium enterprises.

Keywords: Scheduling · Game theory · Multi-agent system

1 Introduction

Contemporary development of transport routes and information technologies offers wide possibilities in alternative arranging the manufacturing processes. Small and medium-sized enterprises increasingly look for such alternatives to solve the problem of planning the production flow. More and more often, these solutions are based on creation the hybrid combinations of several different ways to complete the entire production order in time, without rejecting new orders. The challenges with which enterprises must face include among others the timeliness of tasks execution or the spare time capacity was the reason for developing the new concept of virtual network of production enterprises. This network is a structure where companies work together to execute a common production order. However, the possibility of this kind of cooperation entails complications related with the way of production flow planning [1, 2].

The most serious issue concerns matching the ability and capacity of production of several companies at the same time [3, 4]. Hence market dynamics forces the manufacturers to change the method of manufacturing processes organization. It should result in an increase of functioning flexibility of an enterprise on the market. The factors like: shorter product life cycles, higher innovation level and new solutions introduction results in searching more and more effective methods of aiding planning processes of a production flow. Because of these market challenges it was proposed the solution in the form

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of Virtual Manufacturing (VM) [4, 5]. For VM is characteristic the rule according to which the larger is the number of cooperating enterprises the more complicated is the implementation of the production planning process. This causes that the possibility of utilization the conventional tools for planning process supporting is limited. One of the emerging problems is to organize the shared resources. This is why more sophisticated and flexible planning tools are needed to make possible the development of VM concept. Every VM network should be dynamic and flexible. It should be also characterized by adaptability, it means that each VM structure should be able to re-organize in a real time [6, 7].

The participation in VM, for small and medium enterprises, is the opportunity to reap the benefits that have been so far reserved for large ones. In the VM network could participate, depending on the complexity of the production process, several or more producers. The enterprises creating the VM network share their production capacity and main competencies what leads to producing larger amount, more complicated products of higher quality. The characteristic feature of the VM network is that it is created in the case of emerging order occurs and it is terminated after the completion of this order. The important element of such a network is of necessity the mutual trust of all network participants. This is why the number of participants and its composition are fluid [2]. On the other hand the problem is how to determine the criteria deciding about the exchange of a given participant of the VM network.

The other feature of the VM networks is the possible geographic dispersion of all enterprises involved in it. Hence it is important to adequate plan the cooperation of resources, transportation means, deadlines, etc. [8]. The other problem is related with the level of information inter-connection between the participants. The issue that should be overcome is considered with manufacturing and transportation costs. They are different for particular enterprises creating the VM network. This is why it is needed to ensure the access to quick and efficient tools for task planning and process scheduling at the operational level. The example of decisions that should be taken by such systems is the ones related with transportation route planning.

The paper presents a proposal of the multi-agent meta-model for supporting production flow planning in VM network. The main issue is related with supporting the choice of routes from the permissible set of routes that link individual participants of the network. The proposed approach is based on multi-agent system (MAS) application and the method derived from the game theory. The decision-making situation in discussed problem is considered as a non-cooperative one.

2 Multi-agent Approach

Multi-agent systems (MAS) are the solutions in the area of artificial intelligence. In MAS, at the lowest level it could be distinguished a set of agents A (where an agent $a \in A$). The agent is embedded in a certain environment E. It is also limited with a set of rules R (where a rule $r \in R$). The elements allow defining the interactions between the agents themselves and the interactions between agents and the surrounding them environment. It is difficult to determine a precise definition of an agent. According to the literature an

agent represents a virtual being. It is an abstract concept of an entity embedded in its environment. This entity could utilize certain resources from its environment to obtain its objectives. The characteristic features of an agent are: autonomy, reactivity, communicability. It could cooperate with other agents [9, 10]. A model of an agent is presented in Fig. 1.

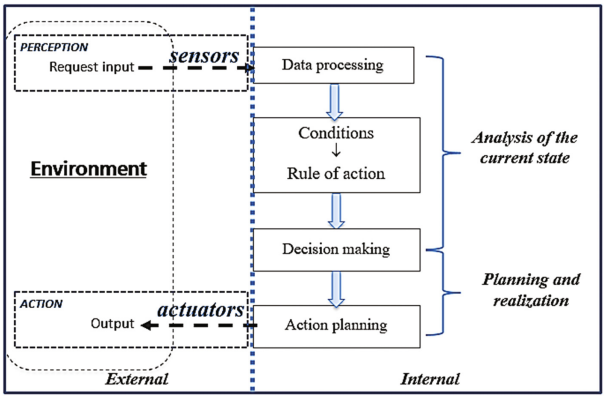


Fig. 1. General structure of an agent [11]

The agents in MAS are gathered in special hierarchical structures that are called holarchies. In Fig. 2 is presented an exemplar holarchy.

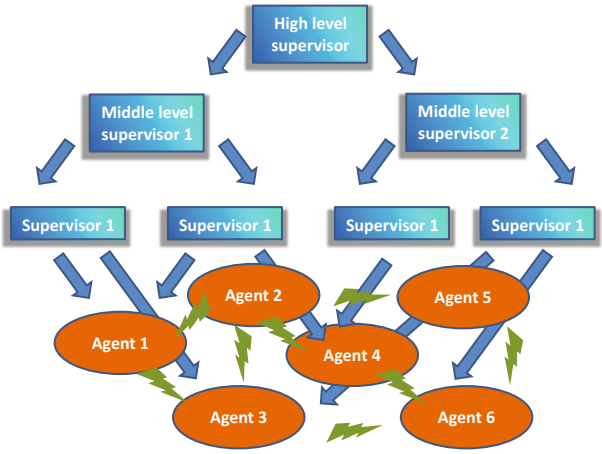


Fig. 2. Holarchy of MAS [12]

The characteristic feature of agents operating within MAS is the fact that they do not possess and cannot obtain the full knowledge on the system. It is related with the decentralization of MAS. Hence agents are no able to solve all the problems existing in the system. So it is possible to state that the operation capabilities of an agent are limited.

They are related with other factors that are dependent upon mutual cooperation. This cooperation, on the other hand, depends on changing environmental conditions and requirements that must be considered by an agent. The cooperation is the basic condition for solving the task that is posed before the entire system.

3 Problem Definition

The decision-making situation, which is considered in the paper, could be defined as a non-cooperative, 2-person, non-zero-sum game with complete information. In the discussed approach the players are represented by the next objective functions: F1-function of minimizing manufacturing costs and F2 – function of minimizing transportation cost between producers.

As it was stated the considered decision problem could be defined as the operational one. For the purpose of conducted researches it was assumed that participants of the VM network are independent. For the production processes are given sets of production orders including the alternative routes. Production orders are executed on chosen production stands from the available set. The proposed model of decision-making problem is therefore related to the production flow planning problem. It could be described as process of searching the routes system that guarantees fulfilling the decisional criteria. The production system is defined as the set of [13]:

$$\mathrm{S} = (\mathrm{M},\ \mathrm{C},\ \mathrm{PP},\ \mathrm{B}) \tag{1}$$

where:

S – the production system,

$M = \{M_i^{\varepsilon}, i = 1, 2, \ldots, m_{\varepsilon}; \varepsilon = 1, 2, \ldots, R\}$ – production resources,

m_{ε} – the number of resources owned by $\varepsilon^{\text{-th}}$ manufacturer,

R – the number of manufacturer in the network,

$C = C^P + C^T$ – the unit production cost (C^P) and the unit costs of transport (C^T):

$$C^P = [C^P_{\varepsilon,k}] = \begin{array}{c} \\ 1 \\ \vdots \\ R \end{array} \begin{array}{c} \begin{array}{ccc} 1 & \cdots & K \end{array} \\ \begin{bmatrix} C_{1,1} & \cdots & C_{1,K} \\ \vdots & \cdots & \vdots \\ C_{R,1} & \cdots & C_{R,K} \end{bmatrix} \end{array},$$

where:

$K = max\ (\mathrm{m}_{\varepsilon})$ – maximum number of resources available in the network members,

$C^P_{\varepsilon,k}$ - the unit cost of technological operation execution on $k^{\text{-th}}$ resource belonging to the $\varepsilon^{\text{-th}}$ manufacturer,

$$C^T = [C^T_{\varepsilon,\varepsilon}] = \begin{array}{c} \\ 1 \\ \vdots \\ R \end{array} \begin{array}{c} \begin{array}{ccc} 1 & \cdots & R \end{array} \\ \begin{bmatrix} C_{1,1} & \cdots & C_{1,R} \\ \vdots & \cdots & \vdots \\ C_{R,1} & \cdots & C_{R,R} \end{bmatrix} \end{array},$$

where:

$C^{T}_{\varepsilon,\varepsilon}$- the unit cost of transportation between manufacturers belonging to the network,

The production order is defined as:

$$PP = (P, MP, N_j) \tag{2}$$

$P = \{P_j, j = 1,2,\ldots n\}$ – production processes,

$MP = \{MP^{w}_{j}, j = 1, 2, \ldots, n;\ w = 1, 2, \ldots, v_j\}$ –production processes matrix:

n – the number of manufacturing processes,

w – version of the process route, v_j –the number of routes version for the $j^{\text{-th}}$ process,

$MP^{w}_{j} = \begin{bmatrix} mp_{11} & mp_{12} & \cdots & mp_{1h} & \cdots & mp_{1H^{w}_{j}} \\ mp_{21} & mp_{22} & \cdots & mp_{2h} & \cdots & mp_{2H^{w}_{j}} \\ mp_{31} & mp_{32} & \cdots & mp_{3h} & \cdots & mp_{3H^{w}_{j}} \end{bmatrix}$, matrix for $w^{\text{-th}}$ version of the route for the *j-th* process,

H^{w}_{j} – the number of technological operations in $w^{\text{-th}}$ route for $j^{\text{-th}}$ process,

mp_{1h} – manufacturer No,

mp_{2h} – production resource No for $h^{\text{-th}}$ technological operation,

mp_{3h} – processing times for each operation.

N_j – batch size,

$B = \{B_{l,\mathrm{k}}\ l = 1, 2, \ldots, R;\ k = 1, 2, \ldots, R;\ R \neq k\}$ – storage capacities for individual producers.

For the above-defined models of production systems and production orders, functions of the objective are defined:

F1: minimizing the production cost:

$$F1(\sigma) = \sum_{j=1}^{h} \sum_{h=1}^{H^{\sigma_j}_{j}} \left(C^{P}_{(mp_{1h}),(mp_{2h})} * mp_{3h} \right) \rightarrow \min \tag{3}$$

F2: minimizing transportation costs between producers:

$$F2(\sigma) = \sum_{j=1}^{h} \sum_{h=1}^{(H^{\sigma_j}_{j}-1)} \left(C^{T}_{(mp_{1h}),(mp_{1(h+1)})} * N_j \right) \rightarrow \min \tag{4}$$

where:

σ_{j}- the route variant selected for implementation for $j^{\text{-th}}$ process, $\sigma = (\rho_{\mathrm{j}})$

The VM network, considered in the analysis, consists of three producers. These producers share their production resources to realize the required production order consisting of two processes P1 and P2. The number of shared operation stations at each producer is equal to three. These elements allow to prepare the multi-agent meta-model of VM.

4 Multi-agent Model of VM Network

The NetLogo environment has been used to elaborate the multi-agent meta-model of the analyzed VM network. It is a multi-agent programming language and modeling environment for simulating complex natural and social phenomena. Agents in NetLogo are operating concurrently, in order to explore connections between micro-level behaviors of individuals and macro-level patterns that emerge from their interactions.

The proposed holarchy of VM network consist of mentioned previous elements that are placed in lines linked together. Each horizontal line represents one participant of the analyzed network (Fig. 3).

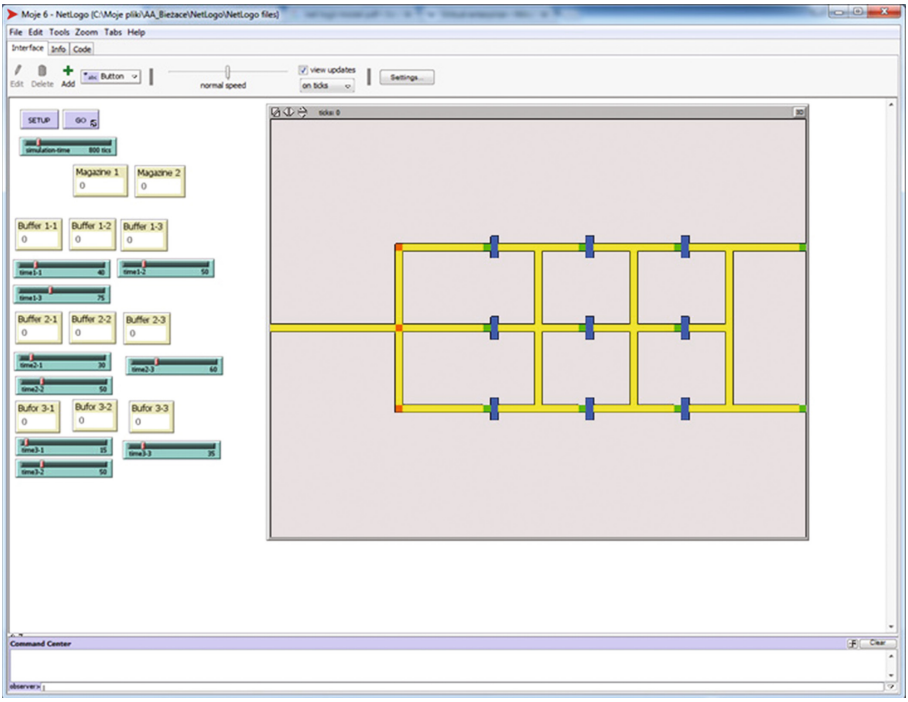


Fig. 3. Simulation meta-model elaborated in NetLogo

The Fig. 4, below, presents an example of conducted simulation. The circles and squares represent elements realized within the processes P1 and P2.

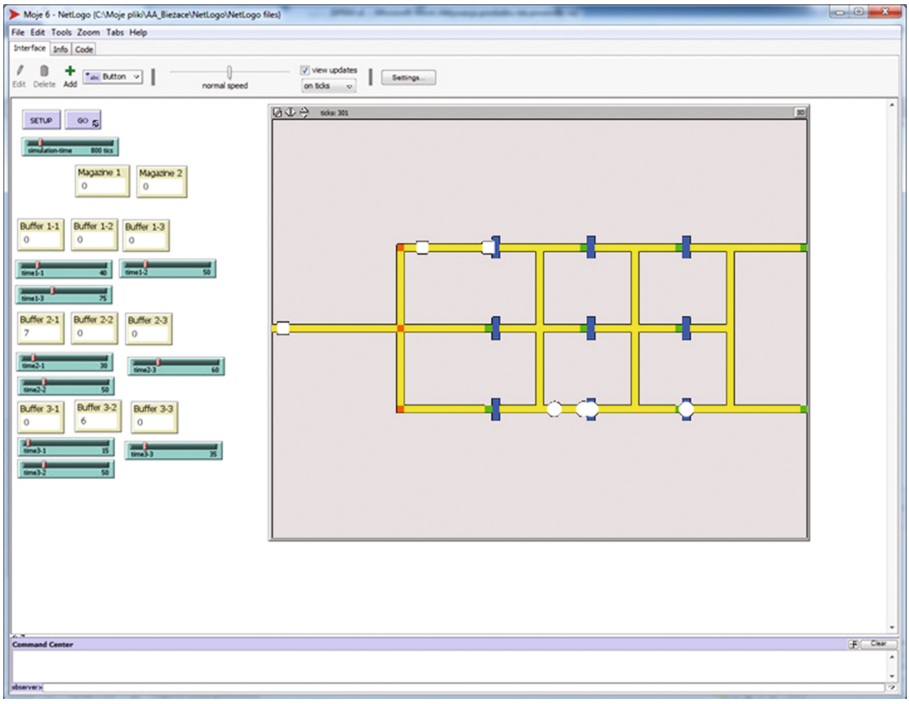


Fig. 4. Example of a simulation

In the presented model are not visible elements responsible for realization the game resulting in the route determining for particular elements.

5 Conclusion

Increasingly, companies are looking for opportunities to exploit their spare capacity. One possibility is to use VM networks. It should be stated that planning production processes in such configurations causes many difficulties. In the paper are presented the possibilities of utilization of multi-agent approach for production resources organizing. It is conducted through the participation of particular enterprises in VM network. Planning production flow in such structures requires using effective AI tools. The possibilities of application of formalism taken from the game theory to define decision-making situation related to production planning and selection of routes could be linked with the application of MAS. It allows increasing the flexibility of resources utilization. The subject of further research will be related with attending to prepare more sophisticated MAS model. It is particularly true in the case of programing the game sequence.

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Multivariate Process Capability, Process Validation and Risk Analytics Based on Product Characteristic Sets: Case Study Piston Rod

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Abstract. Manufacturing processes of technically complex products require highly standardised methods to fulfil technical and customer specifications. To accomplish the demanded specifications, various methods, which can be applied at different phases of the product life cycle, have been developed. One of these methods, within the manufacturing phase, is the process capability index (PCI). The determination of the PCI allows the visualisation of risk with one indicator and failure probability with regard to a manufacturing process. State-of-the-art is the univariate calculation of the PCI based on the analysis of one product characteristic. This paper outlines different approaches for the determination of multidimensional process capability indices (MPCI) based on a product characteristic set including symmetric and asymmetric product characteristic distribution models. The goal of the explained methods is the analysis of risks, the determination of risk indicator MPCI and failure probabilities with regard to complex manufacturing processes.

Keywords: Multivariate manufacturing analysis · Failure probabilities · Process capability index · Statistical process control · Crankshaft · Piston rod · Cp/Cpk

1 Introduction

Manufacturing processes of technically complex products require highly standardised methods to fulfil technical and customer specifications. To accomplish the demanded specifications, various methods, which can be applied at different phases of the product life cycle, have been developed. One of these methods, within the manufacturing phase, is the one-dimensional process capability index (PCI). The determination of the PCI allows the visualisation of risk with one indicator and failure probability with regard to a manufacturing process. The analysis of manufacturing processes and the attendant process optimisation actions leads to a reduced amount of production failures and therefore to a reduced manufacturing risk and reliable products. With decreasing tolerances and parallel increasing product complexity, industrial state-of-the-art methods – based on one-dimensional PCI – must not be thus sufficient anymore [1].

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The multidimensional PCI (MPCI) is one possibility to verify manufacturing processes of technical products based on functional important product character sets. Previous researches exhibited the successful benefit of such multidimensional process capability indices [2, 3]. Nevertheless a general procedure for industrial manufacturers hasn't been developed yet.

This paper presents a method for the determination of a multidimensional process capability index (MPCI) with the help of a case study piston rod. The method considers the risk analysis of a set of functional important characteristics, which follow symmetric and asymmetric distribution models [4].

2 Focus and Goal of the Research Work

The focus of the research work is the development of an approach to determine a multidimensional PCI (MPCI) as an analogon to the common, univariate PCI (state of the art). Precondition for the determination of PCI or MPCI are capable measurement systems and machine tools (cf. [4]). The goal is the analysis of risks, determination of MPCI and failure probabilities of manufacturing processes based on product characteristic sets. An overview of the developed method regarding the estimation of multivariate process capability indices (MPCI) is shown in Fig. 1: The theory and application (case study piston rod) of the method steps are explained in the following sections (every section represents a method step).

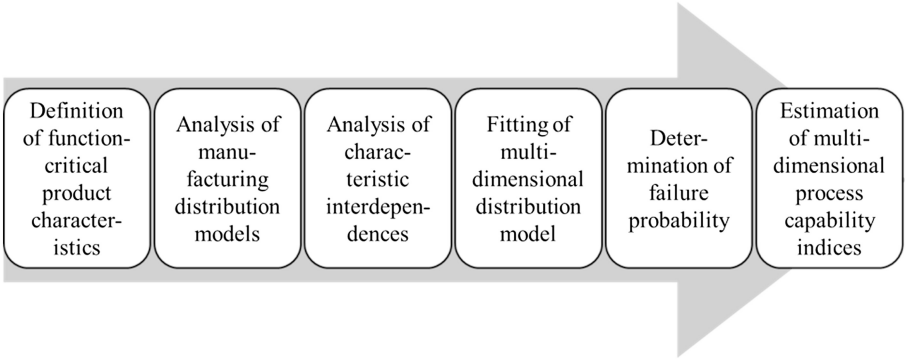


Fig. 1. Overview of the approach for determination of MPC-indices.

3 Case Study Piston Rod: Characteristic Set and Functionality

The presented case study focuses on a manufacturing process of a piston rod. A piston rod is working for transmute the reciprocating motion into rotary motion within a combustion engine. It is part of crank drive, assembled on a crank pin of the crankshaft (piston characteristic big end, Fig. 2). The other end of the piston rod is connected to

the piston based on the piston pin (piston characteristic pin end). The piston rod transmits the gas forces (caused by the combustion) acting on the translational motion pistons. As a consequence, the mass forces of a drive unit are transmitted to the crankshaft sprocket. The requirements regarding geometric and surface characteristics are on a high level: Linear dimensions, alignment, fit and concentricity are important functional characteristics regarding function and efficiency. Therefore the mentioned parts are manufactured within a high precision manufacturing process. The case study focusses on the important functional characteristics of the piston rod, because the manufacturing requirements are representative for the other parts of the combustion engine.

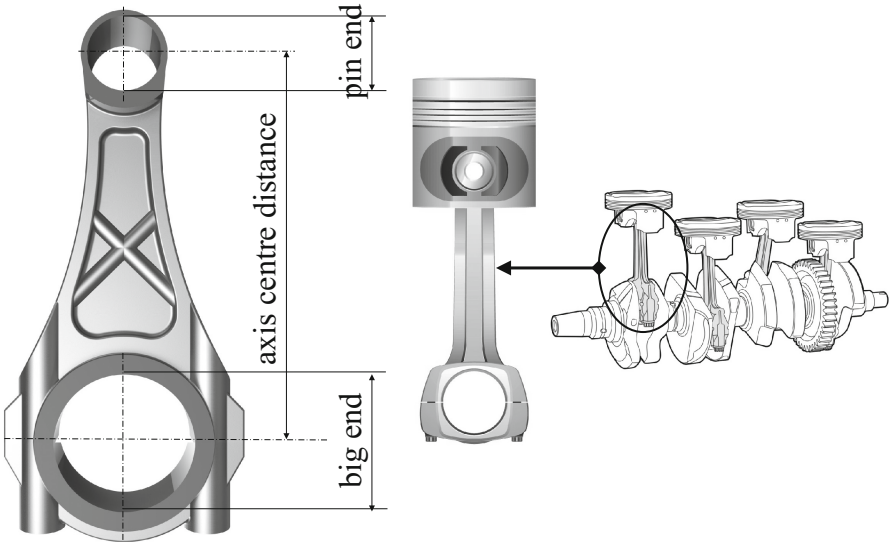


Fig. 2. Important characteristics piston rod (cf. Table 1) and qua ingredient of crankshaft drive (Drawings by colourbox, Nicemonkey and colourbox, Nikita).

The challenge is the fulfilment of the narrow characteristic tolerances. Examples of the piston rod's important characteristic set are as follows: Big and pin end diameters, axis centre distance and axle parallelism (cf. Fig. 2). If these piston rod functional characteristics are manufactured outside the required tolerance area, it has serious consequences on the friction context of the involved components during the combustion process.

Within the case study, the manufacturing process of a sample of n = 200 piston rods were analysed. The functional important characteristics, the tolerance areas as well as their expected distributions parameters (fit based on n = 200 measurements regarding each important characteristic) are shown in Table 1 (cf. also Fig. 1, steps 1 and 2). The distribution assumption was verified and confirmed by a Kolmogorov–Smirnov conformance test [5].

Table 1. Comparison of the piston rod characteristics (Char.) with their tolerance areas (Tol.), nominal value (NV), distribution model (DM) and measurement sample parameters.

Nos.	Char.	Tol.	NV	DM	$\hat{\mu}$	$\hat{\sigma}$
1.	Big end	65.979–66.028	66	ND	65.677	0.009247
2.	Pin end	34.991–35.0	35	ND	34.837	0.005411
3.	Axis centre distance	220.00–220.04	220	Log-ND	218.939	0.013867
4.	Axle parallelism	0.00–0.02	0	Weibull	0.0053	0.006372

4 State of the Art: Process Capability Index (PCI)

The continuously analysis and control of the manufacturing process is the precondition for the obtaining of excellent products. It is possible to gain information with the process capability indices (PCI, industrial standard for univariate product characteristic analysis [6]) by obtaining a determined distribution [7].

In general, process capability is divided into two perspectives: process capability Cp and critical process capability Cpk [6]: Cp represents the ratio between the process scattering and the given tolerance area. Regarding the manufacturing deviations the position of the manufacturing's arithmetic mean inside the ratio considers Cpk [8]. This method is mainly established for normal distributed processes [9]. Equation (1) shows the determination of the process capability Cp, Eq. (2) describes the critical process capability Cpk. As all characteristics are normally distributed, the process capability indices are determinable by using Eq. (3) [7], which shows the density function of the normal distribution.

$$\widehat{\mathrm{Cp}} = \frac{\mathrm{USL} - \mathrm{LSL}}{6\hat{\sigma}} \tag{1}$$

$$\widehat{\mathrm{Cpk}} = \min\left[\frac{\mathrm{USL} - \hat{\mu}}{3\hat{\sigma}}; \frac{\hat{\mu} - \mathrm{LSL}}{3\hat{\sigma}}\right] \tag{2}$$

$$f(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \tag{3}$$

The abbreviations inside the shown equations are as follows:

USL = upper specification limit/LSL = lower specification limit
μ = mean
σ = standard deviation
$\hat{\mu}$ = mean (estimated)
$\hat{\sigma}$ = standard deviation (estimated)

If the process capability index of one product characteristic is below a defined critical value (state-of-the-art value 1.33 [6]) a review of the production process should be done to improve the manufacturing steps and achieve higher capability indices.

Depending on the industrial discipline there are also higher capability requirements such as $\widehat{Cp} > 2.0$ and $\widehat{Cpk} > 1.67$ [6]. An example for a normally distributed characteristic (case study piston rod big end diameter, cf. Table 1) is shown in Fig. 3.

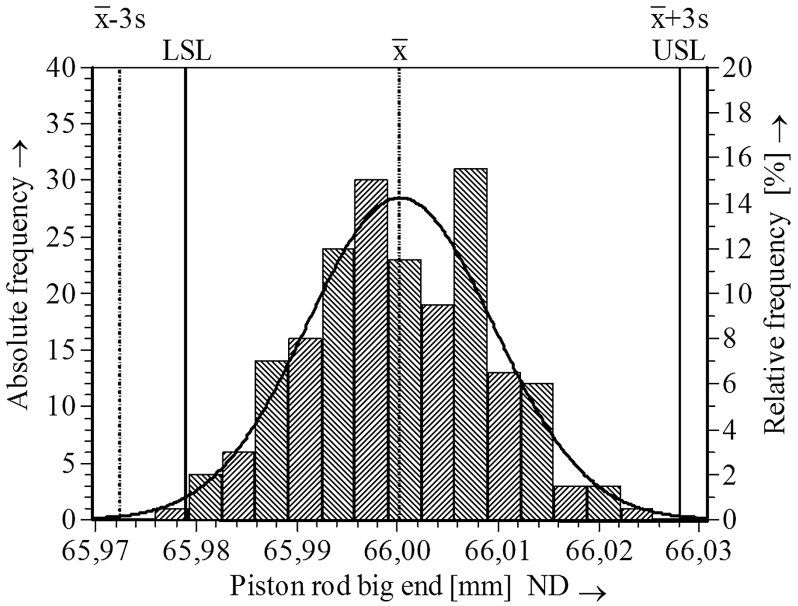


Fig. 3. Classified measurement data of piston rod big end diameter (case study; cf. Table 1) fitted with a normal distribution density function within the given tolerance area.

5 Correlation of Product Characteristics

Precondition of the estimation of MPCI is the knowledge regarding inter-/dependences between the product characteristics (cf. Fig. 1, step 3). State-of-the-art calculations for correlations analysis are based on Bravais–Pearson (precondition: bivariate normal distributed characteristics), Spearman and Kendall (rank based analysis; independent of characteristic distribution models) [5]. The results of the application of these correlation coefficient analyses show the interdependences of the product characteristics. In the case study, the Spearman correlation coefficient was used (Eq. (4)), because two piston rod characteristics are not normal distributed (cf. Table 1; characteristic number three and four).

$$r_s = \frac{\sum_{i=1}^{n}\left(\left(R(x_i) - \overline{R(x)}\right) - \left(R(y_i) - \overline{R(y)}\right)\right)}{\sqrt{\sum_{i=1}^{n}\left(R(x_i) - \overline{R(x)}\right)^2 \sum_{i=1}^{n}\left(R(y_i) - \overline{R(y)}\right)^2}} \tag{4}$$

Abbreviations:
$R(x_i)$ = rank of x_i
$\overline{R(x)}$ = mean rank of x
$R(y_i)$ = rank of y_i
$\overline{R(y)}$ = mean rank of y.

Obviously, the values of the estimated Spearman correlation coefficients are equal nearly 0 (Fig. 4). That means that there are no detectable interdependences between the important piston rod characteristics.

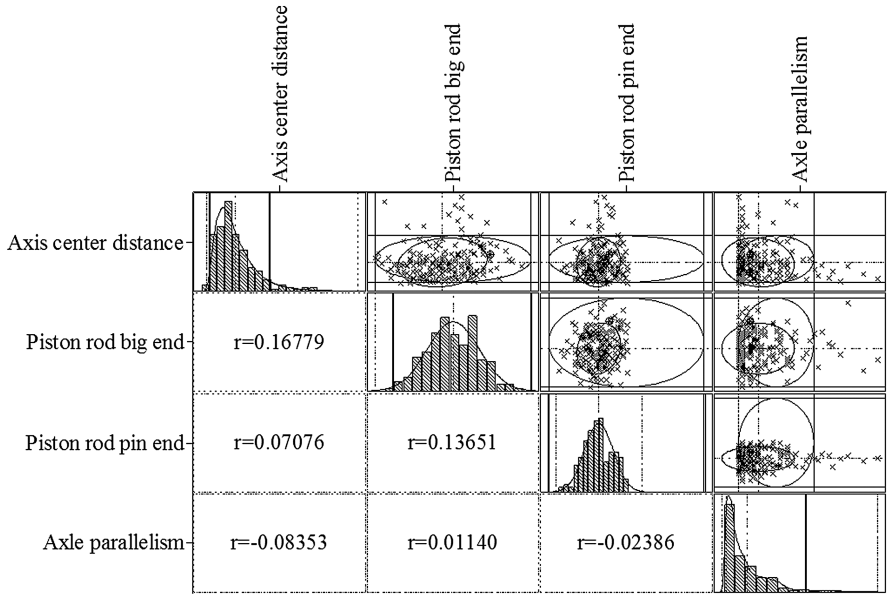


Fig. 4. Correlation matrix regarding to important piston rod characteristics, showing Spearman's rank correlation coefficient, distribution models and bivariate measurement plots.

6 Multidimensional Process Analysis: Distribution and Failure Probability

As a matter of principle, there are three possible approaches to estimate a failure probability with regard to the product characteristics (cf. Fig. 1, step 5); which are explained in the subsequently sections:

1. The individual estimation of failure probabilities and combination to a multivariate failure probability using Boolean algebra (cf. Sect. 6.1).
2. Application of multidimensional distribution models based on a set of important product characteristics (cf. Sect. 6.2).
3. Estimation of failure probability based on Monte Carlo simulations (cf. Sect. 6.3).

The estimation of a failure probability based on a set of a product characteristic set – exemplified using approach number two – is shown based on the case study piston rod (cf. Sect. 6.4).

6.1 Application of Boolean Algebra Based on Failure Probabilities Regarding Each Product Characteristic

Base of operations is the individual estimation of the failure probability for each product characteristic. First, a proper distribution model is fitted to the measurement data of each product characteristic. Second, the complement of the integration – using the tolerance area as integration limits – is the failure probability of the single characteristic. Afterwards the composition of the failure probabilities in due consideration of Boolean algebra rules leads to a comprehensive product failure probability (cf. Fig. 1, step 5). The Eq. (5) shows the determination of the failure probability based on different, univariate characteristic failure probabilities (application on two characteristics). Precondition is the independency of the analysed characteristics (cf. Sect. 5).

$$\begin{aligned} P_{ges}(t) &= 1 - \prod_{i=1}^{n=2}(1 - P_{Ci}(t)) = \ \ldots \\ &= 1 - (1 - P_{C1}(t))(1 - P_{C2}(t)) \end{aligned} \tag{5}$$

6.2 Application of Multidimensional Distribution Models Based on a Set of Important Product Characteristics

Base of operations for the estimation of a failure probability regarding the product characteristic set is the fit of a multidimensional distribution model (Fig. 1, step 4). This approach is feasible regarding independent characteristics (cf. Sect. 5).

The proper multidimensional distribution model (E.g. normal distribution, Weibull distribution [10]) depends on the distribution of the several analysed product characteristics. In case of normally distributed characteristics, the multivariate normal distribution model can be used [11] (Eq. (6)). The parameters of the distribution can be estimated with the maximum-likelihood function [5].

$$f_x(x_1, \ldots, x_k) = \frac{1}{\sqrt{(2\pi)^k |\Sigma|}} \exp\left(-\frac{1}{2}(x - \mu)^T \Sigma^{-1} (x - \mu) \right) \tag{6}$$

Abbreviations:
μ = mean vector
Σ = covariance matrix

In comparison with Eq. (3), μ is a vector and σ a matrix (Σ in Eq. (6)). The multinomial-distribution of two characteristics leads to a bivariate vector μ and a bivariate matrix Σ. The non-correlation is a basic condition regarding this approach: This leads to a tolerance zone in form of a rectangle. Otherwise the tolerance zone

could be ellipse shaped, which would lead to a different integration form. Finally, the complement of the integral of the fitted distribution model, using the tolerance areas as limits, leads to the failure probability (cf. Fig. 1, step 5).

6.3 Estimation of Failure Probability Regarding a Characteristic Set Based on Monte Carlo Simulations

Precondition of the shown approaches before (Sects. 6.1 and 6.2) regarding to the estimation of a failure probability based on a character set is the independence of the product characteristics. This section shows a possibility to estimate the failure probability via Monte Carlo simulation, whatever the characteristics are independent or dependent [4]: the failure probability is estimated based on a multivariate normal distribution, which is fitted on a transformed sample. The measurement data of this sample belongs to different product characteristics. First, the distribution models of each product characteristic are modelled. These marginal distributions are transformed and base of a fitted multivariate normal distribution. Subsequently, the comparison with the given specification limits allows the estimation of the failure probability (cf. Fig. 1, step 5). The essential steps are explained, as follows [12]:

1. Fitting of proper distribution models f_{xi} based on the measurement data regarding the important product characteristics.
2. Estimation of function $\Phi = (\phi_1,\ldots\ \phi_q)^T$, considering $\phi_i(X_i) \sim N(0, 1)$.
3. Transformation of all samples S_i of the marginal distributions via Φ and determination of the estimators $\hat{\Sigma}$ and $\hat{\mu}$ of the multivariate normal distribution, based on the transformed data.
4. Generating of n realisations of the multivariate normal distribution $N_q(\hat{\mu},\ \hat{\Sigma})$. Note: q is the number of marginal distributions and n should be on a high level.
5. Transformation of the lower and upper specification limits via Φ and estimation of the failure probability regarding the n realisations (confirm step 4).

The estimated failure probability should be a good approximation regarding the actual failure probability. There is no guarantee, that the transformed marginal distributions are multivariate normal distributed in realitas. It is based on a model assumption. It is not a common rule, that based on univariate normal distributed $x_1,\ldots,$ x_q follows necessarily multivariate normal distributed $x = (x_1,\ldots,x_q)$ [13].

The advantage of the shown approach is the possibility of consideration of dependent product characteristics (cf. Sect. 5). The disadvantage is the lack of interpretable model parameters, which allows the operator conclusions on the manufacturing process (in opposite to approach approaches Sects. 6.1 and 6.2). Furthermore, the result is an approximation, every Monte Carlo simulation leads to varied result.

6.4 Case Study: Piston Rod, Exemplary Failure Probability

The set of important piston characteristics contains four attributes (cf. Table 1): Exemplary, this section shows the determination of the failure probability based on a

two-dimensional characteristic set: diameter big end and pin end. These characteristics are normally distributed, therefore the shown approach in Sect. 6.2 is proper. Based on Eq. (6) and Table 1, the probabilities P_{IT} and P_F are determinates as follows:

$$\begin{aligned} P_{IT} &= \int_{x_1LSL}^{x_1USL} \int_{x_2LSL}^{x_2USL} f_x(x_1,\ x_2) \\ &= \int_{65.979}^{66.028} \int_{34.991}^{35.050} \frac{1}{\sqrt{(2\pi)^2|\Sigma|}} \exp\left(-\frac{1}{2}(x-\mu)^T\Sigma^{-1}(x-\mu)\right) dx_1 dx_2 \end{aligned} \tag{7}$$

$$P_F = 1 - P_{IT} \tag{8}$$

Abbreviations:
P_{IT} = probability inside tolerance
P_F = probability failure

The graphical visualisation is shown in Fig. 5, obviously, the scattering regarding the characteristic diameter big end is to high whereas the process of the character diameter pin end is not centred.

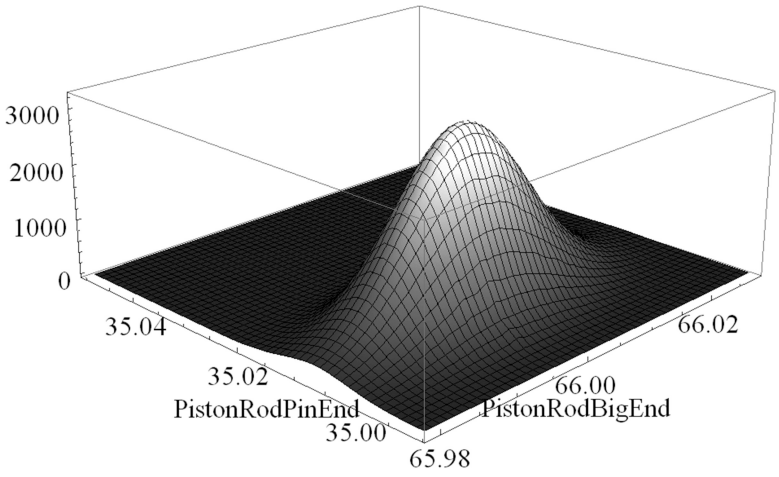


Fig. 5. Two-dimensional normal distribution density function within the given tolerance area; fit based on the characteristics piston rod of the diameter pin end and big end.

This leads to a high failure probability, which is expressed in the unit parts per million (ppm), shown in Table 2.

Table 2. Failure probability based on multidimensional normal distribution fit.

Characteristics	P_F: complement of integral regarding tolerance zones	ppm
Piston rod big end/piston rod pin end	0.01230305	12303

7 Estimation MPCI: Link Between Failure Probability and Cpk

The next step for calculating the MPCI is the link between ppm and the common state-of-the-art one-dimensional capability index Cpk (cf. Fig. 1, step 6 and Sect. 4). Based on the ratio of process scattering and tolerance area (Eqs. (1) and (2)), the determination of the failure probability in the one-dimensional case is feasible [integration of Eq. (3) by using tolerance area as limits]. Therefore, each one-dimensional Cpk value belongs to a failure probability ppm-value. The relationship between one-dimensional Cpk value and ppm value is shown in Fig. 6.

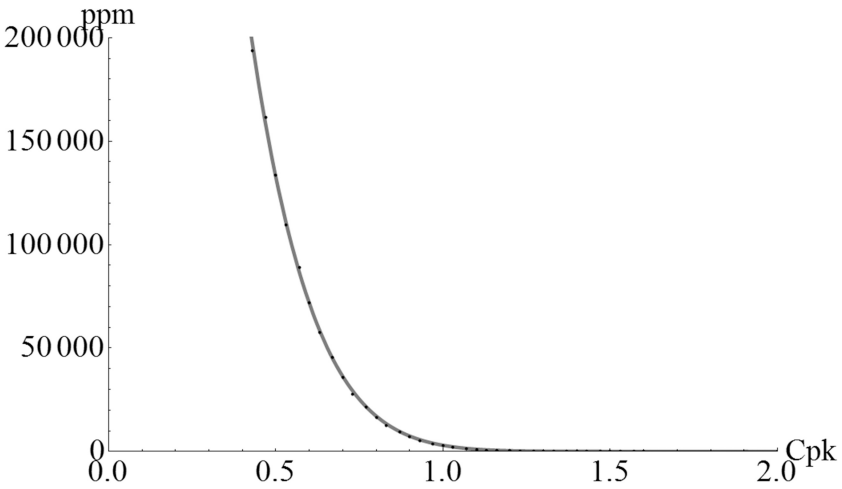


Fig. 6. Non-linear regression of relationship between failure probabilities ppm and Cpk [14].

In addition to the graphical visualisation, a non-linear regression has been calculated using the Eq. (9).

$$y = \beta_0 \exp(\beta_1 \exp(x)) \tag{9}$$

with $\beta_0 = 4.61153 * 10^7$ and $\beta_1 = -3.54913$.

The expression allows the direct conversion of an estimated failure probability into a Cpk value. Therefore the failure probability (unit [ppm]) of the multidimensional analysis leads now directly to the MPCI, as an analogon to the direct conversion of ppm into Cpk (Fig. 6 and Eq. (9)). Within the case study, the expected failure probability regarding the analysis of the important piston rod characteristic set big end/pin end diameter leads to a MPCI value of 0,840969.

8 Conclusion

This paper outlines a method for multidimensional process analyses and the estimation of multidimensional process capability indices - based on symmetric and asymmetric product characteristic distribution models - inside the product manufacturing phase (Sect. 1). Based on the one-dimensional state-of-the-art approach (Sect. 2), the multidimensional approach is developed (Sects. 6 and 7). The presented results were established within a case study piston rod and were calculated due to simulated data (Sect. 3). The paper shows three approaches (Sects. 6.1 to 6.3: Boolean algebra, multidimensional distribution model and Monte Carlo simulation) to calculate the failure probability based on a set of functional important product characteristics.

The essential idea is the analogy of ppm and Cpk, which leads to a MPCI (Sect. 7). With this linkage it is possible to determine a MPCI based on a failure probability of a character set. In this context it is important to underline the comparison between one-dimensional SPC methods (state-of-the-art methods) and the approach of multidimensional process capability indices (MPCI): the added value of the shown MPCI approach is the combination of known SPC methods to detect a risky manufacturing process. The output of the method combination is the base of a MPCI. The MPCI enables the validation and supervising of a production line and the evaluation of the production process by the use of one risk indicator.

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Optimization of Production Organization in a Packaging Company by Ant Colony Algorithm

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Abstract. The paper deals with the production scheduling optimization problem. Real production environment have been considered - a company that produces different types of products; and an optimization method based on the intelligent ant-colony optimization (ACO) algorithm have been proposed. In the paper the original problem formulation for the considered production scheme is shown, also the details of ACO meta-heuristic are proposed and presented.

Keywords: Organization of production · Material flow · Ant Colony Optimization (ACO) · Meta-heuristics · Intelligent optimization methods

1 Introduction

Nowadays production companies face a challenging task that requires performing an analysis of various factors, not only those directly related to the manufacturing process, but also additional ones, e.g. transport between workstations. This task affects the entire production process, especially total production lead time, which is often one of the most important aspects for customers who choose their suppliers [4, 6, 17]. In order to meet the requirements set by customers, companies need to compete both in the delivery time and the price of product. The reduction of time spent on material flow in the company allows also for reducing the production costs, due to the fact that transport is one of the sources of waste in production processes [2, 5, 7, 8, 12, 15]. Sometimes companies choose organisation of production processes intuitively, based on experience of engineers working with the processes [1, 3, 10, 14]. This is the situation often observed in small companies, like the one discussed here. However, this is not always the best method of production process planning. One of the factors that affect material flow is the factory layout, but the other one is the chosen organisation of production processes and this is the main topic of article. Nevertheless, this is often a complex problem that requires a detailed analysis.

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In this case, the company produces four different types of product and uses multiple machines having the same function. Thus, the problem is complicated and has many different solutions. As a tool supporting the process of making decisions during such optimization, the Ant Colony Optimization (ACO) method may be used for example, which is one of intelligent optimization algorithms. The intelligent methods are being used more and more frequently not only in production systems, but also in other types of problems that are difficult to solve. Intelligent optimization algorithms "are usually inspired from the nature" [11] and, in the case of ACO, the inspiration were ants and their way of searching for food, what was wider described in the article.

2 Production Process

In the article ACO is used as a optimization tool for a simplified version of the real process of producing packages in the company – the simplification is that we do not consider the external transport, storage limits or time needed for machine maintenance. We focus on the production process and its lead time. The production process involves operations that need to be done to transform the cardboard (material) into the packaging (final product). There was taken an example amount of customer order, which is total amount of 22 000 pcs of packages in four different types. The first, second and third product are similar and need almost the same operations to be done. These are flap packages, which are the main products of the company. The first one is a traditional, simple package. The second one is almost the same, but the difference is in production process – they are made by a BoxMaker, the machine that can do all operations to obtain the final product. The third version of product is flap package with a print. The fourth product is totally different – a decorative package, often used to pack wine or perfumes. In order to produce all these products, the material need to be subjected to operations, which are summarized in Table 1.

The Table 1 also lists times of operations, machines and work cells. These are important in this article, because of their capacities. Thus, for the purpose of optimization, there were also summarized functions and capacity of all work cells in the Table 2. Capacity of a work cell is the amount of operations that can be performed at one time, for example: there are three machines in the cutting cell (cutters) and each one can handle one operation of cutting, so summarized capacity of the whole cell is three operations at a time. There is no difference between machines in one work cell, so they can be swapped during the process flow. This is very important information that will be used in the following part of article.

An actual situation of producing for the described order of packages was analysed and the results are that the company needs over 207 h to fulfil the customer order, inside the company (the external transportation was ignored as it is not important for the topic of research and has no influence on optimization results). Calculated 207 h are almost 15 work days while company works 8 h per day at two shifts with half an hour break for operators at every shift.

Table 1. Process of production of packages

No.	Operation name	Type of machine	time [s]	No. of machine	No. of work cell
Product 1: Flap package – classic method amount of order: 10.000 pcs					
1	Setting the machine	Cutter and creasing machine	200	1	5
2	Creasing	Cutter and creasing machine	1,3	1	
3	Stacking	Manually	0,8	1	
4	Machine setting	Cutter and creasing machine	180	5	5
5	Setting the machine	Cutter and creasing machine	6,5	5	
6	Putting aside	Manually	1	5	
7	Stapling	Stapling machine	0,9	16	2
Product 2: Flap package – boxmaker amount of order: 1.000 pcs					
1	Setting the machine	BoxMaker	155	19	7
2	Formatting and cutting	BoxMaker	25,8	19	
3	Gluing	Gluing workstation	5,2	17	1
4	Stacking	Manually	1	17	
5	Stapling	Stapling machine	0,7	16	2
Product 3: Flap package – with print amount of order: 10.000 pcs					
1	Setting the machine	Cutter and creasing machine	200	1	5
2	Creasing	Cutter and creasing machine	1,3	1	
3	Stacking	Manually	0,8	1	
4	Setting the machine	Printing complex	180	7	4
5	Preparation of paint	Manually	46	7	
6	Printing	Printing complex	18	7	
7	Drying	Printing complex	24	7	
8	Setting the machine	Cutter	124	3	6
9	Cutting	Cutter	8,5	3	
10	Stacking	Manually	0,8	3	
11	Gluing	Gluing workstation	5,2	17	1
12	Stacking	Manually	1	17	
13	Stapling	Stapling machine	0,8	16	2

(*continued*)

Table 1. (*continued*)

No.	Operation name	Type of machine	time [s]	No. of machine	No. of work cell
Product 4: Decoration package amount of order: 1.000 pcs					
1	Setting the machine	Automatic cutter	1800	9	3
2	Cutting	Automatic cutter	3,8	9	
3	Tearing off	Manually	3,2	9	
4	Gluing	Gluing workstation	12	17	1
5	Stapling	Stapling machine	1,5	16	2

Table 2. Capacities and functions of work cells

No. of work cell	Work cell name	Machines	Work cell function	Capacity of work cell
1	Bounding cell	17, 18	bounding, batch bounding	2
2	Stapling cell	14, 15, 16	stapling of batches	3
3	Cutting cell	9, 10, 11	cutting with pattern	3
4	Printing cell	7	printing, drying	1
5	Creasing cell	1, 5, 6, 2	cutting, creasing	4
6	Blanking cell	3, 4	cutting, pattern cutting	2
7	BoxMaker cell	19	ready-made packages	1

The idea for improving the production process is to use optimization algorithm for better planning and increasing utilization of machines. Then, in the next sections, we propose the mathematical model of the considered production order, and metaheuristic ant colony algorithm.

3 Problem Formulation

In the production process there are given $p = 1, 2, ..., P$ products, dedicated for manufacturing with production machines $m = 1, 2, ..., M$. Production process of each product p is composed of strict sequence of operations (different for different types of products).

Analyzing the details of the considered production process (Table 1) it may be noticed that:

- some seed operations may be grouped into one operation, if they are performed with the same work cells. For example, operation 2 and 3 for product type 1 may be grouped into one operation.
- some operations are the same for different products types, performed in the same work cell ant with the same time (i.e. 2,3 for product type 1 and 2,3 for product type 3).
- the sequences of work cells used for all product types are quite strict – i.e. cell 2 is always used for last operation, cell 1 is never used before cells 3–7, etc.
- each operation is required no more than once for each product.

Let $o = 1,..,\ O$ be the possible operations performed in the production system (for considered problem, some operations will be grouped and threated as one – like described above). Each operation o is unique, and operations are sequences in the same manner like in production processes. (operation o is always performed before operations $o + 1,\ o + 2,...,O$ in production processes).

Taking into account the above observations, the sequences of operation required for each product may be presented in the form of binary matrix $V = [P \times O]$, such that:

$$v_{po} = \begin{cases} 1, \textit{if operation } o \textit{ is required for product } p \\ 0, \textit{otherwise} \end{cases}$$

For example, if the row of matrix V is [1 0 0 1 1], it means that operations 1, 4 and 5 (exactly in this order) are to be performed for manufacturing the product.

Let $W = [O \times M]$ be the binary matrix defining machines possible for completing operations:

$$w_{om} = \begin{cases} 1, \textit{if operation } o \textit{ maybe completed on machine } m \\ 0, \textit{otherwise} \end{cases}$$

Machines with the same set of possible operations build one cell work, however they are modeled as many single machines.

Let t_o be the time required to complete operation o. In the model, it is assumed that each machine is able to perform many operations from the set O. In practical application, switching the operation is connected with additional time, required to adjust the proper machine setting. Let r_{om} be the time required to prepare machine m for operation o. Notice that the setting operation is not done, while machine repeats the same operation o many times.

Let S_{po} be the time of starting and C_{po} be the time of finishing operation o for product p, of course $C_{po} = S_{po} + t_o$. The time of finishing all products C_{max} is equal to the greatest value of C_{po}:

$$C_{max}(\pi^*) = \min_{\pi} C_{max}(\pi)$$

The goal of optimization is to find such sequence π* of performing operation on all machines, for which:

$$C_{max}(\pi^*) = \min C_{max}(\pi)$$

4 Algorithm

For solving of optimization problems, like the considered one, formulated in previous section, exact or heuristic algorithms may be developed and used. Exact algorithms obtains the optimal solutions, but the disadvantage is the long computation time – then they usually are not able to obtain solution for complex problems (e.g. problems with high number of decision variables). For that reason, heuristic or metaheuristic algorithms are being introduced, they allow for finding sub-optimal solutions, but guarantee solving the optimization problem in rational time. For considered problem, the number of decision variable is relatively high (22 000 pcs of products), what causes uselessness of exact methods. Then the metaheuristic approach (based on ant colony optimization) is proposed in the paper, it allows to find the solution close to optimal, within rational computation time.

Ant Colony Optimization (ACO) is a method inspired by natural process of acquiring food by ants. It belongs to the group of meta-heuristics which allow for analyzing many solutions of an optimization problem [16]. The idea of ACO is based on pheromones, which are left by ants that are searching for food [9, 13]. When ants go out to find food for the first time, they routes are chosen randomly. After finding a source of food, they return to the ant colony, leaving pheromone trail behind them [18]. Thanks to this, during the next search for food they are not moving at random, but follow the pheromones. However the pheromones evaporate and the longer is the route, the longer the time needed to find food. Thus pheromones are more intense on shorter routes and they are used by ants as signpost indicating the route to food [11].

The idea of the proposed algorithm is as follows: all single operations required for all products are being considered, in given order – each single operation is represented with the value '1' in the matrix *V*. For each operation the starting time and the machine for performing the operation is scheduled, and the goal is to plan the starting time of each operation as early as possible. The following rules of scheduling are assumed:

(a) for $o,u = 1,..,\ O,\ o > u,$ operation v_{po} may not be considered before operation v_{pu}.
(b) for $o,u = 1,..,\ O,\ o > u,$ starting time of operation v_{po} may not be earlier than completing time of operation v_{pu}.
(c) operation o may be scheduled on machine m, for which $w_{om} = 1$.

Consider a simple example. Assume that the scheduling order of operation for 3 products is following (number of machine and time required for operations are given in brackets: v_{11} (1, 3 s), v_{21} (1, 3 s), v_{12} (2, 3 s), v_{31} (2, 2 s), v_{13} (3, 3 s), v_{32} (3, 5 s). Proposed order satisfies above rule *a*. Schedule is presented in the Table 3. Operation v_{11} have been scheduled as the first one, it can start in time 1. Operation v_{21} was considered as the second one and it have been scheduled from time 4. Next operation (v_{12}) have to be performed on machine 2, but it may not be started before finishing v_{11},

then it starts in second 4. Operation v_{31} may be scheduled at time 1 on machine 2, since machine 2 does not have any job scheduled this time yet. Finally all products will be manufactured in 14 s. Scheduling operation basing on this scheme is very simple, but the sequence of scheduling may be critical for final result. In the considered example, imagine that the position of last to operations in allocation sequence is opposite (v_{32} is allocated before v_{13}). Then, v_{32} may start in second 3, and all products would be finished in 10 s. In proposed ACO algorithm, the best sequence of operations' allocating is assigned be the colony of ants.

Table 3. Operation scheduling at 3 machines

Machine 1	v_{11}			v_{21}											
Machine 2	v_{31}			v_{12}											
Machine 3							v_{13}			v_{32}					
Time [s]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

In considered production scenario, some of machines require preparing (setting) while switching performed operation. In such situations, preparing time r_{om} is taken into account, and scheduled on machine m before operation o.

Modelling the route of ants is made with the graph with the number of nodes equal to number of all operations, given with V. Each node represents one operation. Additionally, initial (starting) node is added to the graph. Finally, graph is expanded with the additional links:

- direct links from initial nodes to the nodes representing the first operation of each product;
- for each node representing the operation v_{po} - direct link to node representing operation $v_{p(o+1)}$
- for each node representing any operation of product p - direct links to all nodes representing operations of other products.

The route of ant starts in initial node, ant have to visit all nodes in the graph. After visiting of any node in the graph, the links leading from other nodes to visited node are forbidden for the ant.

Concurrently to the ant travel, the sequence π of visited nodes is used for scheduling operations, as described above and presented in the Table 1. Finally, the finishing time of all operation is the indicator of the route quality. The pheromones are lived on all links traversed by the ant. The amount of pheromones is inverse proportional to the quality of obtained route (time C_{max} of manufacturing all products). Moreover, the evaporation of pheromones, given with coefficient ρ, is assumed. Finally, the amount of pheromones τ_{nm} on links (n,m), traversed by the ant is modified with the formula:

$$\tau_{nm} = \tau_{nm}(1 - \rho) + (1/C_{max}),$$

The amount of pheromones on links not used by the ant is only decreased according to evaporation ratio: $\tau_{nm} = \tau_{nm}(1 - \rho)$.

In each node n, the next link (n,m) of ants route is chosen randomly, from the set of not forbidden links. Forbidden are links to already visited nodes and links representing such operations for product p, for which the previous operations for p have not been done yet (rule a). The probability of choosing link leading to node m is following [19]:

$$\Phi_{nm} = \frac{(\tau_{nm})^{\beta}(\eta_{nm})^{\alpha}}{\sum_{m \in N_n}(\tau_{nm})^{\beta}(\eta_{nm})^{\alpha}}$$

where:

τ_{nm} - is the amount of pheromone on the link (n,m),

η_{nm} - is the heuristic value, describing the profits of choosing link (n,m). η_{nm} is calculated in the following way. Algorithm finds, in the schedule, the earlier possible time t, when operation related to node m may be scheduled. It is also validated, whether the machine setting will be required for scheduling. Then $\eta_{nm} = r_{om}/t$.

α, β - are the parameters of the algorithm.

The scheme of the ACO algorithm is presented below. The number of ants is a parameter of the algorithm. Each ant leaves pheromones along the route, procedure *Update pheromones* performs operations of reinforcement and evaporation on the graph links [18]. The result of the algorithm is the sequence of visiting nodes, which offer the best schedule of operations on machines.

```
Ant Colony Algorithm
    for each Ant do
      Put ant in initial node
      repeat
        Calculate values of η for possible links
        Random link
      until (all nodes visited)
      Update pheromones
    done
```

5 Results

The main purpose of the algorithm was to solve the production optimization problem presented in the beginning of the paper. In order to obtain the best results from the proposed metaheuristic ACO algorithm, values of all parameters α, β, ρ, and the number of ants should be carefully adjusted. The tuning was performed for a smaller instance of the considered problem: the following number of required products have been assumed: 20 pcs each of product 1 and product 3, 2 pcs each of product 2 and product 4. Experiments for each investigated set of parameters were repeated 10 times, and results were averaged. Examined values of all parameters, as well as selected (assuring best algorithm performance) values are presented in the Table 4.

Table 4. Examined and selected values of ACO algorithm

Parameter	Examined values	selected value
α	1, 2, 3, 5, 8, 20, 50, 100	8
β	1, 2, 3, 5, 8, 20, 50, 100	1
ρ	0.001, 0.0025, 0.005, 0.0075, 0.1, 0.2, 0.3	0.0075
Number of ants	25 000, 50 000, 100 000, 150 000	10 000

Solving the problem for product order presented in the Table 1, some additional simplifications had to be accepted. As it have been noticed, the number of ordered products (22 000 pcs) is too high for building graph representing them, and links between. Also the time, required for obtaining route for ants, as well as scheduling operations and updating heuristic values, would be not acceptable. Then, the optimization process have been performed for less number of products, and multiply obtained operation scheduling sequence. The suboptimal sequence was obtained for: 100 pcs of product 1 and product 3; 10 pcs of product 2 and product 4. Sequence have been repeated to plan the production process of all 22 000 pcs of products (whenever it have been possible, the machine setting operations were eliminated from consecutive sequences).

The best schedule, obtained with proposed ACO meta-heuristic, allow to complete all demand products in time of 179.4 h. It is worth to notice, that proposed optimization model does not take into account possible delays related to transport issues of materials and products, intermediate storage limitations, etc.

6 Conclusion

The main challenge, faced while constructing the solving solution, was the huge number of products, for which the production process have to be planned. In order to mitigate this problem, following method have been proposed: the problem have been solved for smaller number of products first, and then the obtained sequence have been used many times to plan production for all ones. However, it is not guaranteed that results of such approach are really close to optimal. As the future work we plan to search for more efficient model and construction of algorithm, which allow for improving solutions of considered problem.

The aim of the study was to find a solution that allows for reducing the entire production lead time for a given order. The aim was achieved with the use of the Ant Colony Optimization method, which allowed for reducing the time of production process from 207 h (about 15 days) to 180 h (about 13 days) – the exact number of days was presented in Fig. 1.

We need to emphasize the fact, that the performed analysis is based only on production lead time and does not include the near-production processes, e.g. transportation or storage. This is not a huge difference, but important fact is that we did not

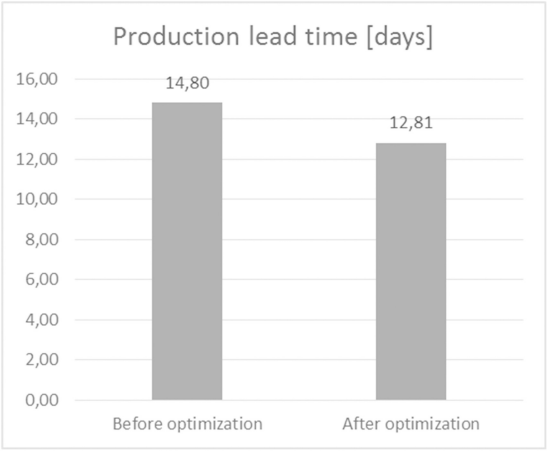


Fig. 1. Production lead time before and after optimization

change anything except the way of performing the production process. The company does not need to buy new machines or change the layout to implement the results. That means that they actually do not need to invest any money. In view of the above, these 2 days of reduction of production process lead time are a change that is easy to reach. Thus the improvement is noteworthy.

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Optimization of the Supply of Components for Mass Production with the Use of the Ant Colony Algorithm

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Abstract. The paper raises the issue of adapting the logistics processes to the changes in the manufacturing area. The continuous improvement of production processes enforces searching for better solutions for the milk run to achieve shorter time of the milk run loop. In the paper we propose integer linear programming (ILP) model ant the intelligent ant-colony based meta-heuristic algorithm for the milkman problem. The tuning process of algorithm and the verification of algorithm performance are reported in the paper. Proposed algorithm is then utilized for solving real-life production line provisioning problem.

Keywords: Logistics processes · Milk run · Ant colony optimization (ACO) · Meta-heuristics · Intelligent optimization methods of production systems

1 Introduction

Nowadays, changes in production processes occur very rapidly; firstly, this is associated with the necessity of the continuous improvement of products models to meet the customers' expectations and maintain the competitive edge; secondly, the continuous improvement of processes at various levels has become a common practice in the industry [1, 6, 9, 11]. According to the system approach to management, all the improvements implemented in a given process entail the necessity of making adequate changes also in the interrelated processes [7, 20]. Thus, the modifications that occur in manufacturing processes require that also other areas (including logistics processes) need to be adapted to the manufacturing processes [5, 12]. One of the issues that should be considered is the need of adapting the way the parts are delivered to the workstations. It results both from the start of the production of a new model (that requires other/additional elements in relation to the previous models), as well as from the improvements in the production area that translate into shorter cycle time (and thus a faster collection of components for production).

The paper examines a case where parts are delivered with the use of the milk run concept. Changes in the manufacturing area result also in changes in the optimal solution

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for the milk run driver stops locations, which are selected most frequently at the start of the method implementation and are rarely modified – mainly due to the fact that this requires a lot of time. The aim of the study is to build a model that would allow obtaining the shortest time of the milk run loop with the use of the resources available, by selecting the number and locations of stops depending on the quantity, size and weight of components delivered to the workstations in the selected example.

1.1 Milk Run Concept in Components Delivery

Milk run concept is a method of delivering materials with a high frequency, but in small quantities. The idea of the method, as the name suggests, is derived from the delivery of milk bottles by the milkmen to houses and flats. The required materials are loaded on trucks and then distributed according to the plan, which includes all target points in accordance with the milk run loop (Fig. 1). Empty containers and packaging are collected from each workstation (like empty bottles) and transported to the warehouse to be replaced with materials for the following round. The method allows increasing the smoothness of delivery of semi-finished products to the production line as well as reducing waste in the form of WIP inventories and unnecessary transport, and thus also reducing the costs [10, 13, 16, 17].

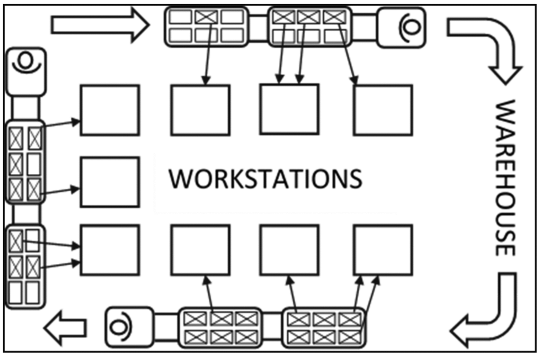


Fig. 1. Milk run concept

In the paper we consider the production line, with workstations and intermediate storage areas (called *areas* in the rest of the paper), provisioned from the logistic train. The train moves along the line and stops in few selected stop locations (called *stops* or *stopping points* in the rest of the paper). Packages are then transported from the train to storage areas, by humans of trolleys. Provisioning time of whole production line is the sum of moving train along the line (constant), time required to stop and start the train (depends on number of stops) and the time to move packages from the train to storage areas (depends on the distance from train stop to storage areas and the number of packages).

2 Model and Problem Formulation

We assume the P intermediate storage areas distributed along the production line (consecutive areas we denote with $p = 1,2,..,P$) and discrete set of S potential train stops (consecutive stops are denoted with $s = 1,2,..,S$). Let w be the cost of starting and stopping the train, the same for each stop. Let v_{ps} be the cost of delivery of all packages from the train staying at stop s to the area p. v_{ps} represents the time of delivery and is calculated as $(d_{ps} / \omega * h_p)$, where d_{ps} is the distance between points s and p (in meters), ω is the velocity of trolley/human and h_p is the number of packages delivered to area p (we assume that capacity of trolley/human is equal to one package).

Let y_{ps} be the binary decision variable determining whether the area p is provisioned from the stop s, and x_s be the binary variable indicating whether the train stops at stop s:

$$y_{ps} = \begin{cases} 1, & \textit{if area p is provisioned from train stop s} \\ 0, & \textit{otherwise} \end{cases}$$

$$x_s = \begin{cases} 1, & \textit{if train stops at stop s} \\ 0, & \textit{otherwise} \end{cases}$$

Values of variables x_s strictly depend on values of y_{ps}, since x_s is equal to 1 only if any of areas must be provisioned from stop s. Let T be the objective function, representing the total time of provisioning. The optimization problem is defined as follows:

$$\min T = \sum_{s=1}^{S} x_s w + \sum_{s=1}^{S} \sum_{p=1}^{P} y_{ps} v_{ps} \tag{1}$$

subject to:

$$\sum_{s=1}^{S} y_{ps} = 1, \ \textit{for each } p = 1, .., P \tag{2}$$

$$P x_s \geq \sum_{p=1}^{P} y_{ps}, \ \textit{for each } s = 1, .., S \tag{3}$$

The goal (1) is to minimize total cost (time) T. T includes time of stopping/starting the train at each stops where train stops (then x_s is equal to 1) and time need to delivery packages to all areas. We assume that the time required for train to move along all production line is constant (depends only on line length and train velocity), then it is not considered in the model. Constrain (2) quarantines that each area will be provisioned from exactly one stop (for each area p one of y_{ps} variables is equal to 1, all others are equal to 0). Constraint (3) defines whether value of x_s should be equal to 1. If any of y_{ps} is equal to 1 for given s (any area must be provisioned from stop s, then value x_s must be greater than zero in order to satisfy this constraint (train must stop at s). P (at left

side) allow to assign value not bigger that 1 to x_s (values of x_s are to be minimized according to objective).

3 Ant Colony Algorithm

Ant Colony Optimization (ACO) algorithms belong to the group of swarm optimization metaheuristic techniques [15] which are inspired by the natural environment. They allow finding a near-optimal solution which are inspired by the natural environment. They allow finding a near-optimal solution [14] for complex problems [3, 4, 19] in a relatively short time. The idea of using ACO as a method for finding the optimal solutions to problems was presented in 1992 by Marco Dorigo [2] who was inspired by the behavior of an ant colony [22]. When acquiring food, ants jointly reach it and then transport it back to the colony, being guided by simple instincts. The selection of transport routes is based on pheromones (synthetic substances secreted by ants during their movements). In the natural conditions, when ants leave the ant colony in search for food, at the beginning they move in random directions. After finding food they transport it back to the ant colony, marking the path as worthy of attention during the following searches. The pheromones affect other ants, which choose the same route and thus further strengthen the amount of pheromones, creating the beaten track from the ant colony. The optimal path appears through the evaporation of pheromones. In the case of multiple possible paths having a similar pheromone intensity, ants choose at random, so their number on each of them is similar and consequently the greatest traffic intensity is on the shortest route, attracting more and more ants. It means that the shortest path (the most optimal solution) becomes selected most frequently (a standard) and the other disappear [3, 14]. These observations became an inspiration for creating computer algorithms used to search for optimal solutions in various areas [21].

For the ACO algorithm, the provisioning system is modeled as a directed graph with $P+S+2$ nodes. Node 0 represents the starting point of the train, nodes $1,2,\ldots,P$ represent the areas, nodes $P+1, \ldots, P+S$ - the stops, finally node $P+S+1$ represents the final end of train route. We add links (edges) of graph according to following rules:

- we add directed links from node 0 to all nodes representing the stops (nodes $m = P+1, \ldots, P+S$). Cost of each link is denoted as w_Ω and it is updated after each step of an algorithm. Calculating of w_Ω is described later in this chapter. Links represent the move of a train to the first stop.
- for each node $m = P+1, \ldots, P+S$ (stops), we add directed links from m to each node $n = 1,2,\ldots,P$ (areas), with cost v_{nm} and directed link from n to m with cost 0. Links represent the delivery of packages from stops to areas.
- for each node $n = P+1, \ldots, P+S$, we add directed links to nodes $m = n+1, \ldots, P+S$, with cost of each link equal to w_Ω. Links represent moving the train to the next stop.
- for each node $n = P+1, \ldots, P+S$, we add directed link to node $P+S+1$, with link cost 0, those links represent finishing the delivery process and moving train to storage.

The aim of each ant is to move from starting point (node 0) to node $P+S+1$, along the graph, visiting all nodes $1,2,\ldots,P$ (areas). In each node, one of possible links is chosen in random manner. The set of links possible at each node $P+1, \ldots, P+S$ is updated according to already visited nodes $1,2,\ldots,P$. Particularly, when node n, representing the area ($n = 1,2,\ldots,P$), have been already visited, all links (n,m) and (m,n), for $m = P+1, \ldots, P+S$ are removed from the graph. This is because nodes representing the areas may not be visited more than once. Moreover, links to node $P+S+1$ (final node) are added to the graph only when all nodes $1,2,\ldots,P$ have been already visited (all areas have been provisioned).

An example of possible moves is presented in the Fig. 2. Assume logistic system consisting of 3 possible stops (nodes *s1, s2, s3*) and 4 areas (nodes *p1, p2, p3, p4*). From start point at node 0 (Fig. 2a), ant can move to one of nodes representing train stops. Assume that, after few moves, the ant is at node *s1*, and nodes *p1* and *p3* have been already visited (Fig. 2b). The next possible moves of ant are: node *p2* (provision area 2) or node *p4* (provision area 4), node *s2* (move train to stop 2) or node *s3* (move train to stop 3). Assume the next steps have been done to nodes *p2* and *p4*, After that, all nodes $p1,p2,\ldots,p_P$ have been visited, and the link to node 8 (finish) is added to the graph (Fig. 2c), finally it is the only possible move.

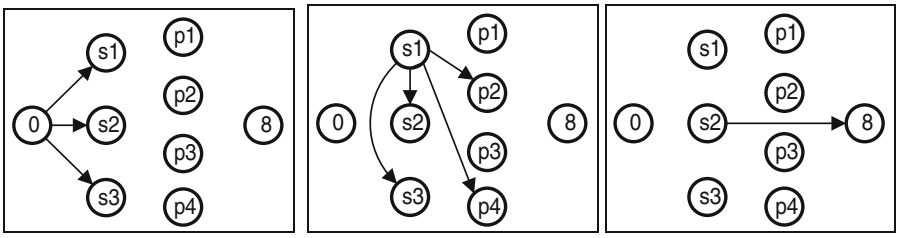


Fig. 2. Possible moves of ant: ant at start node (a), ant at node *s1* after visiting nodes *p1* and *p3* (b), ant at node *s2* after visiting all *p* nodes (c)

Let T_a be the value of criterion obtained by ant a, and T^* be the value of T for the best already found solution. Algorithm 1 presents the pseudo-code of proposed ACO algorithm (based on [18]). The important parameters of the algorithm are the number of colonies and number of ants in colony (the same for all colonies). Each ant in the colony starts from node 0 (line 4), then, in next steps, one of possible links is chosen and ant moves to the next node (lines 5–8). After ant reaches the end node, the cost T_a of ants path is calculated, and the best cost is updated if applicable (line 10). After all ants in colony finished their routes, the pheromones are leaved on graph links (line 12). Pheromones are leaved only along the best path, obtained by one of ants in colony.

Algorithm 1. Ant Colony pseudo-code for considered problem

```
1   T* =
2   for each Colony do
3     for each Ant a do
4       Start ant from node 0
5       repeat
6         Update graph
7         Draw next step
8       until (end node reached)
9       Calculate T_a
10      if (T_a<T*) then T*=T_a
11    done
12    Update pheromones
13  done
14  return solution with T*
```

Operation *Update graph* removes links from the graph, according to the rules described above and illustrated in the Fig. 2 (after visiting p nodes). Also the weights for some links are updated. Particularly, the weights between nodes (n,m), where $n = P+1, \ldots, P+S$ and $m = n+1, \ldots, P+S$ (nodes related to stop points of the train), are recalculated basing on the set of not provisioned nodes $1,2,\ldots,P$ (areas). The weight of link (n,m) is denoted as w_Ω and calculated as the sum of stopping/starting cost of train (w) and the average cost of delivery packages from stop m to all still not provisioned areas. Such construction of costs between stopping points allows to decrease the probability of stopping train in not beneficial nodes s.

The goal of operation *Draw next step* is to choose the next node (given by one of existing links adjacent to present node) for visiting by the ant. The choice is made in random manner, and the probability of choosing node m for ant staying at node n is given by the formula [14]:

$$\Phi_{nm} = \frac{(\tau_{nm})(\eta_{nm})^{\alpha}}{\sum_{m \in N_n} (\tau_{nm})(\eta_{nm})^{\alpha}}$$

where:

τ_{nm} - is the amount of pheromone on the link (n,m),

η_{nm} - is the heuristic value defining the profitability of choosing link (n,m), calculated as the reciprocal of weight of link (n,m). Weights are determined according to the rules presented at the beginning of this chapter. For $m = 1,2,\ldots,P$ (areas) and $n = P+1, \ldots, P+S$ (stops) the weight of link is equal to the cost of delivery of all packages from the train staying at stop n to the area m (v_{ps}), and $\eta_{nm} = 1/v_{ps}$. For $n = P+1, \ldots, P+S$ and $m = n+1, \ldots, P+S$ (nodes related to stop points of the train), $\eta_{nm} = 1/w_\Omega$.

Operation *Update pheromones* is composed of two elements: leaving of pheromone by the ant and pheromone evaporation. We assume, that only one ant in the colony leaves pheromones – the ant c for which the value of criterion T_c is smallest in the colony (ant, which have obtained the shortest route). The reinforcing of pheromones, along the path of best ant is proportional to the path quality:

$$\tau_{nm} = \tau_{nm} + \lambda\left(1/T_c\right),$$

where λ in an reinforcement factor.

We also assume that pheromones on each link evaporate [18], evaporation is done once for each colony, and is given with the formula:

$$\tau_{nm} = \tau_{nm}(1 - \rho)$$

where ρ is the evaporation factor.

Parameters α, β, ρ and λ, as well as the number of ants in the colony and number of colonies are the parameters of an algorithm. The values of parameters may have important impact on the performance of an algorithm, then they should be properly chosen for considered problem.

4 Experiments

The goal of experiments was twofold: the first to tune the ACO algorithm and verify the quality of approximate solutions, the second to solve the problem for real production environment.

4.1 Tuning of Ant Colony Algorithm

In order to guarantee the best performance of proposed algorithm, it should by 'tuned', what means that the values of all parameters (α, β, ρ, λ, number of ants in colony, number of colonies) should be selected in such a way to ensure the best quality of solutions. Tuning process consists in running algorithm with various sets of parameters and observing the results. From the practical reason (infinite number of various sets), tuning is usually provided for discrete values of parameters from assumed range. For tuning purposes, simple production scenario, with 3 stop points and 8 areas have been generated (in random manner). Then, experiments were performed with various sets of parameters. Since the proposed ACO algorithm is not deterministic, experiments for each set of parameters were repeated 10 times, and results were averaged. The values of algorithm parameters, tested during tuning process, and selected (best) values are presented in the Table 1.

Table 1. Examined ACO algorithm parameters

Parameter	Examined values	Selected Value
α	0.1, 0.5, 0.75, 1, 2, 3, 5, 50	0.75
β	1, 10, 100, 1000	1
ρ	0.001, 0.002, 0.005, 0.01, 0.1, 0.025, 0.2	0.001
λ	0.2, 0.5, 1, 2, 5	1
No ants in colony	5, 10, 20, 30, 40	10
No colonies	5 000, 10 000, 20 000, 50 000	10 000

For simple scenarios, used in tuning process, the approximate solutions obtained with ACO algorithm were compared with optimal solutions. Optimal solutions were obtained from CPLex solver [8], using the model proposed in Sect. 2. Obtaining of optimal solutions for more complicated problems (with tens/hundreds of possible stop points and areas), most important from practical point of view, usually is not possible in reasonable time and with reasonable amount of resources (like computer memory or processing power). Then, for more complex scenarios heuristic or metaheuristic (like proposed ACO) methods are the only solution. For the simple scenarios, proposed ACO algorithm was able to find optimal solution of considered problem in around 23% of experiments. Average distance from the optimal solution was 4%.

4.2 Case Study

The decision to build a model to optimize the way of components delivery was inspired by a real company, where the problem mentioned above was observed (which does not exclude the possibility of modifying the program for other cases). The input model is a flow assembly line for batch production, which is schematically shown in Fig. 3.

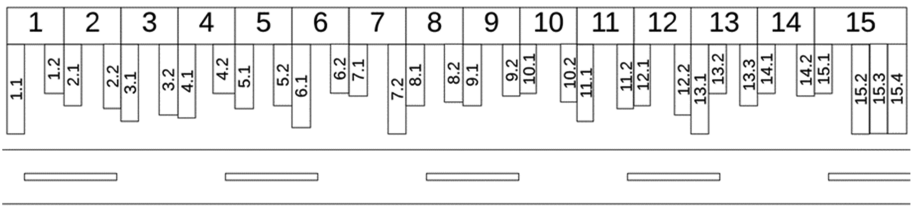


Fig. 3. Scheme of the considered production line

It was assumed that both the locations of the workstations (designated with numbered 1–15) and the distance from the intermediate storage areas (1.1–15.4) to the transport route were fixed in this case. Transports quantity for each workstation (depending on the quantity, size and weight of delivered components), the velocity, starting and breaking time of logistics train and also the velocity of elements delivery were applied to the program as the limitations for the established function of the objective. Additionally, for simplicity of first model, it was assumed that the logistics train is a point.

The potential stopping points of train are important input data for proposed algorithm. In experiments we assumed, that they are uniformly distributed along the production line, at the sector between first (1.1) and last (15.4) storage area. For various experimental scenarios #1–#5, different distance between neighboring stops was set, as presented in the Table 2 (in result, different number S of stopping points was considered in each scenario). It is important to notice, that delivery time T, obtained with proposed algorithm, does not include the time required for moving train from the begging to the end of production line – we have assumed that this time is constant (equal to the length of production line divided by the velocity of train) and does not depend on the number of stops.

Table 2. Experimental setup

Scenario	#1	#2	#3	#4	#5
No of potential stops *(S)*	13	32	62	125	310
Distance from s_j to s_{j+1}	5 m	2 m	1 m	0.5 m	0.2 m

Results of experiments are presented in the Fig. 4. We may observe, that the number of potential stops has the important impact on the quality of solutions. For the considered scenario, the delivery time decreases remarkably while the distance between stops decreases from 5 m (scenario #1) down to 1 m (scenario #3). We may also observe, that further decreasing the distance between stops (and the same increasing the number of potential stops) does not improve importantly the quality of solution – delivery time decreases very slightly for distances between stops less than 1 m (scenarios #4 and #5). We may conclude that optimal distance between stop points, for production line similar to considered in experiments, is equal to 1 m.

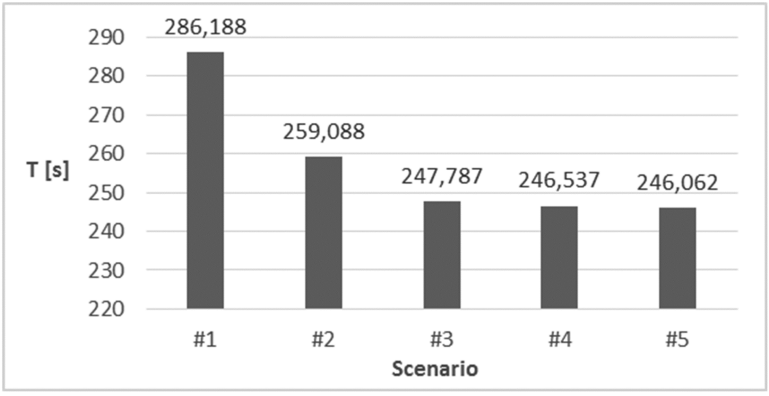


Fig. 4. Delivery time for scenarios 1–5

5 Conclusion

In the paper the milkman problem for production line was considered. The model for finding the solution was created and it enables selecting the number and location of stops to achieve the possibly short time of milk run loop for the selected example. We have proposed the ILP model for considered problem and propose original, intelligent optimization method based on meta-heuristic ant colony approach. For the ACO algorithm we have proposed the construction of graph, corresponding to milkman problem, designed the route selection for ants and selected the optimal parameters for best algorithm performance. For simple problem instances, meta-heuristic results were compared with optimal ones, obtained with CPLex solver. Finally, we have used proposed algorithm to solve the real-life production line optimization problem. Proposed intelligent approach may be successfully applied for optimizing production environments.

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Predictive Scheduling as a Part of Intelligent Job Scheduling System

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Abstract. Production processes are inseparably connected with numerous factors hindering their course. It is therefore essential to ensure that the process is carried out with no disruptions, which demands that these are identified and compensated for in advance. This paper presents intelligent job scheduling system under uncertainty. The first section gives a brief overview of job scheduling in manufacturing. The second section examines robust scheduling as a solution to production process disruptions. Furthermore, the idea of predictive/reactive scheduling is presented, highlighting the essence of predictive scheduling in a production process with two-factor uncertainty.

Keywords: Production scheduling · Robust scheduling · Intelligent scheduling system

1 Introduction

The strive for efficiency of production processes requires that they should be planned and prepared prior to execution. Production scheduling is a vital solution that addresses a number of production-related problems [1, 2].

Although the idea of job scheduling appears uncomplicated, there exist numerous factors, referred to as uncertainty factors, which discard the job schedule immediately after the production process is initiated, which in turn leads to disorganisation and nervousness [2]. The analysis of typical production processes allows us to specify several sources of uncertainty, such as: operation processing time, preparation and due times, time and availability of transportation, machine availability, the availability of personnel and tools, as well as the availability of materials and semi-finished product [2, 3]. When they occur, such problems could result in decreased competitiveness of the company and crumbling trust of customers, which is what no company can afford in the contemporary, highly competitive world. Therefore, there emerges the need for research into consequences of potential disruptions, not to mention their management and compensation, as a method of achieving stability of executed processes [2, 4].

Problems of production process optimisation with the application various solutions are undertaken in many fields [5–7], however, there is a marked deficiency in solutions

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devised for aiding scheduling in actual production systems [1, 4]. In this context, the study was devoted to intelligent job scheduling system accounting for predictive scheduling.

2 Multi-machine Job Scheduling in Production Systems

Job scheduling in actual conditions involves a number of aspects concerned with *inter alia*, production process dynamics or mathematical complexity of scheduling problems. Existing limitations have lead to developing a separate branch of knowledge devoted to the outstanding issues, *i.e. robust scheduling*, which is also referred to as *scheduling under uncertainty*. Robust scheduling is a process, taking into account variability of parameters of the production system, which produces a schedule characterised by its potential for absorbing disruptions. The schedule is developed to counteract instability and nervousness [8–10].

Robust scheduling is inseparably connected with predictive-reactive scheduling, which constitutes a combination of the two aforementioned methods for scheduling under uncertainty [10–13]:

1. Predictive scheduling, is connected with the planning stage, and referred to in literature as *off-line scheduling*, which is when the following schedules are developed:
   – nominal schedule – based on actual parameters of a system,
   – predictive schedule – taking into account uncertainty and flexibility of the executed process.
2. Reactive scheduling pertains to the execution stage and is referred to as *on-line phase*. The schedule is created or modified in production. Any change of the process results in the implementation of an alternative schedule.

Robust scheduling aims at minimising the effect of various disruptions on the process in execution. The developed schedule will thus ensure that no loss of performance occurs in the presence of disruption. Most common techniques of creating robust schedules include [9, 11]:

- redundancy-based techniques,
- conditional scheduling,
- creating partially ordered schedules,
- schedule sensitivity analysis.

Implementation of robust schedules and related techniques enables scheduling in actual production systems, where standard solutions frequently demonstrate gross inefficiency.

3 Intelligent Scheduling in the Production System

Application of robust scheduling principles in production demands employing a series of solutions for analysis of executed processes and building predictive-reactive schedules. This has led us to proposing an intelligent robust scheduling system, presented in Fig. 1.

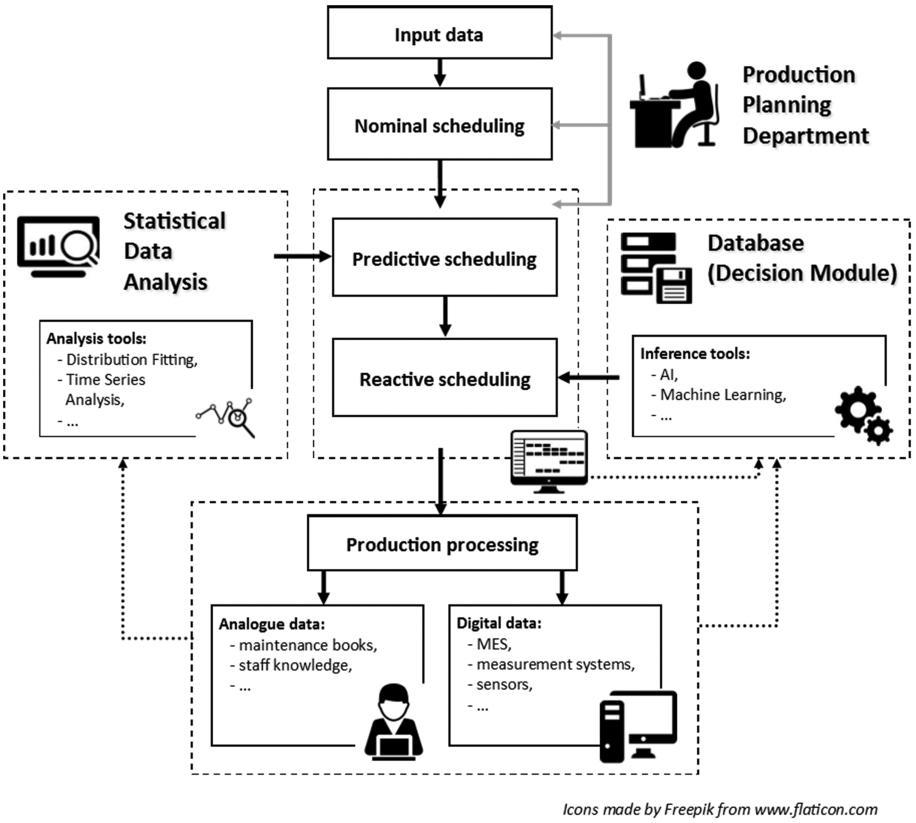


Fig. 1. Overview of the proposed job scheduling system (Source: own study)

The major elements of the proposed system are as follows:

- Statistical Data Analysis Module,
- Database with Decision Controller,
- Predictive-Reactive Scheduling Module.

Each element of the system contributes its functions to the global job scheduling process. The entire system is based on data obtained in the execution of production processes, therefore our model includes feedback. Data acquisition is carried out in either analogue, which requires the input by the operator, or digital manner, managed by specialist hardware. The acquired data is subsequently processed in the auxiliary modules of the system.

The Statistical Data Analysis Module provides support in the predictive stage of scheduling by examining data regarding machine failure and job processing time. Properly selected and processed with statistical tools, the data enables failure prediction and ensures robustness of the schedule by introducing buffer times in crucial areas of the schedule. The use of statistical data in predictive scheduling is a commonly investigated issue [14, 15]. The knowledge of actual job processing times is paramount to building

robust schedules for actual production conditions. The data employed at this stage are statistical and predominantly consist of historical information concerned with analysed disruptions.

The Decision Module is responsible for reactive scheduling stage. The module additionally includes the Database of uncertainty factors and historical data of scheduling problems (past consequences of rescheduling, optimal schedules, lateness of jobs, *etc.*). This AI-based module employs machine learning and grants decisions based on current and historical data, derived from the Database. Such solutions are increasingly widespread particularly in maintenance-related applications [16–18]. Growing database will allow the system to counteract particular risks with appropriate actions. Compared with the module aiding predictive scheduling, this module is characterised by dynamic data acquisition, inference and production scheduling.

The activities of the previously described modules are complemented and integrated by the Predictive-Reactive Scheduling Module. It is discussed here as a separate module to emphasise the key role of the operator in the Production Planning Department. The presented system by no means excludes human work from the entire process; it is rather shifted to an auxiliary function in production planning teams. Planners are responsible for supervision over the entire process of production scheduling, based on their experience and data gathered by the intelligent job scheduling system.

4 Predictive Scheduling with Two-Factor Uncertainty

The presented system is based on predictive scheduling. The essence of off-line scheduling is best highlighted when analysing the effect of uncertainty factors regarding job processing times and failure of selected technological machines. The simulation testing was conducted with LiSA (*Library of Scheduling Algorithms*) software under certain assumptions. The analysis consisted in executing subsequent stages of production process scheduling [11, 19], *i.e.*: defining the production system environment, input data, objective function and selection of scheduling method. Execution of theses stages allowed us to conduct the simulation.

4.1 Assumptions in the Analysed Production Process

It was assumed that the production consists in processing six jobs of defined machine route in the stock of ten machine tools/cells in a layout representing a job-shop system. Each element is a separate product, therefore there is a total flexibility in terms of release time and due dates of particular jobs. The elements are produced in the following batches:

- element 1 and element 2–100 pieces,
- element 3–80 pieces,
- element 4 and element 5–60 pieces,
- element 6–50 pieces.

The assumption is that production must be conducted at a shortest time. In addition, production process disruptions are allowed, and may occur as processing time delays and technological machine failure.

4.2 Input Data

Defining the input data required analysing 6 selected production processes, which provided the basis for the database processed by LiSA software in job scheduling. An example of a technological process is shown in Table 1.

Table 1. Technological process of producing element 5 (job 5) [20]

Operation No.	Machine No.	Operation	Setup time [hours/batch]	Operation time [hours/piece]	Total time [for 60 pieces]
10	1	Turning	0.75	0.01	1.35
20	2	Turning	0.4	0.01	1
30	5	Milling	0.4	0.02	1.6
40	9	Deburring	0.15	0.01	0.75
50	10	Polishing	0.3	0.01	0.9

The technological data served to develop a mathematical model, afterwards implemented in the software. The following were defined [19]:

- set of machines/cells M:

$$M = \{M_1, M_2, M_3, M_4, M_5, M_6, M_7, M_8, M_9, M_{10}\}, \tag{1}$$

- set of processed jobs J:

$$J = \{J_1, J_2, J_3, J_4, J_5, J_6\}, \tag{2}$$

- set of operations – in matrix of set of operations SIJ, which contains information regarding the use of machines in processing of production jobs (columns represent subsequent cells and rows – jobs; execution of a particular job on the machine is denoted by 1):

$$SIJ = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 \end{bmatrix}, \tag{3}$$

- matrix of processing times PIJ contains processing times of particular jobs on machines (and similarly as in SIJ, columns represent subsequent cells and rows – jobs):

$$PIJ = \begin{bmatrix} 3.16 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1.3 & 0 \\ 2.75 & 0 & 0 & 0 & 2.38 & 0 & 0 & 0 & 1.15 & 1.3 \\ 3.58 & 0 & 0 & 0 & 2.78 & 0 & 0 & 0 & 1.15 & 1.3 \\ 3.58 & 0 & 0 & 0 & 1.58 & 2.78 & 0 & 0 & 0.75 & 0.9 \\ 1.35 & 1 & 0 & 0 & 1.6 & 0 & 0 & 0 & 0.75 & 0.9 \\ 0 & 0 & 2.4 & 3.3 & 0 & 0 & 1.4 & 1.4 & 0.65 & 0.8 \end{bmatrix}, \tag{4}$$

- matrix of machine orders *MO* represents the rank of jobs on particular machines (and as in the case of previous matrices, columns represent subsequent cells and rows – jobs):

$$MO = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 \\ 1 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 3 & 4 \\ 1 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 3 & 4 \\ 1 & 0 & 0 & 0 & 3 & 2 & 0 & 0 & 4 & 5 \\ 1 & 2 & 0 & 0 & 3 & 0 & 0 & 0 & 4 & 5 \\ 0 & 0 & 1 & 2 & 0 & 0 & 4 & 5 & 3 & 6 \end{bmatrix}. \tag{5}$$

The next stage of input data preparation consisted in preparing data regarding uncertainty of the analysed process. In generation of the data in question, the following solutions were employed:

1. In the case of job processing times variability the random integer generator, based on atmospheric noise, accessed at RANDOM.ORG was used [21]. The available solutions generated percentage values of job processing times variation in the range of ±10%. A random selection of values generated for job 2, together with processing times are collated in Table 2.

Table 2. Variable processing times for job 2.

Operation	Standard time [hours/piece]	Variability factor [%]	Resulting time [hours/piece]
Operation 1	2.75	−7%	2.61
Operation 2	2.38	−6%	2.26
Operation 3	1.15	−7%	1.08
Operation 4	1.3	2%	1.32

2. Potential machine failure was included in the model as buffer times of suitable duration, which can be also treated as an indispensible machine servicing time. 3 machines subject to the highest workload were selected, M_1, M_5 and M_{10}, and the following failure parameters were defined for each machine:
   - machine M_1, failure can occur after 6 h of processing production jobs, time buffer of 2.5 h,
   - machine M_5, failure can occur after 8 h of processing production jobs, time buffer of 2 h,

– machine M_{10}, failure can occur after 18 h of processing production jobs, time buffer of 1.5 h.

Instances of machine failure were included in LiSA software as subsequent, one-operation jobs processed on machines at risk. Failure times were defined as job availability times of 6, 8 and 18 h respectively. The times were selected so as to occur in the period when the highest number of jobs are processed on the machine. The lengths of time buffers were derived from the technical data obtained from Maintenance Department of a selected manufacturing enterprise [14].

4.3 Objective Function

Defining the objective function is an essential element of any production scheduling process. The criterion should comply with two rudimentary conditions: converge with the objective of the enterprise and facilitate analysis of obtained results [22]. The objective function frequently serves as a gauge of implemented scheduling, and constitutes an excellent solution for comparative analysis of optimisation results obtained by different scheduling methods, including robust scheduling ones [3, 19].

In the present paper, the objective function of scheduling was optimisation of $C_{\max}$ (*make-span*) index, *i.e.* completion time of all jobs. The choice of the objective function was dictated by the initial assumption of minimising job completion time.

4.4 Selection of Scheduling Method

The method chosen for job-shop scheduling in the analysed case was scheduling with algorithm for dispatching rules. Numerous researchers in the field point at scheduling by dispatching rules as one of the most commonly applied methods in actual production systems [4, 10, 11, 14]. There are several advantages of the method, among which these are: quick solution, analysis of alternative scheduling scenarios, easy implementation of the method, which contribute to its popularity in industrial conditions.

The method schedules jobs on particular machines based on certain priority rules, according to which it chooses the next operation [4].

In the presented study, the following rules were applied:

- FCFS – First Come First Served (priority given to operations that first arrive to the machine),
- EDD – Earliest Due Date (priority given to operations with the earliest due dates),
- SPT – Shortest Processing Time (priority given to operations with the shortest processing time),
- LPT – Longest Processing Time (priority given to operations with the longest processing time),
- RND – Random (priority assigned randomly).

4.5 Simulation of Production

The application of LiSA software allowed us to conduct job scheduling for four different scenarios, whose results where then analysed. Each analysed scenario was based on different assumptions.

1. Scenario I: The length of operation times is derived from technological documentation.
2. Scenario II: Operation times are subject to change of maximum ± 10%.
3. Scenario III: three machines subjected to the heaviest workload can suffer failure (suitable service buffers were defined).
4. Scenario IV: three machines subjected to the heaviest workload can suffer failure, and operation processing times are subjected to change of max. ± 10% (a combination of scenarios II and IV).

4.6 Results of Simulation

The results obtained from the analysis indicate that the scheduling method based on several dispatch rules is suitable for application in actual production processes. The schedules produced in the study were obtained in short time and the results are transparent and easily analysed (Table 3).

Table 3. Value of C_{max} for each analysed scenario.

Dispatching rule	Value of C_{max} [hours]			
	Scenario I	Scenario II	Scenario III	Scenario IV
FCFS	20.25	20.36	22.84	22.97
EDD	20.25	20.36	22.84	22.97
SPT	20.43	20.15	24.83	24.65
LPT	18.80	18.81	23.72	23.64
RND	19.88	19.80	24.43	24.88

The obtained values of C_{max} index indicate that the value of makespan heavily depends on a particular dispatching rule applied. In the case of scenarios I and II the best optimisation was obtained with LTP, whereas when time buffers were introduced in the event of machine failure (scenarios II and IV) it was FCFS rule that produced the best optimisation.

It must be mentioned that taking into account changes of operation processing times has negligible effect on the makespan of schedule, while in SPT and RND rules it leads to a slight decrease in due time. However, the factor that did exert notable impact on the makespan was introducing the service buffers in the event of machine failure. In certain cases, the resulting change is considerable, yet in FCFS and EDD the time increases to 2.72 h. The decision whether the delay is acceptable or not is a debatable issue. Eventually, the predictive schedule might be indeed longer, nevertheless, it carries such benefits as increased stability and absorption of disruptions.

5 Conclusion

Production scheduling is an indispensible element of effective organisation and management of any production process. However, existing solutions for designing and optimising production jobs schedules are burdened with limitations due to dynamic nature of manufacturing and high mathematical complexity of scheduling. As a result, classical methods are highly ineffective in the conditions of actual manufacturing enterprises.

The optimised model schedule based on standard data requires continuous updating, which, bearing in mind NP-hardness of scheduling, makes it virtually inapplicable in actual multi-machine production systems. Therefore, researches have been proposing solutions accounting for prediction of certain disruptions in the process, which lead to the development of robust schedules. The latter, nevertheless, do exhibit certain limitations with regards to the accuracy of prognoses and their inconsistency with actual conditions.

This paper proposes an original solution to job-shop scheduling, integrating predictive and reactive scheduling, which is essentially an intelligent process of job scheduling optimisation exhibiting features of machine learning. The process is based on a robust schedule deriving from actual historical data of machine failure or technological operation processing times. The proposed approach enables computing (optimising) the schedule, for instance, at the end of shift, in order to prevent error inheritance that might result from discrepancies between the developed model schedule and actual progress of the production process.

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Process Assessment of Risks in the Production Company with the Use of Linguistic Variables and the FMEA Analysis

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Abstract. The paper focused on the process approach to risk assessment in the production company from the SME. Based on the literature review, there was prepared a proposal of the analytical procedure, taking into account the holistic approach to identifying risks in the enterprise. There was distinguished the three main areas of analysis: the workflow organization together with information flows in the production process, maintenance of technical infrastructure and processes performance within the automotive supply chain. Based on the proposed method of risk assessment, there was conducted an analytical procedure in a selected production company, which is currently under development phase.

Keywords: Risk assessment · Holistic approach · Linguistic variables · FMEA analysis · Production system

1 Introduction

During the risk identification, there should be paid an attention to the greatest number of factors that may directly or indirectly affect the assets of the company being understood in a broad way (not only material goods, but also such elements as employees, customers, contractors, brand, etc.). This requires implementation of a holistic approach to the assessment process performance. The starting point for this approach is a process of risk identification, which should include an analysis of the processes occurring within the organization as well as their relationship with the processes carried out in an closer and further environment. However, the research shows a clear business focus on specific areas and specific risks, while disregarding other issues, no less important in the company [41]. The lack of a holistic approach makes the company's effort and money are targeted solely on reducing a small group of factors generating the risk. This in turn can lead to waste, because other adverse events may disrupt the correctness of the processes performance. Following this, the incurred expenditures will be lost because of the lack of a holistic view of the processes. The unidentified threats from other areas of the business operation prevent achieving the desired results. We limit this process of organizational learning. This makes the managers in the production planning process not fully utilizing their knowledge, which limits the likelihood of adverse events [36]. According to the standard, each

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organization should identify all the risk - the nature of the risks, the circumstances or events promoting their occurrence, the potential consequences and so on - in terms of the organization's objectives for achieving its mission [9, 28, 31]. In the phase of intensive development, companies should make a global assessment of their business risk because the projected increase in turnover rate requires adaptation of the performed processes, financial services, personnel resources, and used infrastructure. This means that there should be conducted a detailed analysis of the basic processes and their associated costs. Employees' work organization and proper allocation of resources are also of particular importance [29]. In the case of production companies from the SME sector, this means first of all the necessity of an analysis of both the workflow organization and information flows in the production process, verification of availability to maintain the production infrastructure and identification of the hazards resulting from the applicable standards of cooperation in the supply chain.

The purpose of this article is to develop a process approach to assess risks in the production company and its application on the chosen example from the automotive sector. Therefore, there is presented a literature review of selected risk management concepts that inspired author to determine the analytical scope for the proposed performance method. Then, there are characterized the research area and the procedure for process approach to assess risks in the production company. On the basis of the proposed approach, there is conducted the analytical procedure in the selected production company from the SME sector and there are presented the final conclusions.

2 Literature Review

There are many different views on what risk is and how to define it [5, 15], how to measure/describe it [4, 22], and how to use risk analysis in a decision making [1, 3]. One of the most often cited risk term definition is given in PN-ISO 31000 standard [35], where risk is defined as *effect of uncertainty on objectives.* However, this definition is very general. A brief summary of classification of risk definitions is given e.g. in [5, 14]. According to the most recent overview prepared by Aven in [6], definitions proposed in ongoing studies mostly relate the level of uncertainty to **the probability of an adverse event occurrence** and its consequences. Therefore, also in this article such a definition of risk is applied.

The author in her research is based on the guidelines of ISO 31000 standard [35]. According to this standard, risk assessment should be holistic in nature and be carried out in three steps of the investigation: (1) risk identification, (2) risk analysis, and (3) evaluation of risk. These steps are included in the proposed model of risk assessment of the production process. Risk analysis may be carried out with varying degrees of detail depending on the context [32]. Analysis can be quantitative, qualitative, or contain some degree of both. Consequences and likelihoods are often expressed using a mathematical model but small also include prior experience or currently available data [32]. In the proposed model of risk assessment there is used FMEA technique. It is one of the risk analysis techniques recommended by international standards [40]. Linguistic variables were used to estimate the value of each parameter used for the risk assessment

[10]. At the same time, in the process of risk assessment are used available data and the results of direct interviews with senior managers and employees of the company.

Based on the ISO 31000 standard, there was established the concept of Enterprise Risk Management. One of the most popular definitions of Enterprise Risk Management conception (ERM) used in the literature is the one provided by COSO II standard. According to COSO II standard [13] Enterprise Risk Management is defined as *a process, effected by an entity's board of directors, management and other personnel, applied in strategy setting and across the enterprise, designed to identify potential events that may affect the entity, and manage risk to be within its risk appetite, to provide reasonable assurance regarding the achievement of entity objectives*. According to COSO II, an organization's ERM system should be geared toward achieving the following four objectives: (1) Strategy: high-level goals, aligned with and supporting the organization's mission. (2) Operations: effective and efficient use of the organization's resources. (3) Reporting: reliability of the organization's reporting system. (4) Compliance: organizational compliance with applicable laws and regulations. In the studies presented in this article, the attention was focused primarily on the operational level. The performed procedure regarded to operational risk, which determines how the internal organizational processes are sufficiently effective and resilient in order to pursue their economic goals [42]. Such risks relate to negative deviations of performance due to how the company is operated, rather than the way it finances its business [15, 27]. It has been argued that there is a great need for improvement in the quality (as regards tools and formal processes to manage operational risk) and scope (such as identification of what risks to focus on) of ORM [21]. Companies frequently deal with operational risk issues as they occur, and often following a crisis or catastrophic event [27].

Taking a holistic perspective in this study, one should be aware that the investigated business processes are performed in a specific environment. Hence, preparing a risk analysis for the production company there cannot be ignored issues related to supply chain risk management (SCRM). The SCRM concept has become a popular topic over the last decade [11, 38, 39]. The increase in the number of publications in this area is detailed analysed by Choi in their literature review given in [12]. The concept of SCRM is based on underlying supply chain risks (specifically origin and effects) and the overall effectiveness of the supply chain [25]. Various sources of supply chain risks have been identified. For example, Jüttner, Peck, and Christopher [20] classified supply chain risks into three categories; environmental (fire, socio-political, etc.), network (outsourcing, demand–supply fluctuations, etc.) and organisational (strike, machine failure, etc.). Manuj and Mentzer [33] proposed a different classification along quantitative and qualitative lines and named eight risk categories; supply, operational, demand, security, macro, policy, competitive and resource. Tang [37] classified supply chain risks into operations and disruption risks. Operations risks are related to uncertainties in a supply chain (such as demand, supply and cost uncertainties), while disruption risks are those caused by major natural and man-made disasters (such as floods, earthquakes, terrorism and major economic crises). When carrying out the risk assessment in the analysed production company, author is guided by the approach given by Tang. In the case of manufacturing companies, the importance of proper maintenance of the machine park is also of particular importance [17, 18]. An important concept, being complementary to

the previously described approach, and that requires a holistic look at the risk factors presented in the manufacturing company is the strategy of Risk Based Maintenance (RBM). The RBM strategy provides a new vision of an integrated asset management, through the use of risk as a criterion for planning maintenance tasks devices [7, 16, 23, 26]. The overall objective of the RBM is to reduce the overall risk, which may result as a consequence of unexpected failure of operating equipment [24]. This method is used to determine the maintenance priorities using risk function [30]. According to this, the system's components with high risk should be controlled and maintained with greater frequency and accuracy than the unit with assigned a low risk [2, 8, 34]. In the studies on the concept of RBM, there is emphasized its use primarily for production systems performance [2].

Referring to the previously presented definitions and taking into account the process perspective, the starting point for risk assessment performance should be to identify threats that may be the cause of failure to achieve the objectives in the production process performance. A holistic approach assumes that the area of analysis will cover different levels of performed process, like e.g. technical elements, human resource, as well as costs and organizational issues. Risk assessment should therefore be preceded by a process analysis that allows to identify potential adverse events.

3 Process Assessment of Risks in the Production Company

Based on the conducted research, in the paper there is proposed a process-based approach to assess risks in the production company, which takes into account the concepts of risk management described in the Sect. 2. The proposed process approach, in accordance with ISO 31000 standard, implies a holistic approach to risk assessment in the company. This means that the identification of potential hazards is done by the way of a process analysis, which includes the analysis of used resources (elements at the input to the process), the course of the process and the expected final result (Fig. 1).

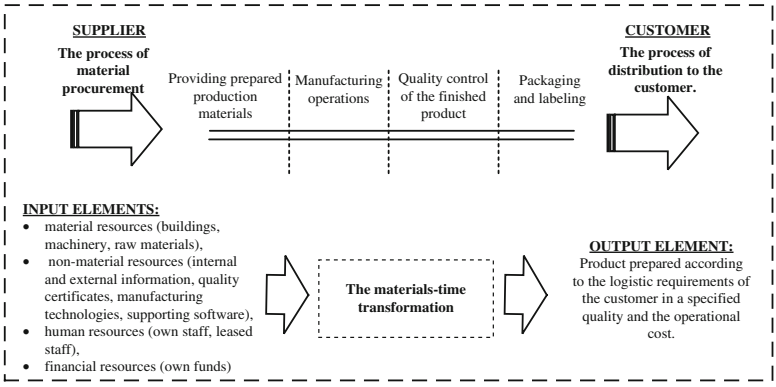


Fig. 1. Characteristics of production process

Process approach also assumes that the process is carried out in a certain environment, which affects its performance. For this reason, the sources of potential hazards are identified as both internal and external ones. Thus, the risk assessment takes into account financial, technical, informational, social and organizational issues.

The correct implementation of the production process depends primarily on: (1) the proper performance of the production line, (2) on-time material supplies, (3) the proper workflow organization, (4) the rapid flow of information. For this reason, the proposed risk assessment procedure, taking into account the concepts described in the Sect. 2, involves analysis of the following areas: (a) maintenance of the production line, (b) production planning, (c) production performance, (d) implementation of the material supplies in relation with suppliers cooperation, (e) flows of information accompanying the production process, (f) costs associated with production performance. The detailed performance procedure is shown in the Fig. 2.

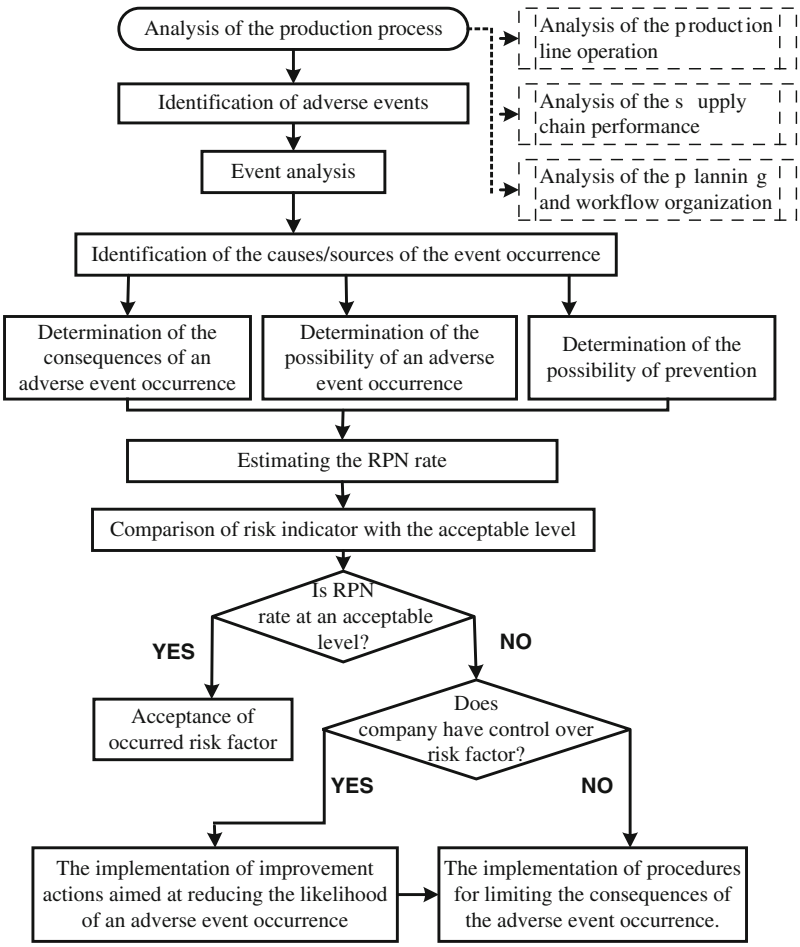


Fig. 2. Risk assessment procedure for production process

4 Risk Assessment for the Production Company from Automotive Sector – Case Study

The audited organization is a company from the SME sector, supplying components manufactured in the largest car companies in the world. Producer's head office is located in a small village in Lower Silesia. Since its inception, the company pursues its business objectives based on the core values: trust, sharing knowledge and progress. Currently, the company employs about 20 full-time employees. At the same time during production peak periods, the company's own employees are also supported by staff from employment agencies. The company has a production hall divided into its adjacent spaces. In the second production area, there was separated zone of packaging and storage of finished products, which occupies about 1/3 of the space. The current ordering system assumed the dispatching of the order to the customer immediately after finishing the manufacturing process, so the performance of the separate warehouse of finished products was not necessary. To the production hall is communicated with raw materials warehouse. In this low storage warehouse was separated the area for semi-finished products, which have passed the first stage of manufacturing process and waiting for further manufacturing operations.

The company is currently in the phase of intensive development and increase market share. In 2016, the company has expanded its portfolio of clients and multiplied the number of maintained contracts. As a result, since September 2016 the management Board registers systematic increase in orders from customers, which is predicted to continue over the next two years. Until recently, the production was carried out according to the pull system principals. Thus, a production order was being opened under the specific orders submitted by the customer. Currently, the company is considering the opportunity to move away from this model of production for production planning system based on forecasts submitted by customers. This is due to the fact that a large number of orders realized in parallel, so far limited the present margin of spare production capacity. As a result, each emergency downtime (due to unplanned maintenance) on the production line or increase in customer orders will result in failure to meet the declared delivery conditions. This could result not only in financial losses connected with defined penalties for delivery delays, but also the loss of the brand, and consequently the lack of contract continuation by the customer in the next time periods.

In view of the current situation, the company decided to carry out a risk assessment for the production process, taking into account current and future operating conditions. The analysis was conducted based on historical data from the years 2015–2016, but taking into account that disruptions that have appeared in the last 6 months will increase with the increase in production in subsequent periods. During the risk assessment for the case company, there was used the model that is described in the Sect. 3 of this article.

The company defines 18 adverse events, which may significantly threaten the proper implementation of the production process. These events have been classified into three groups: (1) the events related to the supply chain performance; (2) the events resulting from the workflow organization within the company, (3) the events related to the maintenance of the production line. The identification of the possible adverse events with characteristics of their possible causes is shown in Table 1.

Table 1. Characteristics of the adverse events for the case company

Notation	Adverse event	Characteristics
The events related to the supply chain performance		
RSC 1	Incomplete delivery	90% of purchased raw materials has only one source of supply. Any supplier disruption influences directly the company's processes performance. Increased number of orders and production based on customers' forecasts make that unplanned increase in customer's demand will not let fulfil the contract in accordance with the declared deadline
RSC 2	Late delivery	
RSC 3	Lack of the required quality of supplied materials	
RSC 4	The pause in supply performance	
RSC 5	The lack of up-dated information about delivery process performance	
RSC 6	Deviations in customers' orders in relation to the forecasts	
RSC 7	Inability to realize the customer's order within the prescribed time period	
The events resulting from the workflow organization within the company		
RPW 1	Lack of competent employees	Increased number of orders result in the necessity to employ new workers, to increase the share of agency workers operation, or overtime working. New employees will have to gain experience in working on the production line, which in the early working periods can increase the extension of individual operations and increase the number of incorrectly made parts. Increased number of new employees result in the greater involvement of foremen that implement them to work, so they will have less time for a routine checking on of performed operations. It is also possible that the current material supply control parameters are mismatched to the new demand. This may result in the need for emergency purchases at higher prices than during the regular orders performance
RPW 2	The formation of bottlenecks in the production line	
RPW 3	Increasing the number of defective goods produced	
RPW 4	Shortage of materials resulting from an incorrect inventory planning	
RPW 5	Lack of proper monitoring of the work of production employees	
RPW 6	Increasing the cost of direct materials due to changes in prices of purchased raw materials	
RPW 7	Increasing the cost of direct labour due to work overtime	
The events related to the maintenance of the production line		
RMO 1	Machine failure due to intensive operation	The increase in the number of orders will increase the intensity of use of the machine park. Until recently, based on the single shift operation there was not used the maximum operational potential of company's machine park. With the introduction of multi-shift operation, there will be lengthen the machines' working time and there will appear threats to many users for each machine, including workers without experience
RMO 2	Lack of adequate surveillance of the production machines	
RMO 3	No data relating to failures occurrence	
RMO 4	Machine failure due to employee	

FMEA analysis took into account the three parameters - the likelihood of a particular adverse event occurrence (L), the consequences for operational business performance (C) and the difficulty in preventing the threat (P). The linguistic assessment was used to determine the value of these parameters. The values of the linguistic variables used to calculate the Risk Priority Number (RPN) are shown in Tables 2, 3 and 4. The interval values of variables L, C and P represent defuzzified values of different linguistic variables.

Table 2. Linguistic variable and its defuzzified values for the likelihood of a particular adverse event occurrence

Likelihood of event occurrence	Characteristics	L [rank]
Low	Not occurred in the last year	1
High	Occurred at least once in the last year	2–3
Very high	Occurred at least once in the last quarter	4–5

Table 3. Linguistic variable and its defuzzified values for the consequences for operational business performance

Consequences for the company	Characteristics	C [rank]
Not noticeable	Waste of unallocated costs occurrence	1
Noticeable	Incurred minor financial losses	2–3
Disruptive	Incurred significant financial losses	4–5

Table 4. Linguistic variable and its defuzzified values for the difficulty in preventing the threat

Possibility of prevention	Characteristics	P [rank]
High	Full control and the ability to counteract	1–2
Limited	Limited control and influence on the adverse event occurrence	3–4
Lack	Lack of control and ways of counteracting	5

For the purpose of the risk assessment, there was established the team of managers and staff, whose task was to give the value of the parameters L, C, P, to determine on this basis the RPN index value, according to the formula:

$$RPN = (L) \times (C) \times (P)$$

The evaluation process took two steps. The first evaluation was ex post type and referred to observation made in 2016. The possibility of an event occurrence and its consequences were estimated based on past experience of the crew. On this basis, there was calculated the current Risk Priority Number at the beginning of 2017. However, the management of the company is aware that a further increase in production when not supported by the methods of risk management, contribute to the growth of risk

indicators defined for the selected events. Therefore, in the second step of the assessment procedure, there was made an attempt to estimate the level of RPN index for each of the defined adverse events at the end of 2017. The prediction was made assuming implementation of no action to improve the current system performance. Estimation of the RPN levels for each event and for both the cases is shown in Table 5.

Table 5. Assessed values of RPN index at the beginning and at the end of 2017

Event	Beginning of 2017				End of 2017			
	L	C	P	RPN	L	C	P	RPN
RSC 1	5	3	5	**75**	5	5	5	**125**
RSC 2	5	3	5	**75**	5	5	5	**125**
RSC 3	3	2	5	**30**	3	5	5	**75**
RSC 4	1	5	5	**25**	2	5	5	**50**
RSC 5	5	1	2	10	5	4	3	**60**
RSC 6	5	3	5	**75**	5	5	5	**125**
RSC 7	3	5	1	15	5	5	3	**75**
RPW 1	1	3	1	3	3	4	1	12
RPW 2	5	1	1	5	5	5	1	**25**
RPW 3	3	1	1	3	5	4	1	20
RPW 4	1	3	1	3	5	5	1	**25**
RPW 5	1	1	1	1	5	4	1	20
RPW 6	1	3	1	3	4	4	2	**32**
RPW 7	3	4	1	12	5	4	1	20
RMO 1	1	3	1	3	5	5	1	**25**
RMO 2	1	3	1	3	4	4	1	16
RMO 3	5	1	1	5	5	4	1	20
RMO 4	3	3	1	9	5	5	1	**25**

The president of the company defined the acceptable level of risk the level RPN < 25. Currently, this ratio is exceeded only for 5 adverse events that belong to the risks arising from the current rules of the supply chain performance. However, if there were not implemented any improvement actions of the current processes performance in the company, the RPN rate reaches an unacceptable level for 12 events at the end of 2017.

The planned increase in production is accompanied by high dynamics of changes related to risk factors occurring primarily in the environment (in the supply chain) but also in the enterprise itself. Reducing the risk assessment procedure exclusively to *ex post* analysis is in this case insufficient. Focusing on historical data will limit the perspective of the analysis and will not allow advance analysis of the parameters to be countered. Hence, there occurs the need to include *ex ante* analysis, which, based on the prediction of future values, will help to identify possible risks. The results of the performed assessment are used primarily to indicate these risks, for which it is necessary to prepare scenarios limiting the possibility of their occurrence or the mitigating

effects of their consequences. These scenarios should be based on knowledge management in the enterprise. Both stages of analysis should also be used when developing scenarios to streamline the processes under investigation. In this case, the *ex ante* analysis will assess the predictable effects of the implemented solutions, while the *ex post* analysis will verify their actual effectiveness after the set period. Inference, carried out on the basis of a comparison of the results obtained in both analyzes, gives the possibility for better investigation of the occurred phenomena and for choosing effective solutions limiting the risks involved. This will ensure that the risk management system is based on the Deming cycle and will strengthen the learning process and continuous improvement of the organization.

5 Summary

Risk management is becoming more popular in Polish enterprises. The need for tools to assess business risk increases particularly when the company enters a phase of development, which is usually linked to an increase in production and gain market share. Such a situation took place also in the analysed production company. The *ex post* risk assessment for manufacturing process showed that the most sensitive area at the moment is the company performance within the supply chain. Priority actions related to implementation of solutions to reduce the RPN rate should be directed primarily at improving the cooperation with suppliers and direct customers. An analysis of the *ex ante* for the expected values at the end of 2017 shows, however, that the lack of improvement activities for present process of production doubles the number of factors, for which the value of RPN exceeds acceptable level. In addition, the risk will increase not only for the area of cooperation in the supply chain, but also for processes performed within the company. This situation shows that in the phase of intensive development of the organization and the accompanying increase in production, the risks associated with implemented processes is dynamic. For this reason, limiting the assessment of risk to the process that is based only on historical data is insufficient. It is necessary to implement a two-stage evaluation procedure, as shown in the above case study, which is based on the concept of a learning organization and the Deming cycle.

Presented in the article research results constitute the part of the research work connected with development of process approach to company's risk assessment. The starting point for the identification of risk in this case is a detailed analysis of the process, allowing for investigation of all the components of the process and the relationships between them. As a result, the researcher selects the selected risk management strategies to the specifics of the evaluated process and adapts assessment tools to the characteristics of the analysed processes and their data. Presented in the article process procedure for manufacturing companies will be further developed and verified for the cases of other sectors.

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Production Costs of Machine Elements Estimated in the Design Phase

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Abstract. This paper presents an approach for production costs estimation at the stage of machine elements design, based on the variant set of cost drivers and the corrected values of this set. The proposed costing method is based on a formalised description of information about constructional, manufacturing and organisational features related to the designed element, and a model of estimating production costs of machine elements based on Activity Based Costing, and is adjusted to unit and small lot production systems.

Keywords: Production process design · Cost estimation · Activity based costing

1 Introduction

The greatest inconvenience, particularly in case of unit and small lot production companies, is lack of knowledge related to measuring tools and proper estimation of costs of the designed products. Designers have to make choices and go on compromises related to the designed products basing on distorted and obsolete information [9]. Wrong decisions taken due to the lack of appropriate tools cause high costs, which result from creating highly complex and differentiated products, whose change during the production process is difficult and connected with further expenses [12]. During project realization, special attention should be paid to maintaining proper level of costs and time of the conducted activities, which is a significant problem for most enterprises [1].

Using Activity-based Costing, including cost drivers, allows to considerably reduce costs on the stage of production processes design, which actively influences cost planning in the future [8]. Managers, who want to control manufacturing costs of machine elements, should use proper tools to check previous, comparable projects and their realizations and become acquainted with the causes of exceeding the assumed cost levels [7]. Also, they should foresee the consequences of taken decisions and of their influence on improving operational effectiveness from the point of view of costs. Thanks to simulating the influence of alternative decisions on the stage of production processes design, it is possible to estimate the level of own costs before the decisions are taken, and the necessary resources are purchased [10]. The aim of this paper is to

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determine own cost of the designed element on the stage of construction production preparation, with little time required, sufficient amount of information resulting from element construction record and using cost drivers related to Activity Based Costing. Solving this problem requires:

- determining costs of activities for a sample production system,
- assuming a proper description of the designed elements basing on the elementary object method, which takes into account constructional, manufacturing and organizational features,
- determining the level of cost drivers on the basis of values of the assumed description of features for the designed elements,
- designing a costing model which would consider the available sets of cost drivers.

2 Assumptions of the Methodology

Production costs estimation is a process of approximate estimation of production costs before all product lifecycle stages are completed. Using costing methods which operate on incomplete information necessary for estimating costs of machine elements is connected with assuming limited accuracy of the obtained results.

The first stage of production costs estimation for the designed elements is to determine the values of cost components which constitute production cost structure. The basic components of production costs in this methodology are costs of direct activities, which are cost drivers assigned to the produced elements. Costs of direct activities are necessary to determine the costs of cost objects, elements, sets, products, etc.

On the basis of the information available in financial-accounting systems about the costs encumbered in previous periods, and the information on the presence of separate activities in the sample production system, costs of direct activities have been determined, as shown in Table 1.

After calculating the cost of direct activities and determining the measures of throughput for these activities, it is possible to calculate the cost rate for particular activities.

The proposed variant costing model for machine elements (Fig. 1) is based on the data related to cost drivers generated using variant model of determining manufacturing process parameters. The data generated using this method is related exclusively to the manufactures element, not the feature describing a particular element, so it will concern only cost components assigned to the elements [3]. The parameter values related to manufacturing processes designed by means of the variant method do not relate directly to the variables influencing the value of particular production cost components. Thus, it is necessary to determine a set of values of cost drivers (Table 2), that is such parameters of the manufacturing process which clearly determine the value of the variables related to the separated cost components and the way of estimating them.

Table 1. Costs of direct activities – a fragment

No	Activity	Activity costs by type in PLN	Costs of indirect activity in PLN	Total activity cost in PLN
1	Adopting orders	14 600.93	35 743.59	50 344.53
2	Preparing documentation – typical product	3 416.04	960.76	4 376.80
3	Preparing documentation – modified product	5 607.96	1 587.39	7 195.34
4	Preparing documentation – new product	10 318.59	2 828.41	13 147.01
…	…	…	…	…
20	Activity performed on universal milling machines	2 269.07	2 366.56	4 635.63
21	Activity performed on gear hobbers	5 699.12	4 740.10	10 439.22
22	Activity performed on multiradial drilling machines	3 898.12	3 493.83	7 391.95
23	Activity performed on centre lathes	26 061.56	18 830.59	44 892.15
…	…	…	…	…
31	Co-operation	1 346.65	365.63	1 712.27
32	Storing elements	1 451.11	309.62	1 760.73
33	Control of elements	30 041.32	6 216.49	36 257.81
34	Storage of finished products	1 529.05	631.81	2 160.86
35	Sale	16 796.87	2 677.45	19 474.32
Total cost of activities				516 146.44

The initial stage of the proposed costing method is to assume a proper description of features of the designed elements, which allows to determine the value of cost drivers related to the manufacturing process for the given element. The description is based on the assumptions given in literature [13]. One of its characteristic features is that it is not limited to describing typical, normalized elementary objects [3], and, apart from information about constructional features, it is enriched by the description of material, organizational and manufacturing features, which allows for a more complete cost estimation [5]. The division of features describing the elements is presented in Table 3.

Manufacturing process search takes place on the basis of similarity of constructional, manufacturing and organizational features of a new element and the already produced one, so on the basis of a parametric description of the designed element, necessary when scanning through the existing base of manufacturing processes in order

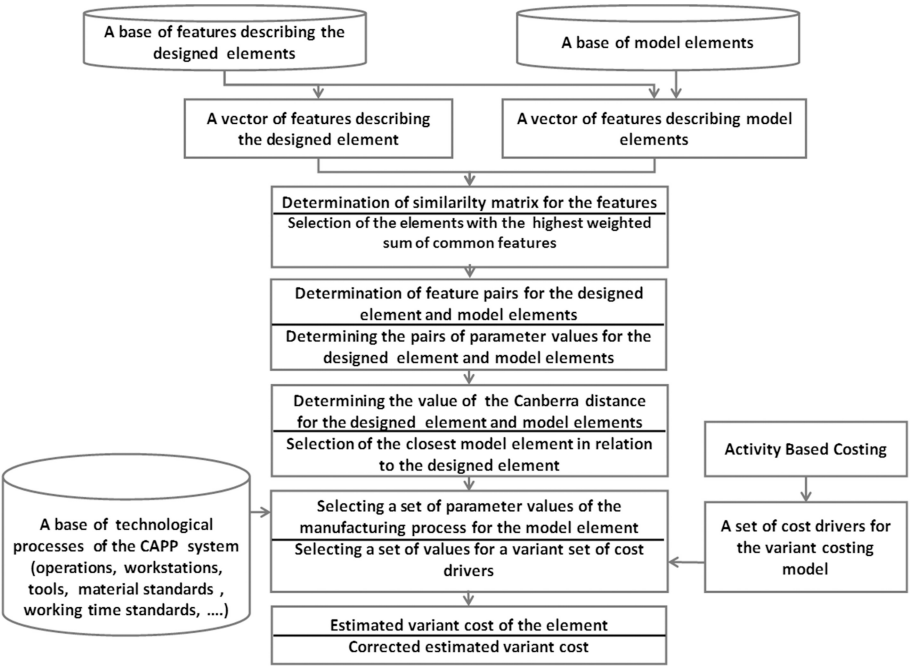


Fig. 1. A general model of procedure in the proposed method

Table 2. A set of cost drivers for the variant costing model

Name	Symbol
Unit time	tu_op_n
Set-up and break-down time	tsb_op_n
Grade	gr_emp_n
Storage item index	id_stor
Standard materials usage	SM
Standard number of semi-product	no_sprod
Production position	id_posit_n
Type of documentation (typical, modified, new)	t_doc
Type of product (finished product, semi-product)	t_prod
Size of a production batch	s_batch

to find the process itinerary for a previously designed element, which is the closest to the new element. With the manufacturing process of the closest element and the data about the value of cost drivers, together with a cost calculation system, it is possible to determine manufacturing costs of a designed element.

The parametric description will later be used when correcting the so called cost drivers on the basis of differences between parameters of the designed element and its closest counterpart.

Table 3. Division of features describing machine elements

Designed element	Constructional elementary objects – objects, which directly create constructional shape of the designed (there can be simple surfaces: chamfer, undercut, or complex ones: threat, toothed ring)	Constructional features describing the designed elements	Geometrical features (determine the external structure): - type of shape (disks, shafts, bushings…) - external shapes (cylindrical elements, flat conical surfaces,…) - additional external shapes (keyways, threats, undercuts,…) - internal shapes (opening, centring holes, multi-grooves,…) - additional internal shapes (flat surfaces, threats, teeth,…) - …
	Features describing the designed elements		Input material features for production (determine the material, its internal properties, form of raw material): - half-product (bars, pipes, casts…) - raw material (steel, iron, non-metal materials) - thermal and thermo-chemical treatment (annealing, tempering, hardening…) - ….
		Manufacturing features describing the designed elements	- variant of the manufacturing process (disc process without thermal treatment, with heat improver, with carburizing and tempering,…)
		Organisational features describing the designed elements	- production series type (unit, series, large-scale) - organization of the manufacturing process - …

3 An Example of Cost Estimation on the Stage of Machine Elements Design

Using the variant costing model for estimating costs of machine elements allows to estimate costs for a new product relatively fast and with less workload, which is sometimes connected with accepting limited accuracy of the obtained results.

The first step is related to separating from the elements base the elements which are possibly closest to the designed element from the point of view of common features describing the elements. An example of the gathered information about the designed element's features in form of a *FP* vector, automatically generated during construction records is presented in part (a) of Fig. 2, whereas part (b) includes an example of a model element together with a *FP* vector (in the authorial module functioning in the SolidWorks software).

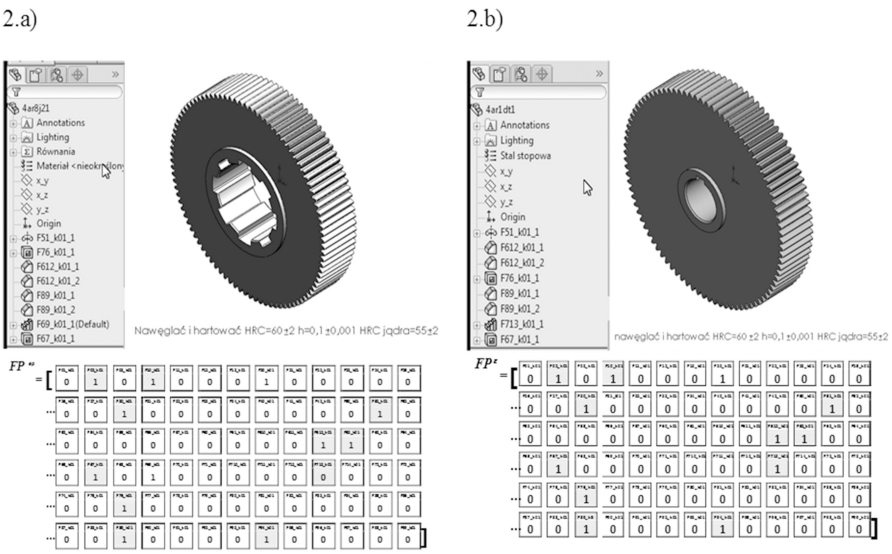


Fig. 2. The feature description of a new machine element (a) and a previously designed machine element (b)

Table 4 explains some symbols included in the *FP* vector for the designed element with sample parameters. The mentioned vector is then compared with analogical vectors of model elements and the technological type is determined, whose model is the most similar to the designed element. This step is connected with separating a sub-set of model elements, which are the closest to the designed element from the point of view of common features with the designed element, on the basis of probability measure *m*, that is a weighted sum of common features of the designed element designed element and model elements (formula 1).

Table 4. Features describing the designed element

Index of the designed element (rotatable element – k01)	Features describing the designed element			
	Symbol-according to the classification	Group features of the classification	A description of features of the classification	No (multiple)
4AR8J2	F02_k01	Production series type F0	F02 - series	1
	F10_k01	Type of shape F1	F10 - disks	1
	F20_k01	Half-product F2	F20 – round bars	1
	F30_k01	Raw material F3	F30 - steel	1
	F51_k01	External shapes F5	F51 – external cylindrical elements graded in one direction	1
	F612_k01	Additional external shapes F6	F612 – external chamfering	1
	F612_k01		F612 – external chamfering	2
	F62_k01		F62 – external grooves	1
	F67_k01		F67 – cylindrical gears with straight external teeth	1
	F713_k01	Internal shapes F7	F713 – internal keyway	1
	F76_k01		F76 – through holes	1
	F89_k01	Additional internal shapes F8	F89 – internal chamfering	1
	F89_k01		F89 – internal chamfering	2
	F94_k01	Thermal and thermo-chemical treatment F9	F94 – carburizing with simultaneous tempering	1

$$m = \sum_{i=1}^{I} w_i \cdot p_i \tag{1}$$

$$\text{where } p_i = \begin{cases} 1, if\ fp_w = fp_p \wedge fp_w \neq 0 \\ 0, otherwise \end{cases}$$

Where:

w_i - weight values determined on the basis of the influence of parameters describing feature i on real production costs,

fp_w - determined feature with binary value 1 in FP vector for the model element,

fp_p - determined feature with binary value 1 in FP vector for the designed element.

For the exemplary element, 9 model elements have been selected, for which this value amounts to 11, which means the highest number of common features.

Next, for the common features of the designed and model elements, it is necessary to compare pairs of common features and the parameters together with their values describing the given features.

The next step involves selecting the element from the set, for which the Canberra metric value mC (formula 2), determined on the basis of values of parameters describing features of this element and the designed element, is the lowest. The element has been chosen from the set, which is the closest to the 4AR1DT designed, and for which the distance 3.69 was the shortest.

$$mC = \sum_{p=1}^{P} \left| \frac{wc_{n_p}^{ep} - wc_{m_p}^{w}}{wc_{n_p}^{ep} + wc_{m_p}^{w}} \right| \tag{2}$$

where:

$wc_{n_p}^{ep}$ - feature value of the designed element ep by the n-th occurrence for parameter p;

$wc_{m_p}^{w}$ - feature value of the model element w by the m-th occurrence for parameter p;

During the he last stage a set of parameter values of the manufacturing process is chosen (stored in the CAPP system bases), and then, on the basis of a variant set of cost drivers and current rates of direct costs and activities, a variant cost for the designed element is prepared (in authorial software) – Fig. 3.

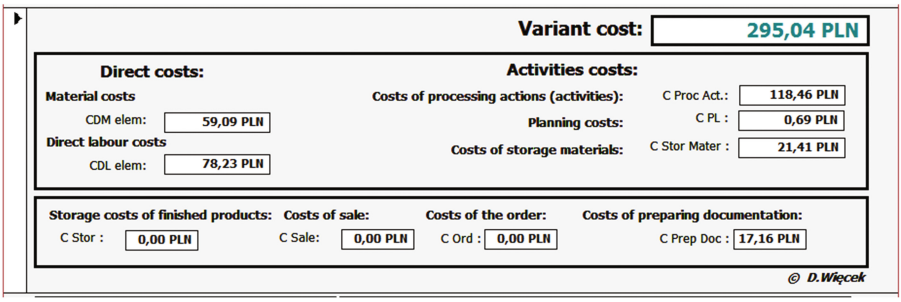


Fig. 3. Estimated variant cost of the designed element

Going away from comparing information in form of classification codes for the sake of comparing complete sets of information about features of the manufactured elements on the one hand improved the quality of searching for similar elements, but on the other, it significantly increased the amount of processed information.

The next stage of bringing the estimated costs closer to the actual costs of the

designed element is to correct variant values of cost drivers on the basis of parameter values of the features describing the designed element in relation to the parameter values of the features related to the variant element.

4 Estimating Costs of an Element Basing on Corrected Variant Set of Cost Drivers' Values

On the basis of the parameter values of the features describing the designed element related to material, semi-manufacture, dimensional and organizational features the values of variant cost drivers are corrected. The costs, which will change as a result of correcting values of cost drivers are costs of direct materials (*Cdm*), costs of direct labour (*Cdl*), costs of processing actions (*Cproc Act*) and other costs, for which the size of a production series is a cost driver *s_batch*.

Costs of direct materials may change as a result of other kind of assumed raw material (*r_mat*), a different half-product (*no_sprod*) and different dimensions of the designed element (*x_brut, z_brut*) and the variant element. These changes may influence the choice of storage item (*st_it*), and, consequently, the change of material unit price, and, above all, the change of standard materials usage (*SM*). The change in value of direct materials costs *Cdm* and material norm resulted in the changed value related to activity costs of the supply process *Cstor* – Table 5.

Another group of costs which undergo changes due to corrected cost drivers are

Table 5. Corrected variant costs of direct material

Designed element index	x_brut	z_brut	r_mat	no_sprod	st_it	k_mat	SM	Price	Cdm	Cstor
4AR8J2	179.36	50.8	18HGT	H-93200	180	7.85	10.2555	4.2	43.0734	16.7212

costs of a direct labour *Cdl* and costs of processing activities *Cproc Act*. The change shall be caused by different value of standard time consumption, resulting from changed machinability parameters of the declared raw material for the designed element and the raw material assigned to the variant element – Fig. 4. Standard time will also be influenced by the size of production series.

On the basis of the machinability group for the raw material related to the variant element, the machinability group of the designed element and variant unit time, the corrected unit time is determined. Taking into consideration the size of a production batch and set-up and break-down time, we obtain the corrected standard time consumption. The corrected variant costs for the exemplary element are presented in Fig. 5.

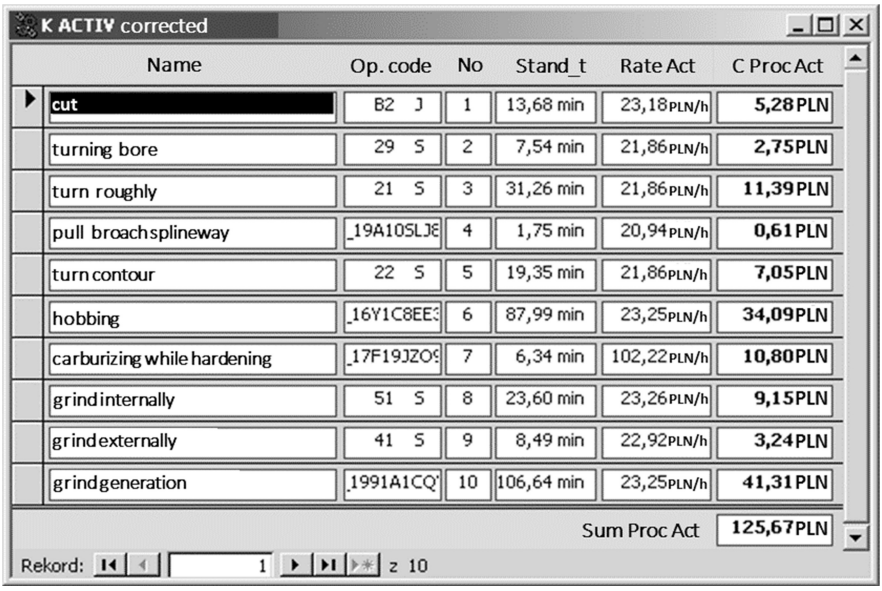


Fig. 4. Corrected variant costs of processing activities

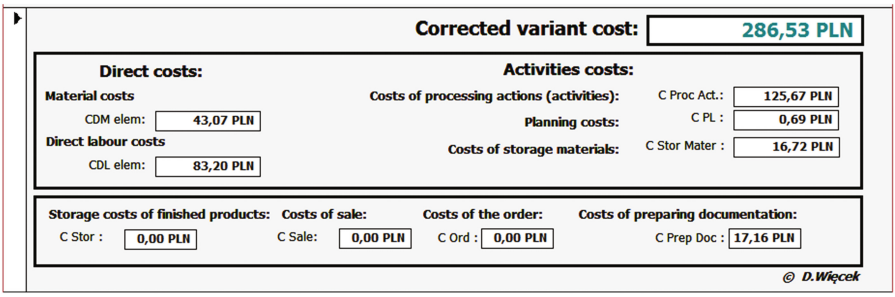


Fig. 5. Estimated corrected variant costs of the designed element

The costs, whose value depends on production batch size did not undergo any changes, as the values of this parameter for both the variant element and the exemplary element are equal.

After preparing the manufacturing process for a chosen constructional form of a product, the next stage is to estimate total production costs resulting from organizational production preparation, which can proceed according to many different organizational variants. The obtained solutions on this stage differ from each other with respect to the cooperation range in producing particular elements, batch size and delivery frequency, the size and stock of inventory, the production process structure (manufacturing methods, applied machining tools), methods of human resources

management, etc. [4, 6]. Taking the above differences into consideration, it is necessary to select the variant according to basic criteria which include cost, time of production, and product quality and functionality [2, 11].

5 Conclusions

The developed methods of production cost estimation (related to both direct and indirect costs) for a new product on the stage of production processes' design allow to identify costs of activities, and, at the same time, ensure certainty for marketing staff and managers during price and delivery conditions negotiations for each new product. Thanks to the proposed solutions, there is a possibility of informing designers about the high material and manufacturing costs, that is costs of ordering (significant number of suppliers), maintaining the excessive amount of different materials and costs related to the diversity of manufacturing processes.

Values of prime costs of machine elements depend on values of parameters of constructional, manufacturing and organisational features determined on the stage of production processes design. Accuracy of the methods based on the variant approach to creating a set of cost drivers' values is dependent on the proximity of the designed element and the so called variant element, which is significantly influenced by the number of variant elements, for which data is stored in the databases of the CAPP system.

The proposed methods require full implementation of activity based costing in an enterprise, operation of the CAPP system with an up-to-date base of technological possibilities of the production system and an analysis of constructional documentation in order to create a base of features describing the designed elements. The proposed solutions were adapted to production systems operating in conditions of unit and small series production.

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Reliability Assessment of Production Process – Markov Modelling Approach

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Abstract. In the presented paper, authors focus on the issues connected with production processes reliability assessment. Such analyses regard considering many different factors and requirements. Thus, based on the developed multi-dimensional definition of production process reliability, the seven-state Markov model of production process performance is presented. Later, there is provided a comprehensive sensitivity analysis of the developed model based on the expert opinions in the area of model parameters estimation. The work ends up with summary and directions for further research.

Keywords: Reliability assessment · Manufacturing process · Markov model

1 Introduction

The increasing intensity of global competition to develop new products in shorter times, with higher reliability and overall quality, as well as a significant reduction of products life cycles, has amplified the need for new and efficient methods for quality engineering and reliability estimation and prediction [6, 17] and is visible in various fields of application (see e.g. [7, 10, 11, 21]).

The reliability issues in manufacturing mostly refer to the product reliability evaluation mostly connected with quality ensuring or manufacturing system reliability modelling being related to functions of the components [15]. Taking one step further, in order to provide a complex assessment analyses, decision-makers should focus on manufacturing process reliability perceived in a broader way relating to machines, materials, operators, methods, measurement and inspection, as well as other process elements. Such an approach makes that traditional manufacturing system reliability modelling methods are not suitable to solve this problem.

The model that integrates product quality with manufacturing process reliability is presented in e.g. in works [5, 15]. In [5], authors present the solution that is based on the analytic network process (ANP) use and process knowledge network approach implementation. In the second work, authors focus on mission reliability modelling method for manufacturing systems with low degree of automation. The third interesting approach regards to quality-reliability chain modelling for complex manufacturing

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process, where authors investigate the QR-co-effect between product quality, system reliability and component reliability and is presented in [2].

However, the known approaches mostly focus on the two problems of product quality and system reliability. Other important process elements that influence the reliability characteristics are omitted in the analyses. Following this, the paper is focused on the development of the seven-stated Markov model for production process reliability assessment based on multidimensional production process reliability definition, given e.g. in [4]. The developed model is also analysed with taking into account the expert opinions in the area of model parameters estimation. The presented article is the continuation of authors research work connected with development and investigation of production process reliability assessment method that helps decision managers in their every-day work.

Following the above considerations, in the next section, there is provided a short literature review in the investigated research area. Based on this research, there is presented a Markov model for production process performance. Later, the sensitive analysis of the given model is developed based on the obtained expert opinions in the area of model parameters estimation. The work ends up with summary and directions for further research.

2 Production Process Reliability Assessment with Markov Approach Use – Literature Review

General review of the literature concerning the reliability of assessment of production process is presented in publication [3], where the main classification of reliability assessment models and methods is investigated.

In this article authors focus on the application of a Markov process approach in the evaluation of production processes performance. In this area there are a few articles worth mentioning. In one of them [20], the authors use a discrete time Markov chain model of a multistage manufacturing process with inspection and reworking. They focus on influence on interferences at the input (such as the effectiveness of inspections at the input to the process), load requirements and manhourly requirements, as well as total cost in order to achieve the process without distortions.

It is also worth to refer to another article [12], where the authors propose a new technique to reduce the number of Markov states. It will allow to adopt Markov models with continuous and discrete Time Markov Chain in more complex processes or systems. Other authors [2] reject the application of Markov model as a tool valuable to solve problems in production systems be-cause of too complicated calculation and construction. On the other hand, the authors in [14] apply Markov model of Quick Response Manufacturing System to evaluate the reliability of the production system. They identify weaknesses of their system (like e.g. the need of rework of defective product) and give advices how to improve those weaknesses. Moreover, among the many articles in this area, the publication [13] presents the advantages and disadvantages of Markov processes implementation in the field of machinery enterprises and possibilities of application are presented.

The presented short literature review in the analysed research area indicates that there are investigated various aspects of manufacturing systems reliability. The authors of this paper focus on the more comprehensive view on the reliability issues of production processes performance taking into account five main aspects of manufacturing system operation and maintenance.

3 Markov Model for Production Process Performance

Based on the presented literature review, one of the possible modelling approach for system/process reliability estimation is a Markov model.

3.1 Production Process Reliability Definition

In order to develop a Markov model for production process performance, the main definitions should be provided. Based on the literature review given e.g. in [4], authors propose the production process reliability definition as *an ability of a production system to completely fulfil the production plan of fully valuable final products in a specified period of time under stated conditions*. The given process conditions regard to the five main areas [4]:

- machines and equipment performance and their failures occurrence possibility,
- maintenance and logistic support infrastructure performance and their failures occurrence possibility,
- information flows and information reliability,
- possibility of the occurrence of unwanted random hazards/threats (internal and external type),
- processes of decisions making by policy makers and human factor reliability.

The complex reliability assessment analysis should cover the investigation all of the mentioned areas providing a valuable contribution to processes performance improvement. To satisfy these requirements, the multi-state reliability theory should be implemented, where the process may assume many states ranging from perfect functioning to complete failure. Taking one step further, the Markov processes approach may be used as a valuable tool to model the main relations between the defined production process performance conditions.

Because a Markov model is a mathematical system that undergoes transitions from one state to another, between a finite or countable number of possible states [1, 19], the main production process states should be defined.

Let's consider a manufacturing system under continuous monitoring. Taking into account the presented reliability definition, production process may be in one of seven reliability states being defined in accordance with the production plan and process conditions performance (Table 1). The production process state is given as a pair: the first give the possibility of production plan performance, while the second one the process condition state. The two states marked at grey in the table are not possible to occur in the real-life systems, thus they are excluded from the further reliability analysis.

Table 1. Production process states general characteristic

State no.	Plan performance	Process condition performance	Production process state
0	Perfect	Perfect	UP state
1	Perfect	Partially imperfect	UP state
2	Perfect	Imperfect	DOWN state
3	Partially imperfect	Perfect	DOWN state
4	Partially imperfect	Partially imperfect	DOWN state
5	Partially imperfect	Imperfect	DOWN state
6	Imperfect	Perfect	DOWN state
7	Imperfect	Partially imperfect	DOWN state
8	Imperfect	Imperfect	DOWN state

According to the defined reliability states, the perfect performance of the production plan means that there are manufactured fully valuable products in the right quantity and without any delays. Partially imperfect plan performance may regard to time delays or problems with products right quality and quantity. Imperfect performance of production plan means that based on the available resources there is no possibility to fulfil the defined plan in the defined period of time. The production process conditions performance perfectly if there is no occurred problems in machines, human factor, and support asset performance, the information is perfect (available and reliable), and there is no additional unwanted hazard events identified. Partially perfect performance of production process conditions regards usually at least to have reliable production machines and available human and information resources to fulfil the production plan. These three resources are usually critical for any manufacturing system flexible and reliable performance.

Let's also assume that production process experiences random failures in time and each failure entails a random duration of repair before the manufacturing system is put back into service. System after repair is as-good-as-new. Let's also assume that any information about failures in the system is reliable and comes immediately.

3.2 Seven-State Markov Model

For the analysis of the production process performance, we can associate its performance to a Markov seven-state model, on the basis of the defined set of states and defined assumptions (Fig. 1).

The graph describes behaviour of the production process with two successful (0, 1) and five mutually exclusive failure states (3, 4, 5, 7, 8) as shown in the Fig. 1 and Table 1. The modelled process is repaired from states: 3, 4. Worth taking a consid-

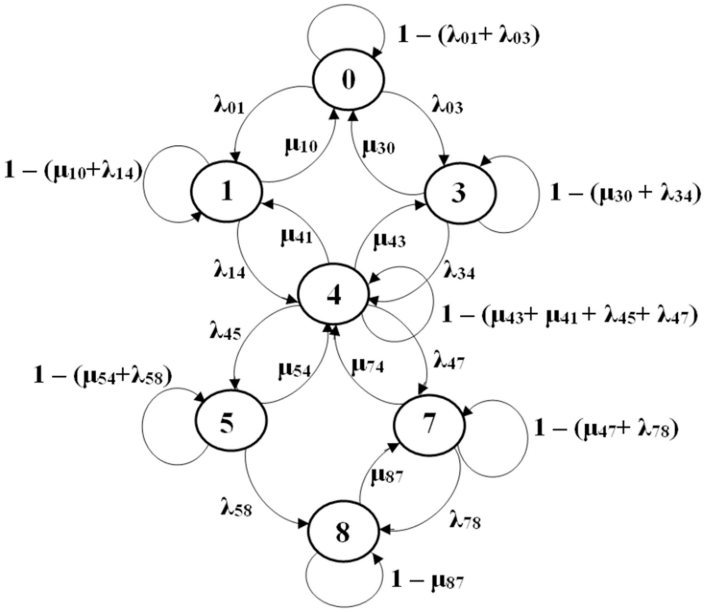


Fig. 1. Seven-state Markov model

eration is the state 4 that defines partially imperfect plan and process conditions performance. From this state, a process may pass to UP state (if the plan will be properly realized) or to another DOWN states, depending on the resources availability and plan performance level.

The detailed interpretation of the given theoretical model is presented in work [18].

Following [8, 16] we can formulate the probability expression for the model:

$$\begin{cases} P_0'(t) = -(\lambda_{01} + \lambda_{03})P_0(t) + \mu_{10}P_1(t) + \mu_{30}P_3(t) \\ P_1'(t) = \lambda_{01}P_0(t) - (\mu_{10} + \lambda_{14})P_1(t) + \mu_{41}P_4(t) \\ P_3'(t) = \lambda_{03}P_0(t) + (\mu_{30} + \lambda_{34})P_3(t) + \mu_{43}P_4(t) \\ P_4'(t) = \lambda_{14}P_1(t) + \lambda_{34}P_3(t) - (\mu_{43} + \mu_{41} + \lambda_{45} + \lambda_{47})P_4(t) + \mu_{54}P_5(t) + \mu_{74}P_7(t) \\ P_5'(t) = \lambda_{45}P_4(t) - (\mu_{54} + \lambda_{58})P_5(t) \\ P_7'(t) = \lambda_{47}P_4(t) - (\mu_{74} + \lambda_{78})P_7(t) + \mu_{87}P_8(t) \\ P_8'(t) = \lambda_{58}P_5(t) + \lambda_{78}P_7(t) - \mu_{87}P_8(t) \end{cases} \quad (1)$$

Where the following notations are used:

λ_{ij} – failure rate associated with states i and j

μ_{ij} – repair rate associated with states i and j

$P_i(t)$ – probability of being in state i at time t

$P'_i(t)$ – first derivative of $P_i(t)$ function with respect to t

Taking into account steady-state solutions, there is possible to estimate the steady-state availability ratio K:

$$K = \lim_{t \to \infty} K(t) = \lim_{t \to \infty} [P_0(t) + P_1(t)] \tag{2}$$

The availability is a calculation of various operational functions at the system and process level, and is interpreted as the percentage of time that the system will be ready to perform satisfactory in its intended operational environment. For the presented model, the level of production process availability depends upon the particular level of parameters λ_{ij} and μ_{ij}. This confirms the necessity of the developed model detailed analysis performance in addition to the real-life manufacturing systems operation.

4 Sensitivity Analysis of the Developed Markov Model

The preliminary sensitivity analysis of the developed model was presented in work [18]. The analysis was based on the assumptions that a parameter $\rho = \mu/\lambda$ obtained the following values: $\rho = 1$, $\rho = 0.1$, and $\rho = 0.01$. The performed analysis mainly focused on the calculation of availability function $K(t)$ of the system and probability of being in the state 4 – $P_4(t)$. The presented analysis results were obtained when all λ_{ij} parameters and all μ_{ij} parameters are the same.

However, in order to analyse the possibility of such model implementation for real-life complex manufacturing systems performance, the more detailed information about the possible values of parameters λ_{ij} and μ_{ij} should be provided. Following this, in the next subsections authors focus on Markov model use for the automotive industry sector.

4.1 Assumptions for Detailed Sensitivity Analysis

The analysis is performed for the Polish automotive industry sector, taking into account the serial production type.

In the first step of the conducted analysis, the probability of occurrence of given production process states (failure rates and repair rates values) is estimated based on the interviews with experts having long experience in manufacturing systems and processes analysing and managing/improving.

The conducted surveys also revealed important information that the perfect production plan usually takes into account some disturbances being possible to occur during normal business operations. A good example here is the scheduling process of production plan that is prepared with taking into account some level of production staff absence (about 6%). As a result, if during the scheduled time period the assumed level of employee absence is not exceeded, the plan is executed perfectly. Following this, we may state that the production plan is resilient for some disruptions occurrence.

Table 2. The estimated values of model parameters λij and μij based on expert opinions

No.	Transitions between the states	Possible scenarios	Probability of occurrence	Estimated probability
1	λ_{01} ⓪ → ①	**May occur when e.g.:** production plan was realized with uncertain and changing information (e.g. the not predicted change of the production schedule), production plan was realized with incomplete crew of the production line caused by e.g. mass illness, strikes, production plan was completed faster according to the schedule, but this resulted in machine failure (e.g. before important national holidays/events crew want to quickly finish the job).	Very likely to occur	0.1
2	μ_{10} ① → ⓪	**May occur when e.g.:** production plan was completed and there were no changes, e.g. in the production schedule, production plan was carried out with the full crew of the production line, production plan was completed, and machine failure was removed (due to e.g. spare parts availability).	Very likely to occur	0.2
3	λ_{03} ⓪ → ③	**May occur when e.g.:** despite the availability of all resources and information, production process proceeded slower than it should, and the plan was not fully realized (e.g. the night change usually does not complete fulfil the plan because of the limited supervision, moreover staff productivity after the weekend or holidays fall significantly).	Low possibility	0.001
4	μ_{30} ③ → ⓪	**May occur when e.g.:** having available all the resources and information, the normal staff productivity is maintained.	Very likely to occur	0.2
5	λ_{14} ① → ④	**May occur when the production plan is partially completed due to e.g.:** random events like e.g. delivery delays, production materials unavailability that causes production schedule delays, crew absence connected e.g. with strikes, illness, etc.	Medium possibility	0.01

(*continued*)

Table 2. (*continued*)

No.	Transitions between the states	Possible scenarios	Probability of occurrence	Estimated probability
		too low level of necessary resources, machine failure (at production line) that cause inability of completely fulfilling the production plan on time.		
6	μ_{41} ④ → ①	**May occur when e.g.:** delivery delays that incurs test procedure of available resources and rescheduling the production plan in order to produce the products of the right quantity on time, absent employee were substituted by temporary crew, the strike was ended, and as a result the production plan was completely fulfilled, machine failure was minimally repaired in order to fulfil the production plan, later the perfect repair is necessary to be performed.	Low possibility	0.001
7	λ_{34} ③ → ④	**May occur when e.g.:** production plan was partially completed due to machine failure (small defect occurrence), production plan was partially completed due to crew absence, production plan was partially completed due to low quality of delivered production materials (necessary quality inspection before production).	Almost unlikely to occur	0.0001
8	μ_{43} ④ → ③	**May occur when production plan was partially completed due to e.g.:** occurred machine defect was removed, however the production delay was too high to complete production plan on time, crew returns to production, but the production delay was too high to complete production plan on time, the delivered production resources were inspected and approved for production, but the production delay was too high to complete production plan on time.	Very likely to occur	0.2
9	λ_{45} ④ → ⑤	**May occur when production plan was partially completed due to e.g.:**		0.0001

(*continued*)

Table 2. (*continued*)

No.	Transitions between the states	Possible scenarios	Probability of occurrence	Estimated probability
		machine failure need external resources availability (maintenance service, spare parts delivery), continued crew absence (e.g. due to strike), the delivered production resources were inspected and not approved for production, the partially produced final goods are of poor quality and have to be removed from the production line, etc.	Almost unlikely to occur	
10	μ_{54} ⑤ → ④	**May occur when e.g.:** the failed machine was minimally repaired and production was continued (machine still demands complex repair performance due to lower productivity), crew partially returns to production and production was continued, material resources needs quality inspection before production performance, information about the possibility of production changeovers in order to its continuation.	Very likely to occur	0.2
11	λ_{47} ④ → ⑦	**May occur when e.g.:** due to machine failure occurrence (full inability to production performance) – decision about its repair, the crew fired home, the production plan was not realized at all, due to very low external temperature (weather conditions), the internal temperature (at production hall) is too low to continue the production process (e.g. heating system failure).	Almost unlikely to occur	0.0001
12	μ_{74} ⑦ → ④	**May occur when e.g.:** the machine failure cannot be completely repaired, needs for special tools/spare parts, the production is partially continued, the internal temperature (at production hall) is under the minimum level and decreases crew productivity.	Very likely to occur	0.2
13	λ_{58} ⑤ → ⑧	**May occur when e.g.:**		0.0001

(*continued*)

Table 2. (*continued*)

No.	Transitions between the states	Possible scenarios	Probability of occurrence	Estimated probability
		machine failure need complex repair/replacement, no possibility to continue the production process performance.	Almost unlikely to occur	
14	λ_{78} ⑦ → ⑧	**May occur when e.g.:** the machine repair process failed and cause its damage (further repair is costly ineffective), the heating system failure cannot be removed due to continuous bad weather conditions.	Almost unlikely to occur	0.00001
15	μ_{87} ⑧ → ⑦	**May occur when e.g.:** despite necessary replacement of failed machine, the waiting time for delivery of new machine is too long, so the machine is partially repaired in order to provide the possibility of production performance, despite bad weather conditions the heating systems is partially repaired and the internal temperature is higher, but the production cannot be performed due to necessary inspections of machines at production line.	Almost unlikely to occur	0.0001

The results of experts' opinions are summarized in the Table 2. The fifteen possible transitions between process reliability states are described providing the short characteristic of possible scenarios occurrence, the descriptive probability of occurrence (according to a scale: very likely to occur, medium possibility, low possibility, almost unlikely to occur), and estimated by experts values of failure/repair ratios.

After the analysis of the above presented Table supported by the experts from the area of production processes management, it was established that the most likely to occur are the states no. 0, 1, and 3. Following the current trends in reliability of production systems, usually enterprises cannot allow for failure of production process occurrence. Therefore, the states no. 5, 7, and 8 occur extremely rare in practice. This also implies that they may be omitted in the further research analysis due to their negligible influence on process reliability level.

Moreover, all the reliability states that are greater than state no. 4, are connected with critical situation occurrence from the company's point of view and cause a significant increase in the maintenance costs or even may lead to production system total uselessness. Following this, in the next Sections the sensitivity analysis of the developed model is provided.

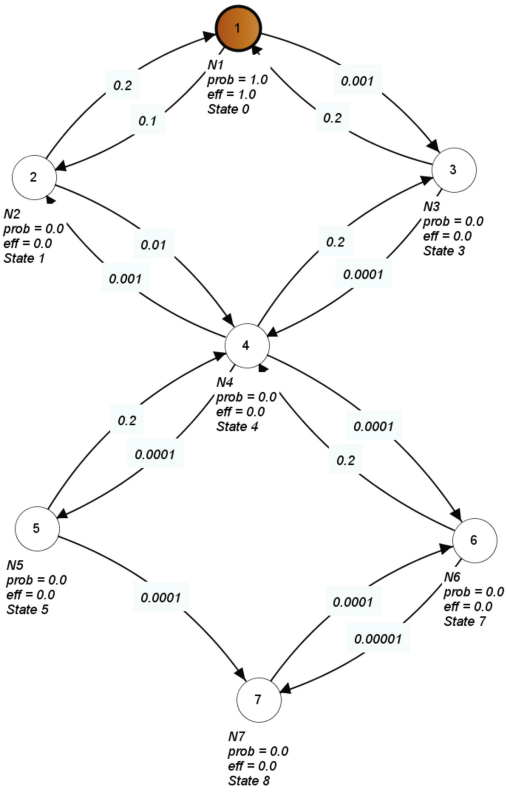


Fig. 2. Markov seven-state model analysed in GRIF Markov software

4.2 Preliminary Sensitivity Analysis for Availability Ratio

The sensitivity analysis of the developed Markov model was made using Markov Graph module of GRIF 2011 Software [9]. It was divided into two main steps. In the first step, the seven-state Markov model is analysed (Fig. 2). Later, the simplified Markov model (four-state model) is analysed. The performed analysis mainly focuses on the calculation of availability function K(t) of the system and probability of being in the state no. 4 - $P_4(t)$.

Obtained, chosen results of sensitivity analysis for availability ratio K, given by the Eq. (2), and system probability of being in the state no. 4 are presented in the Figs. 3 and 4.

The presented analysis results are obtained for transition rates given in the Table 2. For the presented assumptions, the system availability ratio is equal to 0.9657, and the probability $P_4(t)$ equals 0.0155.

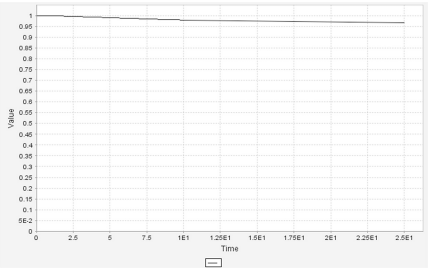


Fig. 3. System availability ratio.

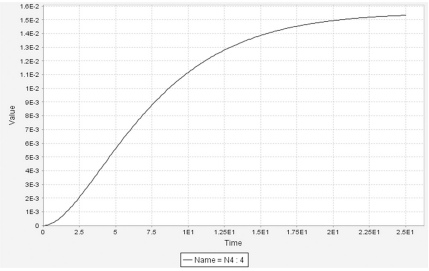


Fig. 4. Probability $P_4(t)$ of the system.

4.3 New Markov Model and Its Sensitivity Analysis

The simplified Markov model includes only four main states that may occur in the manufacturing system according to the obtained experts' opinions. The model is presented in the Fig. 5 and the obtained results of sensitivity analysis are presented in the Figs. 6 and 7.

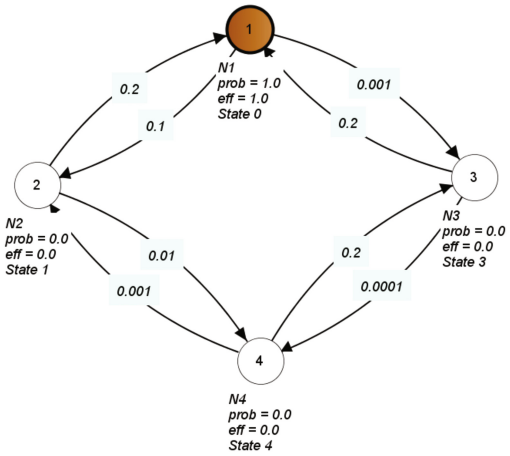


Fig. 5. Markov four-state model analysed in GRIF Markov software

For the presented new simplified model, the system availability ratio does not change its level, and the probability $P_4(t)$ equals 0.0153. This confirms the expert opinions that the transition states no. 5, 7, and 8 have a negligible influence on manufacturing process performance due to their very limited possibility of occurrence.

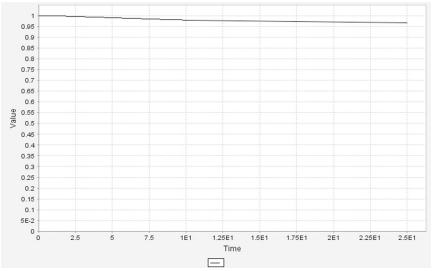


Fig. 6. System availability ratio based on simplified Markov model implementation.

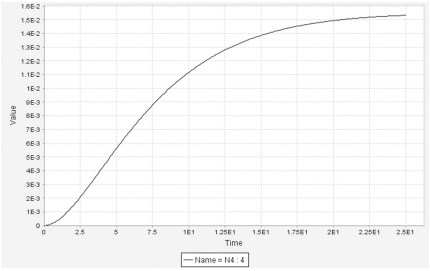


Fig. 7. Probability $P_4(t)$ of the system based on simplified Markov model implementation.

Moreover, it's worth to investigate what is the influence of transition rate level change on system reliability characteristics. Thus, below there is presented the availability ratio in the situation when the failure rates increase two times or repair rates decrease two times (Table 3).

Table 3. The results of sensitivity analysis

Transitions between the states	A*	A*/A
0–1	0.9527	0.99
1–0	0.9551	0.99
0–3	0.9686	1.00
3–0	0.9544	0.99
1–4	0.9403	0.97
4–1	0.9669	1.00
3–4	0.9670	1.00
4–3	0.9573	0.99

The results of the analysis are indicative. They point to logically justified influence of various defined scenarios on manufacturing system reliability characteristic. The greatest influence on the availability ratio of the system has the transition from the state 1 to the state 4 (perfect production plan into imperfect production plan performance with satisfying imperfect conditions). The influence of other transitions between the states (0–3, 4–1 and 3–4) is negligible.

5 Conclusions

In the presented paper, authors present the results of their research work connected with development and investigation of production process reliability assessment method that helps decision managers in their every-day work.

In the presented work, authors develop a Markov model for production process reliability assessment and present the subjective estimation of transitions probabilities. Based on the expert opinions, authors conclude that the developed seven-state Markov model may be simplified to the version of four-state Markov model providing the similar results of reliability analysis (the same availability ratio level and very similar $P_4(t)$ probability level for both the models).

Following this, the authors' further research work will be focused on real manufacturing systems performance analysis and more detailed sensitivity analysis for the given Markov model development.

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Soft Modelling-Based Methodology of Raw Material Waste Estimation

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Abstract. The paper looks at soft modelling-based estimation of raw material waste for various variants of a technological process under development. A methodology of assessment of new technology variants, in terms of minimization of the input material waste, is presented. Results of an analysis of variants of a new technology of manufacturing of the middle layer of a flooring board, carried out according to the developed methodology, are shown. The assessment is performed in an original software tool for waste simulation. It is shown that the developed methodology supports the estimation of material waste and assists in the selection of the optimal variant of the process, taking into consideration the constraints of the organization.

Keywords: Soft modelling · Decision making process · Statistical model · Simulator · Wood · Timber wood · Material waste · Bonding process

1 Introduction

When a manufacturing process is designed, various decisions are taken concerning the process control in variable manufacturing conditions. The decisions are then optimized taking into consideration the possible variants of the technology under development.

In the selection of the optimum variant, various aspects and decision-making criteria are employed. Assessment of possible variants should be based not only on a cost analysis, but also on consideration of other factors – technical, technological, organizational and environmental. It also important to consider factors influencing the organization of production such as logistics (internal transport) [1], production flow, production capacity and other.

Manufacturing of prototypes in order to verify possible variants is impractical and economically unjustified. In an industrial environment, there is a chance that a decision on the optimum technology variant, given certain criteria and organizational constraints, can be taken randomly and intuitively, without support with appropriate analyses or a planned strategy. To avoid errors and random choices, reference to proven scientific

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methods must be made or new solutions in the field of statistical, multi-criteria decision-making support, artificial intelligence or knowledge management methods must be developed [2–5]. Recourse must be also made to solutions within the field of manufacturing planning and organisation [6–8]. Nowadays, in the Industry 4.0 era, methods and solutions within the areas mentioned above constitute the underlying fundamentals of decision-making procedures.

This paper looks at the estimation of material waste for different variants of a technological process under development. The methodology shown was developed in a research and development project carried out at a timber industry company. The research covered the manufacturing process of three-layer flooring boards. The raw material (wooden planks) used in the process is characterised by a high variability of parameters (geometric features, defects).

The costs incurred by a company operating in the wood processing business are mostly related to material waste due to large operational allowances. Such approach is justified by the high level of risk related to the inconsistencies of raw materials. According to Orłowski [9], in the production of laminated floorboard elements, the raw material costs are the most important component of the overall production costs and exceed 80%.

Raw material waste in the manufacturing process of flooring boards is high and may amount to as much as 70% [10]. Therefore, the necessity to improve the process through mitigating the waste is the driving force in the development of new manufacturing technologies and techniques. New decision support methods and approaches are being developed to assist in the selection of the optimum technology variant, given certain assumptions. Mendes [11] and Oliveira [12] propose information systems addressing Cutting Stock Problem and enabling the optimization of purchases and consumption of materials. Optimization of cutting is also an area of research for Danwé [13]. His team solved a problem of log cutting optimization based on a real shape model of the logs and designed a software package – cutting optimizer. Borysiuk [14] describes an approach to change the production processes in order to optimize them and minimize waste on the example of plywood industry company.

2 Research Problem

The research covers estimation of raw material waste in the manufacturing process of one of the three layers of a flooring board–the middle layer.

The middle layer, the so-called mat, constitutes the structural component of the product. The input (raw material) for the middle layer are wooden planks obtained through cutting logs of wood by means of a circular saw. The planks, optionally pre-treated, are cut longitudinally into chocks. The chocks are then cut into slats, of which the middle layer is made. The slats are put one beside the other and bonded with glue. The thus prepared mat is forwarded for the next stage of manufacturing – the process of bonding the three layers into the final block.

Material waste in this manufacturing process is extremely high and generates high costs to the manufacturer. The waste may result from the applied technology, e.g. the

wood shrinks in the drying process or kerfs are created in the process of cutting the planks with a saw. The waste may be generated by the raw material itself – timber is non-homogeneous and has various defects, such as knots, stains, wane or curvatures. Waste of the raw material is also caused by the instability of geometric parameters. Timber is wasted when ends of boards are cut off to obtain the desired length and width of the board. Excessive technological allowances also generate waste [10, 15].

There is a lot of room for improvement of the manufacturing process of the middle layer. Optimization of the process is aimed at more economic use of the raw material. As part of the research and development project carried out at the company, the researchers undertook to develop a completely new technological process.

The underlying concept of the new technology are the middle layer mats made of modules rather than individual slats. For this purpose, boards (the prepared input material) are first bonded into chocks, and next cut into modules (Fig. 1).

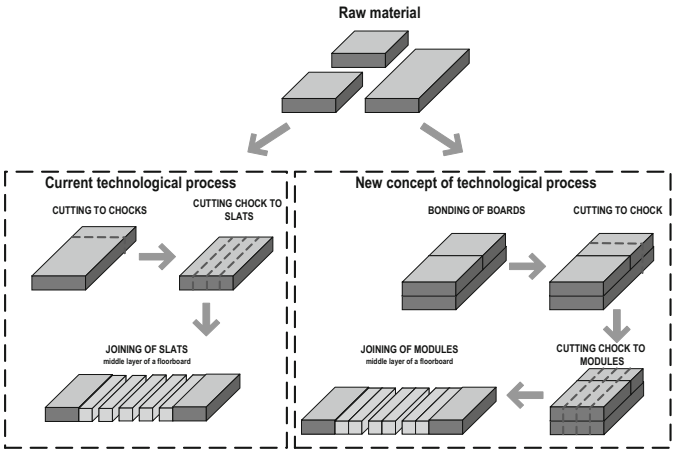


Fig. 1. Comparison of the present and the new concept of the technological process of the floorboard middle layer. Source: Own study

Variants describing the layout and principles of bonding and cutting of boards into modules, with estimated waste of material for each variant, have been developed. Grouped by geometric parameters, the variants are as follows (Fig. 2):

– number of layers (y),
– number of rows (x),
– block length (z).

The variants allow for the inclusion of defective boards, boards without quality defects or both types of boards. Depending on the type of defect, the defects may be cut out, e.g. nods or wane (causing waste of material), or the board may be cut into shorter pieces, e.g. in the case of curvatures (thus, the defect is eliminated and the waste of raw material minimized).

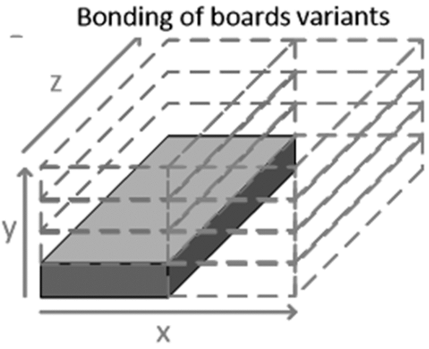


Fig. 2. Assumptions for the construction of board bonding models: x – number of rows; y – number of layers, z – block length. Source: Own study

Taking into consideration the constraints related to the layout of boards for bonding, the variants are as follows:

- Sorting of boards – boards of a certain length are selected for the layout to ensure that certain parts of them do not form the surface where their faces are bonded; this is important for the quality of the final product (the so-called clipping zone, i.e. the part at which the finished board is joined with another one when laid on the floor),
- FIFO (First In First Out) – the boards are bonded in the same sequence in which they are fed from the cutting stage.

Taking into consideration the factors mentioned above, sixteen variants of board bonding layouts were developed (sixteen variants of the technological process).

The concept of joining modules rather than slats for the middle layer mats makes the analysis more complex due to the many variants in which the process can be carried out. For each variant, there is certain waste of the raw material in the process. Some of the variants under analysis were difficult to examine in the manufacturing environment due to the limited resources available.

Considering the limited resources in terms of costs, time and technological and technical possibilities of carrying out experiments to verify the proposed variants, the authors undertook further research.

It follows from the above that there is a need for the development of a methodology and a tool to support the decision-making process concerning the selection of the optimal technology variant, based on the criterion of minimum waste of raw material. An important factor to be taken into consideration is the special nature of wood, which is highly variable in terms of geometric parameters and defectiveness. The researchers undertook to develop of a soft modelling-based methodology of estimating the waste of raw material.

Soft modelling does not take into consideration the nature of modelled phenomena, and can be used for any manufacturing process [16]. The values of model parameters are determined on the basis of experimental data, collected in the manufacturing process rather than during arranged experiments. There are two basic groups of soft modelling methods: statistical, and based on artificial intelligence (learning systems). Soft modelling may assist in the solution of various manufacturing problems [16–18], such

as foreseeing the course of the manufacturing process, the process control, and detecting process regularities.

3 Results

3.1 Soft Modeling-Based Waste Estimation Methodology

In order to select a technology variant for further research, a methodology of raw material waste estimation was developed. The methodology is universal and can be applied for various technological processes.

The methodology consist of the following stages (Fig. 3):

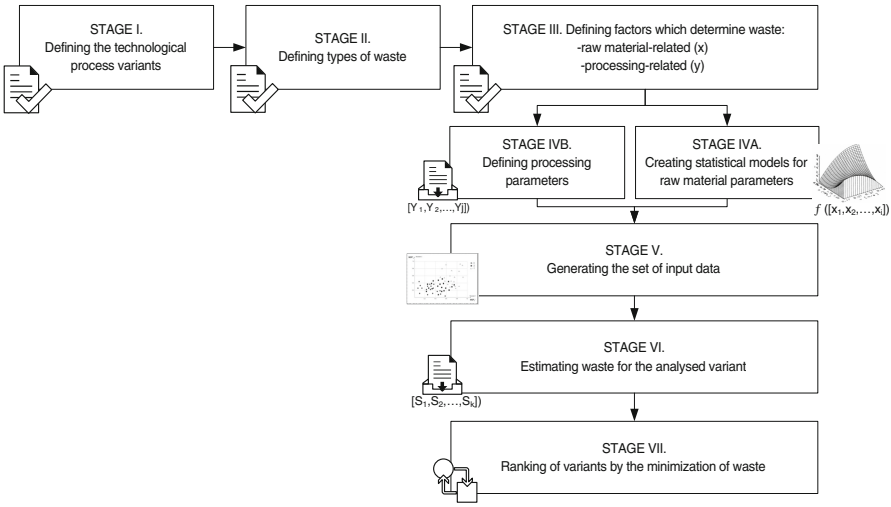


Fig. 3. Key stages of the waste estimation methodology. Source: Own study

STAGE 1: Defining the Technology Variants for the Analysis: At this stage, a set of technology variants is defined, to be analysed and ranked by raw material waste at further stages.

The set of technology variants T:

$$\mathrm{T} = \left[T_i\right] \; i{=}1,\; 2, \ldots,\; n.$$

STAGE 2: Defining Types of Waste: At this stage, possible sources and types of waste are defined for a given technology variant. The waste may be related to the raw material, tool or machine used, etc. This stage is of key importance for the determination of the input parameters for the waste model.

The set of types of waste S:

$$\mathrm{S} = \left[S_j\right] \; j{=}1, 2, \ldots, k.$$

STAGE 3: Defining Factors Which Determine the Waste: At this stage, factors which possibly determine and mitigate the types of waste defined at the previous stage are defined. There are two types of them:

1. Those related to the input raw material – geometric features and properties of the raw material – further referred to as the raw material parameters: $\mathrm{PM} = \left[\mathrm{PM}_l\right] l = 1,\ 2, \ldots,\ q$;
2. Those related to the processing – types of tools used, settings of the machine, etc. – further referred to as the processing parameters: $\mathrm{PO} = \left[\mathrm{PO}_s\right] s{=}1,\ 2, \ldots,\ z$

   At this stage, the matrix of factors determining individual waste types is defined:

$$\mathrm{MS} = \begin{array}{c|cccccccc} & PM_1 & PM_2 & \ldots & PM_q & PO_1 & PO_2 & \ldots & PO_z \\ S_1 & 1 & 0 & \ldots & 1 & 1 & 0 & \ldots & 1 \\ S_2 & 1 & 1 & \ldots & 1 & 0 & 0 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ S_k & 0 & 0 & \ldots & 1 & 1 & 1 & \ldots & 1 \end{array}$$

STAGE 4A: Creation of Statistical Models for the Material Parameters: At this stage, a variability model for the raw material-related factors is determined. The first step is the selection of a measurement system and assessment of its utility according to the MSA methodology. Step two consists in the determination of the type and parameters of the distribution of probability for a given factor, on the basis of observation of a random sample.

The matrix of the factor variability models:

$$\mathrm{M(PM)} = \left[f\left(\mathrm{PM}_1\right); g\left(\mathrm{PM}_2\right); w\left(\mathrm{PM}_3\right); \ldots; m(\mathrm{PM}_q)\right],$$

where: f, g, w, …, m – distribution of probability of variables PM_l.

STAGE 4B: Defining the Processing Parameters: At this stage, values of processing parameters are determined, e.g. the type of tool, speed of machining, etc.

STAGE 5: Generating the Set of Input Data: at this stage, the input raw material data is generated on the basis of the statistical models determined at a previous stage.

STAGE 6: Estimating the Waste for the Variants Under Analysis: At this stage, the value of waste is estimated for each variant of the process under development.

The matrix of waste for the technology variants:

$$ST = \left[ST_{ij}\right] i{=}1,\ 2, \ldots n;\ j{=}1,\ 2, \ldots, k$$

.

STAGE 7: Ranking of Variants by the Minimization of Waste: At this stage, the technology variants are ranked by the minimization of waste.

3.2 Implementation of The Methodology

The developed methodology was applied for the estimation of raw material waste in the process of manufacturing of the floorboard middle layer.

First, variants of the new technological process were defined. The technology was selected based on the number of boards and the manner of bonding, taking into consideration the organizational and economic potential of the company. Sixteen variants were selected for the analysis, resulting from:

- number of layers: three and two,
- number of rows: one and two,
- raw material: without defects and defective,
- raw material feeding method: bonding on the FIFO basis, bonding preceded by sorting and selection of chocks (the clipping zone control).

Once the variants were defined, the type of waste that may occur in the process were determined, as follows (Fig. 4):

- the kerf created in the process of cutting bonded blocks into chocks,
- the kerf created in the process of cutting chocks into modules,
- the leftovers resulting from the lack of ability to cut a chock,
- material cut out due to knots,
- material cut out due to wane,
- imprecisely planed material.

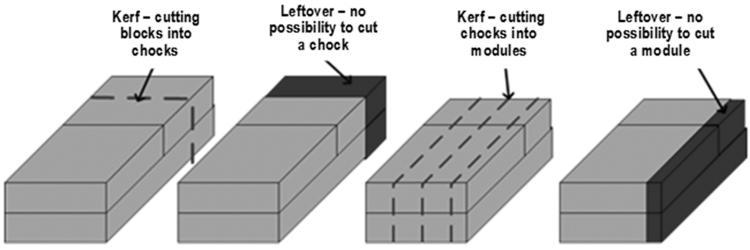


Fig. 4. Waste of material in the new technology – examples. Source: Own study

At stage three, factors determining individual types of waste were defined, as follows:

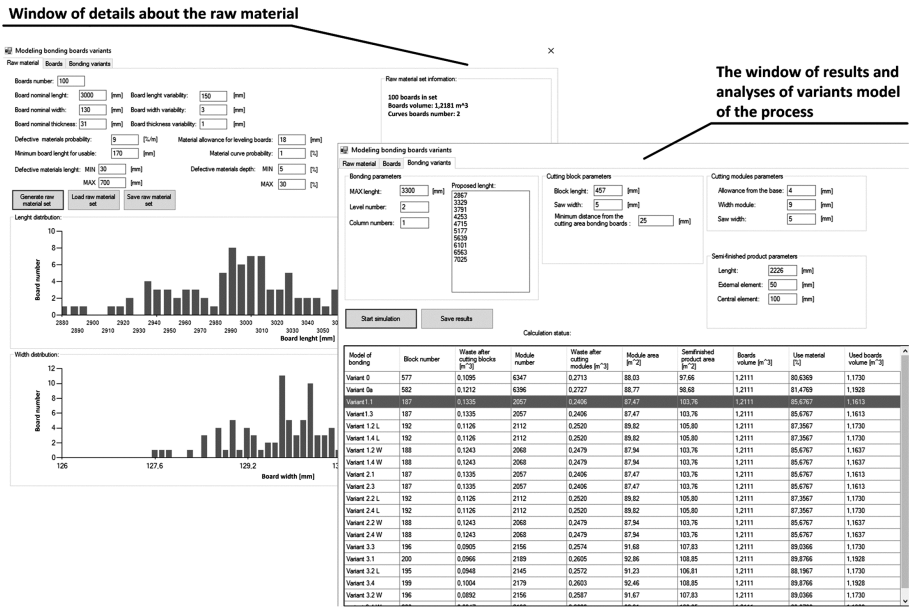
- material-related factors: occurrence and layout of knots, occurrence and layout of wane, occurrence and layout of curvatures,
- processing-related factors: tool parameters (e.g. the width of the saw), feed rate, speed of machining, length of chock, width of module, dimensions of the ready product (the mat).

At stage four, a random sample of 400 planks was selected. Next, each plank was assessed in terms of the number and location of material defects, and the thickness, width and length of each plank were measured. Then, the distributions of probability for the

material properties were modelled – 400 samples of timber (400 planks) were taken into consideration and their statistical distribution of amount and types has been specified on the basis of frequency of their appearing on the surface of timbers.

Further stages were carried out in the original software tool – a simulator facilitating simulation of waste for each technology variant. The simulator supports the decision-making process and determination of assumptions for further technical and economic analyses for the purpose of designing (and implementation) of the new technology.

The basic functionality of the simulator includes the modelling of material properties for predetermined size groups of planks, generating sets of raw material and calculation of raw material waste for individual technology variants, given the predefined processing parameters. The simulator also supports the calculation and visualisation of statistical data for the generated set of raw material (Fig. 5).



Model of bonding	Block number	Waste after cutting blocks [m^3]	Module number	Waste after cutting modules [m^3]	Module area [m^2]	Semifinished product area [m^2]	Boards volume [m^3]	Use material [%]	Used boards volume [m^3]
Variant 0	577	0,1095	6347	0,2713	88,03	97,66	1,2111	80,6369	1,1730
Variant 0a	582	0,1212	6396	0,2727	88,77	98,63	1,2111	81,4769	1,1928
Variant 1.1	187	0,1335	2057	0,2406	87,47	103,76	1,2111	85,6767	1,1613
Variant 1.3	187	0,1335	2057	0,2406	87,47	103,76	1,2111	85,6767	1,1613
Variant 1.2 L	192	0,1126	2112	0,2520	89,82	105,80	1,2111	87,3567	1,1730
Variant 1.4 L	192	0,1126	2112	0,2520	89,82	105,80	1,2111	87,3567	1,1730
Variant 1.2 W	188	0,1243	2068	0,2479	87,94	103,76	1,2111	85,6767	1,1637
Variant 1.4 W	188	0,1243	2068	0,2479	87,94	103,76	1,2111	85,6767	1,1637
Variant 2.1	187	0,1335	2057	0,2406	87,47	103,76	1,2111	85,6767	1,1613
Variant 2.3	187	0,1335	2057	0,2406	87,47	103,76	1,2111	85,6767	1,1613
Variant 2.2 L	192	0,1126	2112	0,2520	89,82	105,80	1,2111	87,3567	1,1730
Variant 2.4 L	192	0,1126	2112	0,2520	89,82	105,80	1,2111	87,3567	1,1730
Variant 2.2 W	188	0,1243	2068	0,2479	87,94	103,76	1,2111	85,6767	1,1637
Variant 2.4 W	188	0,1243	2068	0,2479	87,94	103,76	1,2111	85,6767	1,1637
Variant 3.3	196	0,0905	2156	0,2574	91,68	107,83	1,2111	89,0366	1,1730
Variant 3.1	200	0,0966	2189	0,2605	92,86	108,85	1,2111	89,8766	1,1928
Variant 3.2 L	195	0,0948	2145	0,2572	91,23	106,81	1,2111	88,1967	1,1730
Variant 3.4	199	0,1004	2179	0,2603	92,46	108,85	1,2111	89,8766	1,1928
Variant 3.2 W	196	0,0892	2156	0,2587	91,67	107,83	1,2111	89,0366	1,1730

Fig. 5. The simulator – the views from the software tool. Source: Own study

At stage 5, a set of data on the input material (planks) was generated and at stage 6, the waste of raw material was calculated (Table 1). The waste of raw material is the total of the volume of material resulting from the specific character of a given variant and the knowledge obtained from the process, recorded in the form of soft models.

According to the methodology, at the last stage, the technology variants were ranked (Table 1) by the percentage of the input material used to obtain the final product. In the ideal variant, 100% material is used.

It results from an analysis of the simulation results (Table 1) that variant no. 10 is optimal, where more than 71% of the input material is used. Here, boards are bonded in three layers and two rows, the material is free from defects (B) and is fed sorted. In the

group of variants where the material is defective (Z), the optimal variant in terms of the utilization of input material is variant no. 15 (two layers, one row, feeding of sorted material) – ca. 70% of the input material is used.

Table 1. Results analysis – ranking of the technology variants. Source: Own study

Variant	Number of layers	Number of rows	Material	Material feeding method	Use of material (%)	Ranking position
1	3	1	B	FIFO	69.06	8
2	3	2	B	FIFO	68.69	9
3	2	1	B	FIFO	69.18	7
4	2	2	B	FIFO	66.96	15
5	3	1	Z	FIFO	68.17	12
6	3	2	Z	FIFO	68.23	11
7	2	1	Z	FIFO	68.53	10
8	2	2	Z	FIFO	65.02	16
9	3	1	B	sort.	71.48	2
10	3	2	B	sort.	71.69	1
11	2	1	B	sort.	70.93	3
12	2	2	B	sort.	69.67	6
13	3	1	Z	sort.	70.42	5
14	3	2	Z	sort.	67.43	14
15	2	1	Z	sort.	70.57	4
16	2	2	Z	sort.	67.58	13

Legend: Z – defective, B – free from defects, FIFO – First In First Out, sort. – sorted

4 Discussion and Conclusions

At the concept phase, several variants of a new technology are taken into consideration. One of the objectives of selection of variants for further analysis is the minimization of the generated waste. Waste may be estimated through preliminary examination, experiments, or manufacturing of prototypes. However, in industrial practice, these methods of waste estimation are impractical due to their high cost or organizational constraints. Therefore, a methodology and a tool supporting the decision-making process in the selection of a technology variant based on the criterion of minimization of waste are proposed. The methodology is based on soft modelling. According to the authors, it may be found especially useful in the timber industry, where, in general, waste of raw material is high. Although, simulation-based methods for the analysis of production processes can be found in the literature [8, 18–21], there is no similar solution of this type, discussed in the paper, in the literature of the subject.

Assumptions for a new technology may be determined with the use of the methodology. With the assistance of the developed simulator, variants for further work on the design of a new technology may be recommended.

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Study on Tracking the Mined Ore Compound with the Use of Process Analytic Technology Tags

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Abstract. The growing need of reducing the use of raw materials and energy in the chain of supplying goods draws the attention to all aspects of the most energy intensive processes like mining and processing of metal ore. Processing of raw materials strongly depends on their parameters, hence the more accurate identification of them should improve the process efficiency. The Process Analytic Technology with information carrying tags (pellets), annotating transported or processed raw material – is investigated within the *DISIRE* project. The application of *DISIRE* PAT for non-ferrous minerals processing is dealt with the copper producer KGHM S.A. The ore exploited in its underground mines in Poland is among the most difficult for processing. The ore compound is recognized in-situ – in mining faces. On the way to processing plants down the transportation system consisting of belt conveyors and ore bunkers, the portions of ore from numerous mining faces are converted into an unknown mixture. The study of PAT tags implementation to assign the conveyed ore with the relevant information to recognize the mixed ore compound is presented.

Keywords: SPIRE · DISIRE · Ore lithology · Belt conveying · RFID tags

1 Introduction

The traditional, energy intensive process industry in Europe is becoming less competitive due to the European policy of climate protection by GHG emission limitations that causes high energy costs. In order to mitigate the resulting deindustrialization of Europe ("carbon leakage" effect) substantial efforts have to be taken towards increasing the energy efficiency of the European industry. SPIRE (Sustainable Process Industry through Resource and Energy Efficiency) is a proposal for Public Private Partnership (PPP) that aims to regain competitiveness of the ailing European process industry by "the collaborative efforts of public research and technology organizations and academia as well as industry stakeholders throughout Europe, along and across the value chain" [9]. SPIRE consists of several groups of projects. One of them is the DISIRE (Distributed In-Situ Sensors Integrated into Raw Material and Energy Feedstock) research project, launched in 2015 within the HORIZON 2020 framework and grouping 15 partners from several European countries [13]. The project is focused on the idea of use of the

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Integrated Process Control (IPC) for the improvement of process industry by the implementation of Process Analytical Technology (PAT) pellets (tags) embedded into the processed (or transported) raw material for storing and reading relevant information.

PAT has been defined as "a system for designing, analyzing, and controlling manufacturing through timely measurements (i.e., during processing) of critical quality and performance attributes of raw and in-process materials and processes, with the goal of ensuring final product quality" [12]. It has been implemented in the industrial processes that require the highest standards of accuracy and quality assurance like pharmaceutical development [6]. The idea has been adopted for the needs of ore tracking to improve mining and processing of metal ore and aggregates [2, 7, 11].

Mining and ore processing are among the top energy intensive industrial processes. Therefore, copper ore tracking in the chain of mining, transportation and processing has been included into the list of industrial work packages of the DISIRE project [13]. The investigation is focused on the tracking of ore transported from mining fields to the processing plants in order to improve the ore processing (see Fig. 1). Poland's KGHM S.A. – the industrial partner of the dedicated work package "Non-Ferrous minerals" is the biggest European copper producer.

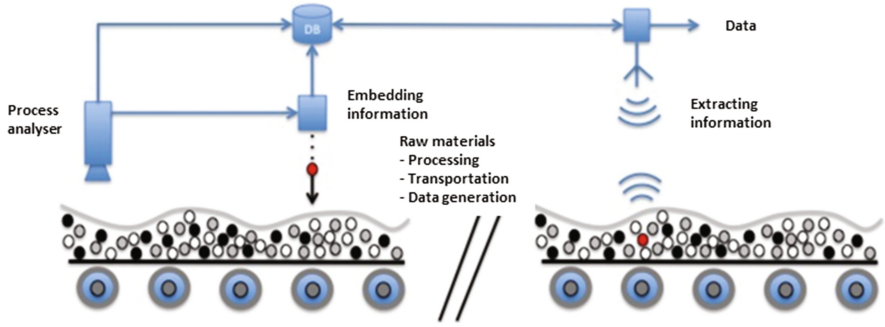


Fig. 1. DISIRE concept for the pelletizing process of raw material transporting [13]

2 Copper Ore Lithology Identification

The reasons for addressing the problem of variations of ore lithological compound on the feed to a concentration (processing) plant in KGHM S.A. underground operations in Poland were raised in [4] on the basis of several papers [1, 3]. As stated in [1] "the lithological types of ore treated by KGHM S.A. have not only variable crushing and grinding parameters, but also different floatability, which is the main reason for the creation of unique conditions for treatment during the grinding and flotation operations". The mined deposit has the form of a seam, which vertical profile consists of dolomites, shale and sandstone (from top to bottom – see Fig. 2). These lithological forms occur at the same time, but in different proportions, thus having a significant influence on the grinding and flotation conditions [1]. The influence of various proportions of lithological components in copper ore supplied to concentrators on the specific energy consumption

of grinding with the use of Bond work index was analyzed in [10]. Indeed, the different ore mixtures require very different (up to 50%) amount of energy for grinding processes. Moreover the parameters of grinding should be adjusted according to the actual ore compound otherwise some energy is lost for unproductive work or the resulting granulation of the grinded material is not sufficient.

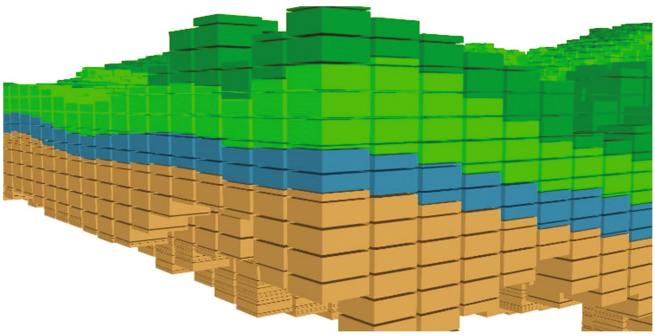


Fig. 2. Visualization of the structural block model of the balance ore from a mining field in a KGHM S.A. mine (applied legend of ore lithology: green – dolomites, light green: streaky dolomites, blue: shale, orange: sandstone)

KGHM employs the room-and-pillar mining method at all of its mines in Poland. Mining is done simultaneously at several mining faces in mining fields. Though the ore compound is recognized in-situ, after blasting, loading onto trucks and then from trucks onto belt conveyors, the portions of different ore are mixed in the complex transportation system consisting of sectional and main conveyors and ore bunkers. The final ore mixture compound is unknown. If each portion of uploaded ore is annotated with a pellet (tag) written with the relevant information, necessary to identify its compound and on the feed to the processing plant all pellets are read (see: Fig. 1) then there would be an opportunity to make an assessment of the resulting ore stream compound. This information could then be used for the proper settings of the ore processing equipment or – if possible – for blending the ore to get mixtures that decrease the consumption of grinding energy.

3 Ore Tracking System Prerequisites and Challenges

For the needs of analyzing and testing the proposed solution of the PAT system, the east branch of the KGHM Lubin mine was chosen (Fig. 3). At the moment several information systems support industrial process of mining, transport and beneficiation of the ore. These systems are focused on maintaining both the high rate of ore output and reliable work of all elements of the machinery equipment. There is a lot of information already collected and saved on a regular basis that would be useful for the needs of the PAT system for tracking the ore compound.

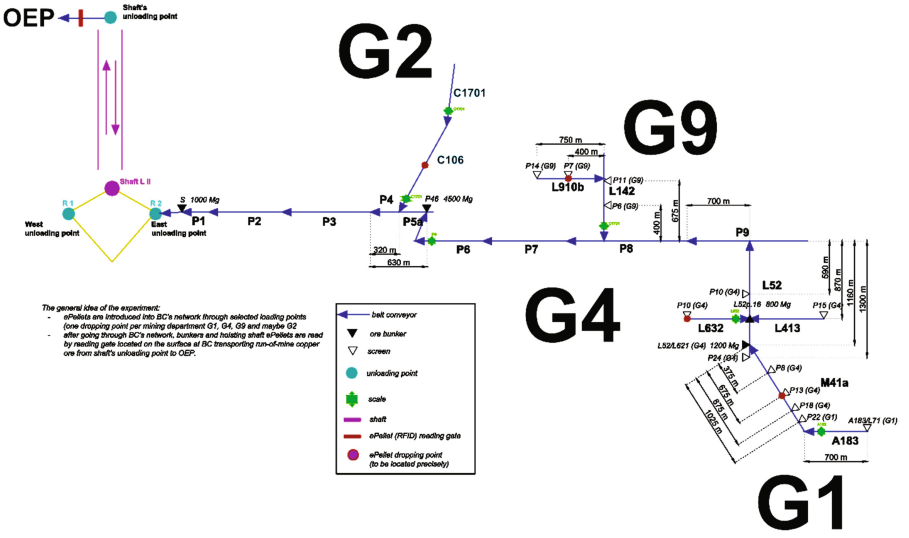


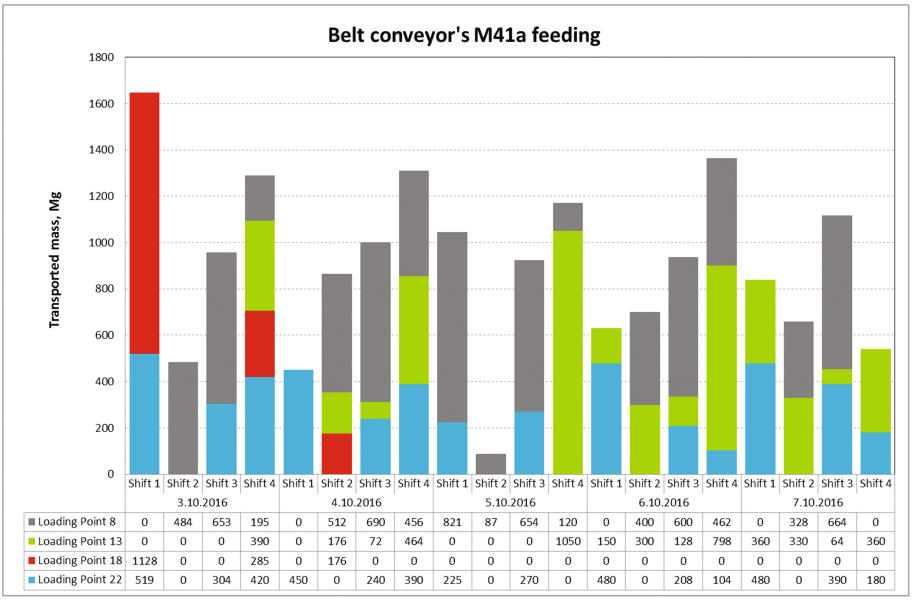
Fig. 3. KGHM Lubin East mine transportation system selected for industrial trials; G1, G4, G9 – active mining departments delivering ore from mining fields by trucks onto loading points (unfilled triangles), filled triangles – ore bunkers with maximum capacity, Lx, Px – belt conveyors, OEP – Ore Enrichment Plant

The most useful information system that supports mining operations and ore production is MOPRONA [5]. Data are fed to MOPRONA on a regular basis from mine plans and schedules as well as from operational shift reports and from other databases (like BDG – geological channel samples data). In the MOPRONA schedules are compared with production reports though the exact reconciliation is not feasible as the final production results refer only to the summed ore tonnage and averaged grade. Despite that there are input data of the ore compound and grade identified at active mining faces (from the nearest geological channel sample), these data are not further analyzed due to the lack of ore tracking data in MOPRONA. Chart presented on Fig. 4 shows the variations of the ore loadings on 4 screens installed on the single reported conveyor from several mining faces. For a given shift each screen is assigned with a known mining face from where the ore is hauled. These data are also recorded in MOPRONA. Location of mining faces is documented on digital mine plans (DGN format).

The flow and mixing of consecutive portions of uploaded ore depend on the sequence of truck arrivals at the loading points with regard to the exact layout of all elements of belt conveyor system: sectional conveyors with loading points, main conveyors and ore bunkers as presented on Fig. 3. Weights installed at several points of the system are used for recording conveyed tonnage of ore.

The following main difficulties were recognized after the analysis of the mine transportation system:

- The ore flow is complex and not fully recorded. Therefore, a simulation was proposed as the best solution to analyze this problem and find the best alternative. Simulation



	Shift 1	Shift 2	Shift 3	Shift 4	Shift 1	Shift 2	Shift 3	Shift 4	Shift 1	Shift 2	Shift 3	Shift 4	Shift 1	Shift 2	Shift 3	Shift 4	Shift 1	Shift 2	Shift 3	Shift 4
	3.10.2016				4.10.2016				5.10.2016				6.10.2016				7.10.2016			
Loading Point 8	0	484	653	195	0	512	690	456	821	87	654	120	0	400	600	462	0	328	664	0
Loading Point 13	0	0	0	390	0	176	72	464	0	0	0	1050	150	300	128	798	360	330	64	360
Loading Point 18	1128	0	0	285	0	176	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Loading Point 22	519	0	304	420	450	0	240	390	225	0	270	0	480	0	208	104	480	0	390	180

Fig. 4. Variations of ore supply during 20 consecutive shifts uploaded onto several loading points of a sectional belt conveyor (data source: MOPRONA)

models are usually easy to explain and understand [8]. However *MOPRONA* together with the recorded operating time of conveyors generate a lot of data for the validation of the simulation models. Such simulations can be performed with the use of dedicated tools [14].

- There is a specific problem of the ore behavior inside ore bunkers. Copper ore consists of lumps of different size. The ore flow through a bunker is turbulent. There are various methods of modelling this phenomenon like cellular automata or discrete element methods. These investigation are done in the *DISIRE* project [9, 13].

The *FlexSim* program was proposed due to its versatile modelling techniques and objects which can be used to build and analyze a detail mode [14]. *FlexSim* offers also a lot of diagrams which can illustrate various process flow steps and simplify the explanation of the modelling relationships. *FlexSim* is a discrete-event, object-oriented simulator.

It has been employed to build the model of flow the ore with the embedded e-pellets (treated as separate objects added to the portions of ore uploaded by trucks). On the Figs. 5 and 6 the model of the analysed belt conveying system and the simulation results are presented.

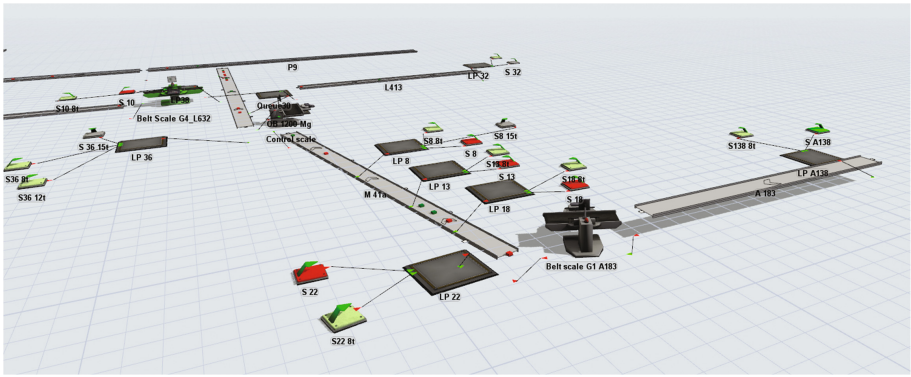


Fig. 5. Modelled east branch of the conveyor system in the Lubin mine for simulation ore flow and pellet experiment. Cubes on conveyors represent e-pellets. Each parcel represents one load. Colours represent different weights of load discharged by trucks or loaders (source: FlexSim)

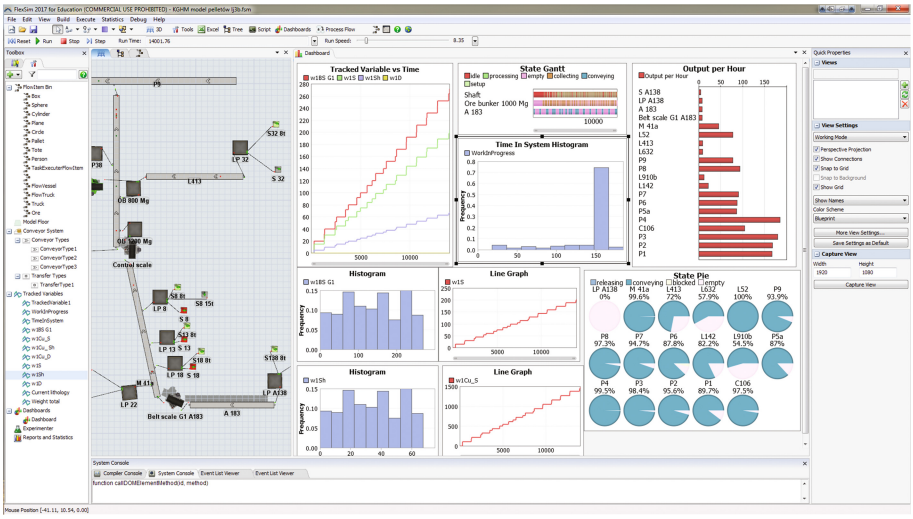


Fig. 6. Presentation of one shift simulation results (4 h of loading = 14400 s) including: line chart of ore weight on the 1st scale by lithology: red – total (w1BS G1), green – sandstone (w1S), blue – shale (w1Sh), number of pellets per hour in selected objects (mostly conveyors) and pie chart showing state of selected objects. The conveyor A 183 transported over 260 tonnes of ore including 200 tonnes of sandstone containing 1500 kg of Cu (source: *FlexSim*)

The analysis of the first results of simulations have proved that the model can provide a rough assessment of the ore compound and grade on the feed to the processing plant on the basis of data already available in the information systems in KGHM mines. However, the simulation results have to be tuned with the help of an additional information gathered from the resultant ore stream. The PAT e-pellets (tags) are the proposed answer.

4 The Proposed Workflow of the Ore Tracking System

The above issues have been used for creating the scheme of planned workflow of the ore lithology tracking process with the use of *DISIRE* PAT tags. The workflow is presented in the form of IDEF0 schemes (Fig. 7).

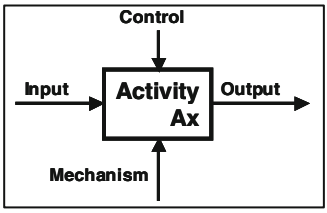


Fig. 7. IDEF0 description scheme

The workflow consists of activities done with the use of information systems either already used in the KGHM mines (MOPRONA, BDG, Microstation, Belt Conveyors control system) or proposed (*FlexSim*, *DEM* software, statistical software). The specialised equipment for writing and reading e-pellets (see Fig. 1) is also added.

Within the general scheme several particular solutions are investigated. First, it is not obvious which place is the most suitable to identify the portion of mined ore with a pellet:

- at the loading point on a BC screen (a number written to the pellet identifies the truck and the mining field where the truck was loaded); these numbers can be prepared in advance on the surface and marked pellets are then dropped by an operator of the BC loading point (who operates a hydraulic hammer breaking oversized ore lumps onto the screen); assistance of the operator on the spot is then required,
- directly at the mining face where a truck is loaded (a number written to the pellet should then identify the mining face and the truck payload); these numbers can either be prepared in advance; the marked pellets are then dropped into the portion of ore loaded onto the truck by an operator working in the mining field,
- alternatively, there is a possibility of marking special pellets added to the blast holes (they should be blast resistant) and after the blasting pellets are loaded together with the mined ore onto a truck [2]; such activity can be automatized.

Regardless on the chosen method of marking the ore, there is an important problem of a loss of some pellets [2]. The actual tag detection rate in the KGHM copper ore mines harsh environment will be identified during planned in-situ experiments.

The ore mined in mining fields by KGHM mining departments (G1, G4, G9 on Fig. 3) is supplemented with some ore mined from developments by outsourcing companies that build new drives. These portions of ore would not be identified but the limited tonnages allow to neglect them for the final results of mixed ore lithology.

At the moment the actual ore lithology in the mining parcels is taken from the channel samples, documented in-situ and recorded in the BDG system, then supplied to MOPRONA. This lithology is assigned to the nearest mining faces of the currently

exploited room-and-pillar drives. Any fluctuations of the mined ore compound that could occur during the shift are therefore neglected. Alternatively, data from the digital, geological block model, containing the actual lithological and grade data can be used. The model is being created during the project of implementation of the KGHM Mine Planning System based on the mining industry standard *Datamine Software* [15]. This project has been just completed and the model is being implemented in the KGHM mines.

Depending on the chosen source of the ore lithology data (BDG channel samples database or 3-D orebody block model) alternative information has to be recorded. On the Fig. 8 both data sources are included. In MOPRONA, the markings of the mining faces are used (that also denote the channel samples). In the block model the necessary information would be X, Y coordinates rather for creating an outline within the model to evaluate more accurately the currently mined mining block of a balance ore seam. In such a case the X, Y coordinates have to be provided instead of mining faces markings (already available in the mine plan in the DGN format).

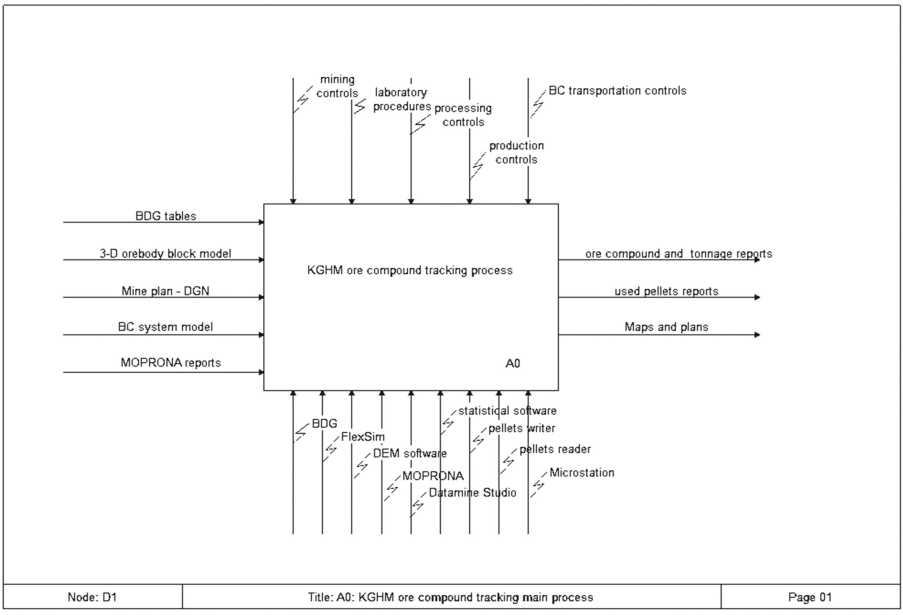


Fig. 8. A general overview of the ore tracking process expressed by an IDEF0 scheme

The results of the ore tracking process would be supplied to the ore processing control systems supporting the grinding, milling, separating and flotation of the ore.

The scheme representing the main activities of the ore tracking process with the use of channel samples data (Fig. 9) shows the general relations between applied tools, necessary input and expected output of the consecutive activities.

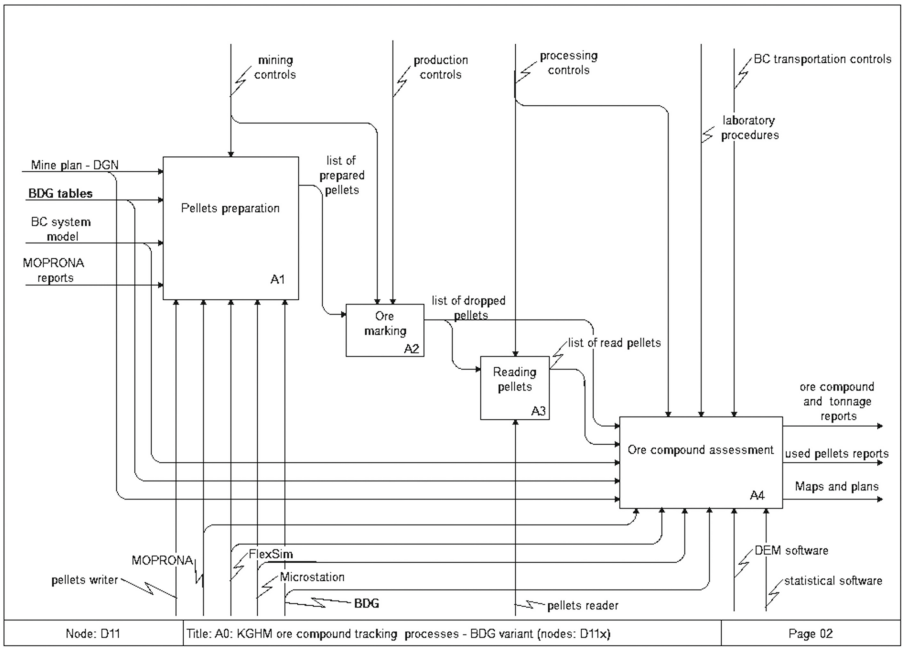


Fig. 9. Main activities of the ore tracking process

The final results should contain the ore compound and tonnage reports (exported to the processing plant information systems not described in the paper) and used pellet reports and supplementary maps and plans – data considered to be necessary for further tuning the system and used therein.

5 Final Remarks

The discussion on the ore tracking process with the use of PAT sensors for the needs of copper ore mining, conveying and processing in the Polish KGHM underground mines is presented.

Basing upon the gathered knowledge of the mining operations and existing information systems the workflow of the ore tracking system is proposed.

The investigation is then focused on the development of the simulations of the BC transportation system (*FlexSim*), modelling of the ore flow through the bunkers and statistical analysis of the information from the detected sensors. The series of in-situ experiments is planned to be done in the selected branch of the KGHM Lubin mine.

It has to be noted that even the smallest improvement of the processing of the ore due to the recognition of the ore compound will return substantial energy savings and should increase metal recovery. The annual ore output reaches some 33 million tonnes, from which some 430 thousand tonnes of Cu is obtained. Assuming very conservative

estimations of just 1% of ore grinding energy saved and the metal recovery increase by 0,1%, the annual savings should reach some 2,5 million euros.

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The Use of Neural Network Model in the Assessment of Annoyance of the Industrial Noise Sources

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Abstract. In this article, there was made an attempt to use artificial intelligence methods in the assessment of industrial noise annoyance. There was discussed the research carried out under laboratory conditions and with using the calculation formulas. The results of the use of the neural network model, for the selected variables are more satisfactory, in the context of the methods used. One of the advantages of the presented approach is the possibility of predicting the assessment of noise annoyance for different values against input parameters.

Keywords: Industrial noise annoyance · Neural network model · Psychoacoustic aspects · Sound quality

1 Introduction

The noise problem is not only related to source, but to the source and receiver simultaneously. Acoustic climate of an environment is shaped by different sources, the impact of which can be described using physical characteristics [2, 19]. Particularly, the acoustic climate in an industrial environment is shaped not only by stationary sources, but also by sources coming from transport vehicles. Emission of noise sources in the environment also depends on conditions of technical objects (e.g. industrial machinery, vehicles). Pattern measures, taking into account the exploitation characteristics of single and complex technical structures are included in [3, 4, 9, 12–14, 21].

These types of sources directly influence on the areas of factories and industrial zones, it means – infrastructure associated with an industrial installation and residential districts. The impact of the transportation sources is usually characterized as an annoyance. This annoyance is caused not only by traffic, but also by vehicles and roads of their movement.

Research on the impact of the transportation on the industrial environment focuses on the use of methods assessing the noise annoyance. For this purpose, there are used physical and psychoacoustic measures. The transportation systems belong to the mobile noise sources, which significantly complicate the assessment problem.

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The basic measure of psychoacoustic standardized noise annoyance, is the time-varying loudness [5]. Additional measures such as: sharpness and tonality are standardized only for stationary signals. Other measures, i.e. roughness and fluctuation strength are determined on the basis of the accepted procedures, but they are not standardized.

While loudness of stationary sounds has been standardized for decades, standards for sharpness of stationary sounds and for loudness of time-varying sounds have been the subject of publications in 2009 [6] and 2010 [5], respectively [20].

The noise annoyance can be determined in the laboratory by playing sounds. Listeners assess the annoyance of the noise signals with used the 11-point numerical scale ICBEN.

Existing methods for assessing the noise annoyance are expressed by different formulas and do not refer explicitly to a single model. These methods determine an approximation of the annoyance assessment, in the context of the assumptions and simplifications of physical and psychoacoustic aspects of the sources.

Deficiency of the developed noise annoyance assessment models, as well as the partial approach to the assessment methods, justifies the need for research on the use of selected intelligence methods to solve the problem described. Therefore, in the article, the authors made an attempt to use the neural networks to support the development of the assessment model of the industrial noise annoyance.

2 Measures Described Acoustic Quality

Current research on the sound quality assessment is focused on the evaluation of acoustic comfort as well as on the evaluation of annoyance.

The basic problem of determining the sound quality is a lack of the reference standard i.e. the pattern. The sound quality may be expressed positively or negatively. The negative assessment of the sound quality of acoustic events concerns unpleasant, annoying and disturbing perception or causing negative associations.

Processing acoustic signals by a human belongs to the complex and complicated issues. The results of studies show, that noise events influence different aspects (i.e. physical, psychological and psychoacoustic) for the processing of auditory sound.

The physical aspect is determined by changing the sound depending on the frequency and direction of emission. The psychoacoustic aspect relies on perception of sound by the inner ear and depends on the structure and time as well as the distribution frequency. The psychological aspect is determined by the context of sound. It means, type of information and personalized attitude to the perception of different sounds affect the classification of auditory events.

Two of the mentioned aspects of the processing acoustic signals by a human, are described by the proposed measures, relating to the acoustic quality of the industrial environment:

– physical – the standardized and quantitative assessment methods are represented by the averaged sound level: L_{Aeq}, L_{day}, $L_{evening}$, L_{night}, L_{den} according to the environmental noise directive [7],

– psychoacoustic (loudness, sharpness, roughness and fluctuation strength), and other parameters, which are included in the description of the acoustic environment i.e. the quantity of the acoustic sources (their spatial arrangement), as well as the direction and speed of moving sources.

The psychological aspects of the processing the acoustic signals has highly subjective character, which means that for every person is different.

3 The Problem of the Assessment of the Noise Annoyance

In the perception context of the processing and evaluation of the acoustic signals, there can be distinguished objective and subjective nature of sound. The objective representation of the sound perception includes basic parameters of the physical description of the acoustic signal, such as the sound level, the spectrum, the psychoacoustic measurements, the tonality, the impulsiveness, the duration and time structure of sound. The subjective representation of the sound perception includes non-acoustic factors, such as: the mood, the context, emotions, the space and the attitude. Submission of objective parameters and subjective factors for an individual recipient is the resultant of the noise annoyance. Therefore, the noise assessment cannot be expressed only by the sound level. Variables, which accompany the noise annoyance can be reduced to interferences of the perception process, containing the different context. In particular, the interferences include variables of time and day, place, current activity and individual features (e.g. sensitivity of noise, fear of the source, age, attitude to the source).

The results of the study in 2000–2010 showed very weak correlation between the level of annoyance and applied noise measures. Depth studies in this area published in [22], as well as in [10], presented large differences in the noise annoyance assessment of the same sounds made by listeners. It was caused by individual sensitivity of particular persons to the noise.

Another approach to the assessment of annoyance has been proposed by Zwicker [23] in the form of the umbiased annoyance (UBA). In this perspective, the noise annoyance does not depend on the relationships between the noise source and the listener. The umbiased annoyance was defined as a combination of the measures: sharpness (S), fluctuation strength (F), loudness (N10 = ten percent percentile) and was corrected by the time of day.

$$UBA = d\left(N_{10}\right)^{1,3}\left[1 + 0,25 \cdot (S-1) \cdot \log\left(N_{10}+10\right) + 0,3 \cdot F \cdot \left(\frac{1+N_{10}}{N_{10}+0,3}\right)\right] \quad (1)$$

where: $d = 1$ for the time between 22:00–6:00,

$d = 1 + \left(\frac{N_{10}}{5}\right)^{0,5}$ for the time between 6:00–22:00.

Corrected UBA formula, proposed by [24], as a measure of the psychoacoustic annoyance (PA), is a combination of the loudness (N5 – five percent percentyl), the fluctuation strength and the roughness – for the sharpness.

$$PA = N_5 \cdot \left(1 + \sqrt{w_s^2 + w_{FR}^2}\right) \tag{2}$$

For: $S > 0,75$:

$$w_s = (S - 1,75) \cdot 0,25 \cdot \log(N_5 + 10) \tag{3}$$

For: $S \leq 0,75$:

$$w_s = (S - 1,75) \cdot 0,25 \cdot \log(N_5 + 10) \tag{4}$$

$$w_{FR} = \frac{2,18}{N_5^{0,4}} \cdot (0,4F + 0,6R) \tag{5}$$

It should be noted, that in each of the multicomponent formula of the assessment, the loudness variable is the main factor [17].

4 The Assessment of the Mobile Noise Annoyance: A Case Study

Sources of road noise can be categorized as a class of mobile sources of organized and unorganized character. In the organized context, the position changes continuously. It is assumed to be constant or floating acoustic power at the time. In the unorganized context, the position and the duration changes stepwise. There can be distinguished the acoustic events of determined and randomized character [18].

In the process of modeling the sound emission from the environmental noise source, there are seeked relationships between quantities characterizing the noise source, and the propagation parameters of the sound field. They are entry information to the assessment of the noise annoyance.

According to the directive [7], the assessment of the impact of the road noise in the environment is carried out based on the noise maps technology. In this perspective, the relationship between the source and the reception point is modeled by:

- the geometric parameters determining the spatial structure of the objects (e.g. buildings, roads, green areas) in the environment,
- the acoustic parameters determining the objects in the environment,
- a set of indicators for assessing the acoustic climate.

The assessment is a quantitative and refers to an estimate of the acoustic climate indicators (L_{Aeq}, L_{DWN}, L_N).

In this case, we have to deal with the noise annoyance varying in time. The indicator of noise, used in the quantitative assessment and referring to the averaged energy, does not include the time structure of the acoustic signal. This means, that signals of the same value L_{Aeq} are assigned to different time structures. As a consequence, this causes different assessment of the noise annoyance. The difference may be caused by different loudness values.

Considering this issue, there have been proposed alternative indicators with using the calculation of the loudness N10 or N5. For nonstationary sound signals, there was proposed the models developed by [23] as well as by [8]. Determination of N10 or N5 using the above mentioned models, leads to different results for the same signals [17].

Despite the use of approximate models defining the loudness varying in time, there is no satisfactory measure, which would represent the noise loudness. It also means the lack of standardized measure of the noise annoyance assessment, which would take into account a direct relationship between physical and psychoacoustic sound parameters.

4.1 Psychoacoustic Experiment of the Assessment of the Noise Annoyance

The psychoacoustics research uses the methodologies, which allows to determine the relationships between physical stimulus and auditory impression, caused by this stimulus. Selection of such methodology depends from the research objectives, experiment location, its duration, etc. Used research methods are focused mostly on the determination of the perception threshold, including absolute or differential values for measured auditory impressions [16].

In the psychoacoustic experiment the magnitude estimation method was used. It belongs to the scaling methods group. These methods allow for quantification of impression level caused by the stimulus. Their purpose is to estimate impression of the stimulus characteristics. The experiment consisted in estimating values of the acoustic signal in a closed room, by assigning a number, which corresponds to a received impression. In the experiment participated 80 people, between the ages 22–50 years. There was proposed the point grading scale of the noise annoyance, ranging from 1 to 5. The following rating values was assigned:

1 – at all, 2 – low, 3 – medium, 4 – much, 5 – unbearable.

Table 1. Examples of results of the the annoyance noise assessments for the emitted signals in the classes: $L_{Aeq} = 80$ [dB], $L_{Aeq} = 56$ [dB]

Address point	Median	Kurtosis	Standard deviation	Normalization
DW13a_7_80	2	0,07	0,80	1,00
DW27_1_80	2	1,81	0,81	0,42
DW27_2_80	2	0,45	0,78	0,12
DW27_9_80	2	1,94	0,67	0,12
KOZ10a_9_80	2	1,05	0,64	0,04
DW13a_8_80	2	–0,58	0,65	0,00
DW13a_9_56	5	0,90	0,60	0,63
DW13a_10_56	5	0,07	0,61	0,41
DW27_4_56	5	1,11	0,58	0,70
DW27_8_56	5	2,23	0,65	0,44
KOZ10a_4_56	5	3,58	0,54	1,00
KOZ10a_5_56	5	1,09	0,76	0,00

In the framework of the experiment, each person individually assessed annoyance of the acoustic signal, emitted from the speaker (the mobile sources of the road noise). The respondents evaluated 30 recorded samples. The recorded signals samples corresponded to reference points at the facades of buildings in the environment. The samples were calibrated in the five classes L_{Aeq}: from 56 to 80 [dB(A)]. During the experiment, the samples were emitted randomly with the same time duration – 10 [s].

The results of the experiment, presented in the Table 1, were expressed with using basic statistical models. The responses were averaged and subjected to normalization.

4.2 Determination of the Psychoacoustic Measures of the Noise Annoyance Assessment

For the purpose of further analyzes, selected parameters were standardized, i.e. UBA and PA (Table 2). The loudness values, for 30 input samples were calculated in accordance with the (5). To determine the roughness and sharpness values, there was used the (1). The fluctuation strength was calculated on the basis of the sound pressure from time history.

Table 2. Examples of results of the the annoyance noise assessments in the class $L_{Aeq} = 80$ [dB]

Punkt adresowy	N5	N10	S	R	F	UBA	PA	Norm. UBA	Norm. PA
DW13a_7_80	23,04	21,62	2,2	0,7	0,54	87,92	32,96	1,00	0,99
DW27_1_80	29,12	25,2	2,1	1	0,68	108,47	44,05	0,20	0,00
DW27_2_80	25,37	24,57	2,4	0,7	0,43	107,29	36,39	0,24	0,65
DW27_9_80	28,03	26,33	2,2	0,7	0,52	114,36	39,31	0,00	0,39
KOZ10a_9_80	28,24	25,7	2,4	0,2	0,44	114,28	36,94	0,00	0,60
DW13a_8_80	24,66	23,92	2,4	0,4	0,31	101,14	32,88	0,47	1,00

4.3 Discussion of the Results

The results derived from the experiment and also obtained with using the psychoacoustic measures, i.e. UBA and PA (Eqs. 1 and 2), indicate the presence of divergences in the assessment of the annoyance of the examined acoustic signals (Fig. 1). The values of the assessment of the acoustic signals, in other classes of L_{Aeq}, show greater divergence.

Further analysis was targeted to values of each of the psychoacoustic measure for all tested samples. It showed the importance the loudness parameter N5 and the sound level at low frequencies (20 ÷ 100 Hz) in the convergence of the results derived from the experiment and also calculated (Fig. 2). The variability of shaping the experiment results in comparison with the calculated values of the psychoacoustic measures, indicated the need for in-depth research in this area. Therefore, it was justified to determine the importance and influence of individual psychoacoustic measures in the assessment of impressions, derived from the acoustic signals.

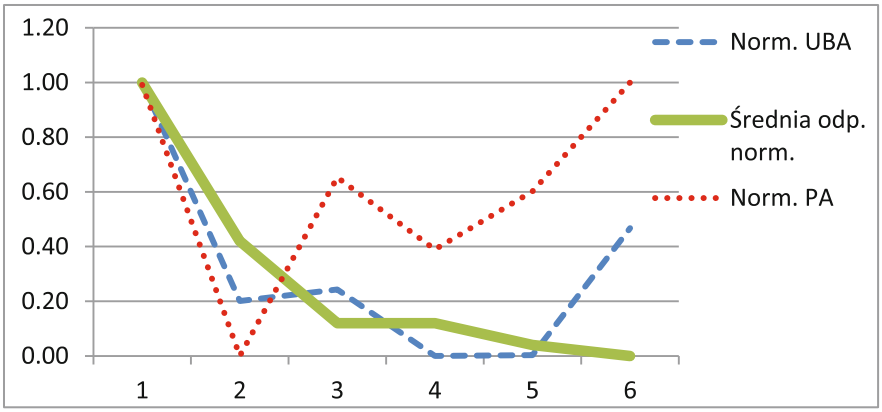


Fig. 1. The results summary of the assessment of the noise annoyance derived from the experiment and the calculation (after normalization) for the samples of the class LAeq = 80 [dB]

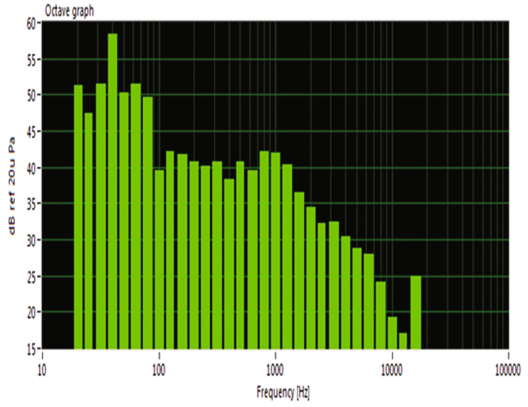


Fig. 2. The frequency distribution of an exemplary sample No. DW27_9_80

The results of research undertaken in the sound perception field [20] indicate, that besides loudness, other psychoacoustic parameters like sharpness and roughness are important for the sound quality assessment. The sharpness determines the relationship between the loudness of high frequency components and the total loudness, while the roughness assesses modulation characteristics.

5 Modelling Noise Annoyance with the Use of Neural Network

The measures of the noise annoyance assessment, expressed in formulas of UBA and PA (1), (2), in comparison with the results of the experiment, showed significant divergences (Fig. 1). This justifies research on the use of more effective methods of supporting the noise annoyance assessment. In this regard, the authors made an attempt to use

artificial intelligence methods (i.e. neural networks) to support selection of measures of the noise annoyance assessment (Fig. 3).

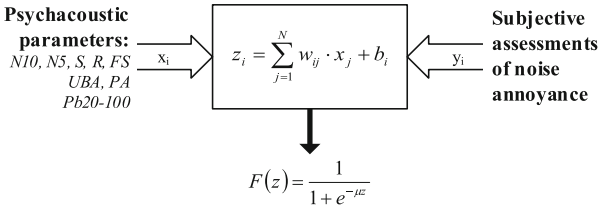


Fig. 3. The way of selection of measures of noise annoyance assessment supported with the neural network

In particular, there was looked for relationship between physical and psychoacoustic input variables (x_i) and the output values (y_i) derived from the assessment of the experiment.

$$y_i = F(z_i) \tag{6}$$

$$z_i = \sum_{j=1}^{N} w_{ij} \cdot x_j + b_i \tag{7}$$

where: z_i – active potential, $w_{i,j}$ – weights of connection, b_i – threshold parameter.

From among various activation functions, the sigmoid function are commonly used:

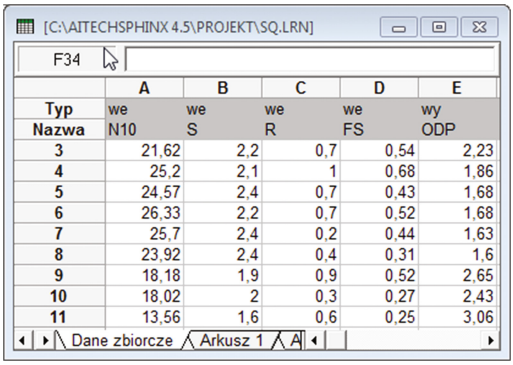
$$F(z) = \frac{1}{1+e^{-\mu z}} \in (0,1) dla\ \mu > 0 \tag{8}$$

There was proposed a variant combination of the psychoacoustic measures, as an input data to build the neural network model. For the input of each variant, there was assigned the output in the form of averaged values of the listeners assessment from the experiment (Fig. 4). For modeling needs, there were adopted two hidden layers. There were developed three neural network models in the following combinations of the input variables, i.e.

A. four: N10, S, R, FS,
B. three: N5, Pb20-100, S,
C. two: UBA, PA.

For this purpose, there was used the support system – Neuronix 4.5.

Each of the developed neural network models was subjected to the learning process (Fig. 5). There was selected the rms testing method with epsilon = 0.01, at the learning tolerance of 0.1 and testing tolerance of 0.15.



	A	B	C	D	E
Typ	we	we	we	we	wy
Nazwa	N10	S	R	FS	ODP
3	21,62	2,2	0,7	0,54	2,23
4	25,2	2,1	1	0,68	1,86
5	24,57	2,4	0,7	0,43	1,68
6	26,33	2,2	0,7	0,52	1,68
7	25,7	2,4	0,2	0,44	1,63
8	23,92	2,4	0,4	0,31	1,6
9	18,18	1,9	0,9	0,52	2,65
10	18,02	2	0,3	0,27	2,43
11	13,56	1,6	0,6	0,25	3,06

Fig. 4. A sample screen of Neuronix program with input and output data of the network model

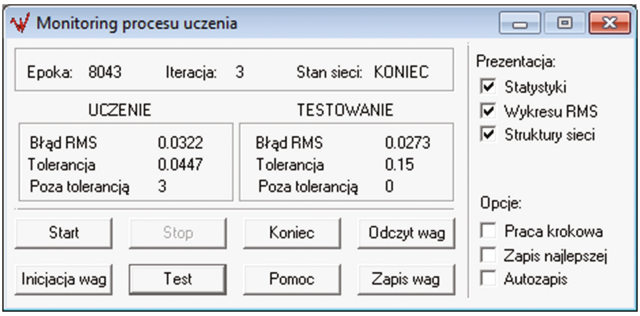


Fig. 5. A sample screen of Neuronix program with monitoring of the network learning process

After obtaining the min. value by the network quality RMS indicator, there were generated the best network parameters (Fig. 6). This also means, that the inaccuracy of the RMS indicator for learning and testing process, reached the minimum value.

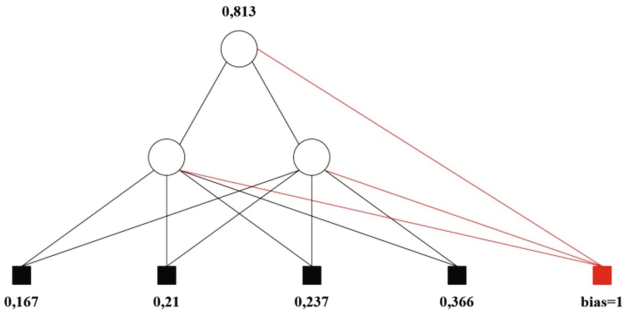


Fig. 6. Visualization of the structure of the best network

In the next step, there was running network models responding to the identified combinations of input data. The obtained values were summarized with the output values of the network model (Figs. 7 and 8).

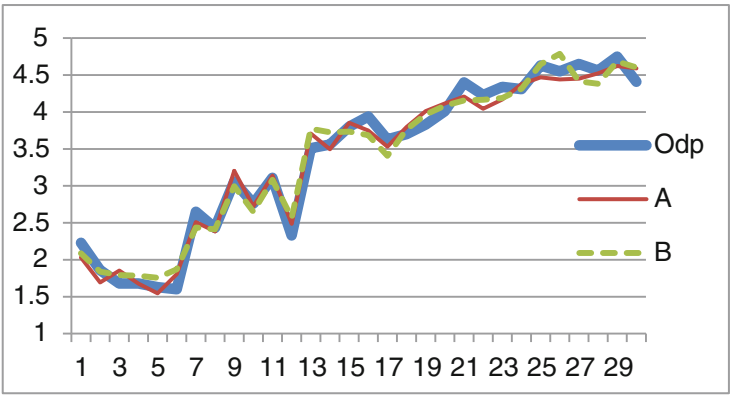


Fig. 7. Development of output (after running the network) with the averaged results of assessments of the experiment for four and three input variables

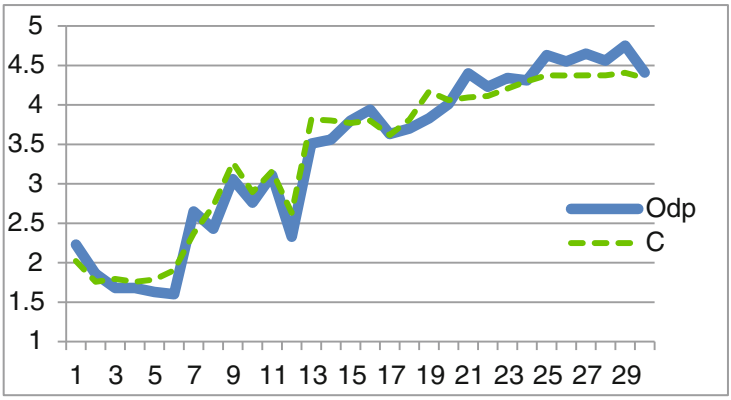


Fig. 8. Development of output (after running the network) with the averaged results of assessments of the experiment for two input variables

The results of use of the neural network in the selection of the input variables, show better data adjustment for three and four input variables (Fig. 8). The analysis of distribution of inaccuracy, presented:

– the biggest inaccuracy between a set of input and output data occurred at the level of 0.34, with using two input variables,
– the smallest inaccuracy with a value of 0.20 with four input variables.

6 Conclusions

The results of the research on the existing approach to the assessment of noise annoyance were not satisfactory to the authors. Comparison of the noise annoyance assessment with the experiment, in relation to used measures, showed divergence for different classes of L_{Aeq}. It should be emphasized that, under laboratory conditions there was used a single measure of noise annoyance. The authors assumed improvement of the method of the noise annoyance assessment by adding a rating scale of emotions to the point grading scale of noise.

Preliminary results from the application of neural networks showed a greater convergence with the results obtained under laboratory conditions in comparison with the relevant measures of the noise annoyance assessment. The proposed way of supporting selection of the assessment measures of noise annoyance with using neural networks, can also be applied in the assessment of the impact of other sources. Further research on the use of intelligent methods in the assessment of noise annoyance will be developed in the direction of modeling various physical and psychoacoustic parameters and improvement of neural network models, as well as the development of scenarios shaping acoustic climate in industrial and urbanized environment [11, 15].

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Transport Trolley Control in a Manufacturing System Using Simulation with the FSAW, FWASPAS and FTOPSIS Methods

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Abstract. The paper is a case study of the application of fuzzy MCDM methods to transport trolley control in a manufacturing system. For this purpose, three methods (FSAW, FWASPAS and FTOPSIS) are applied and compared with their non-fuzzy versions using discrete simulation in Matlab Simulink with SimEvents. The aim of the control is the suboptimal selection of the transport trolley's destination (the appropriate production line), which depends on time efficiency and equal workload of machines. The application of MCDM methods is compatible with flexible automation.

Keywords: FMCDM method · FTOPSIS method · FSAW method · FWASPAS method · Production line · Manufacturing system

1 Introduction

The automation of production lines is a non-trivial problem and requires complex control systems with scheduling rules for discrete processes, able to rapidly make appropriate decisions, adapting themselves to changing conditions and production requirements [1]. Nowadays, manufacturing systems are much larger with an increasing number of production lines and workstations, requiring sophisticated (intelligent) flow control methods. The use of Programmable Logic Controllers (PLCs) allows to program various solutions, such as Artificial Intelligence (AI) methods [2–4], Petri nets [5–7] and multi-agent systems [7]. The AI methods can handle the uncertainties generated by incomplete or inaccurate data. Moreover, tools based on hybrid AI methods have a low computation complexity and can be implemented on small production lines, or in systems with low-capability microcontrollers [2].

Using the approach proposed in [1], this paper presents applications and a comparison of Fuzzy Multi-Criteria Decision Making (FMCDM) methods as a non-standard solution of flow control in manufacturing systems. In particular, the fuzzy versions of the Simple Additive Method (SAW) [8], Weighted Aggregated Sum Product ASsessment (WASPAS) [9] and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [10] methods are applied and compared. These methods have been chosen because of their simplicity and popularity (WASPAS being one of the

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newer methods). They allow for control using multiple simple parameters and complex indicators related to the machines and manufacturing processes. This approach supports the optimization of the manufacturing process.

The evaluations of transport trolley's destinations are performed against the criteria on the basis of the past operation of the production lines. The values of the parameters are averaged over the whole range of assortment. Because of the flexible production and automatic changeover, the evaluations obtained are not precise for the current type of work piece. Moreover, there is uncertainty as to the estimated waiting time for the release of a production line [1]. For these reasons, the methods applied use fuzzy environment.

The use of SAW (fuzzy SAW, or FSAW) and TOPSIS (fuzzy FTOPSIS, or FTOPSIS) in technical applications can be found, so far, in very few publications [11, 12], which are related to the control problem in manufacturing systems. These methods are mainly used in the evaluation and selection of flexible manufacturing systems (production lines) [13–17] or workstations in a manufacturing system [18]. Recently, several authors [19–21] applied WASPAS in the manufacturing process. Chakraborty et al. [19] used WASPAS to real-time manufacturing problems (selection of a flexible manufacturing system, of a machine in a manufacturing system, of an automated guided vehicle etc.). Nevertheless, there are still some interesting and relevant problems to be addressed.

The remainder of the paper is organized as follows. In Sect. 2 the basic ideas of the FSAW, the FWASPAS and the FTOPSIS methods are outlined. Section 3 presents the problem and its solution; the implementation of these methods using simulation is described. The results of the simulations and a comparison of the methods are also presented. Section 4 consists of a summary of the results and conclusions.

2 The Fuzzy Multi-Criteria Decision Making Methods: FSAW, FWASPAS and FTOPSIS

The MCDM methods allow to order the decision variants depending on their numerical evaluations (the manufacturing process parameters) with respect to several criteria. Therefore, they allow to minimize the intervention of experts in the evaluation of decision variants which is of particular importance in the applications to the automation of production systems.

Every MCDM problem is based on the analysis of the following preliminary decision/evaluation matrix, which can be transformed into a fuzzy decision matrix:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1N} \\ x_{21} & x_{22} & \cdots & x_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ x_{M1} & x_{M2} & \cdots & x_{MN} \end{bmatrix}, \tag{1}$$

where M is the number of alternatives ($m = 1, \ldots, M$), N is the number of evaluation criteria ($n = 1, \ldots, N$) and x_{mn} is the evaluation of mth alternative with respect to nth criterion ($x_{mn} \in \mathbb{R}$). Since we suggest to use the trapezoidal fuzzy numbers, the elements of matrix X have the following form (Fig. 1):

$$x_{mn} = (a_{mn}\, b_{mn}\, c_{mn}\, d_{mn}). \tag{2}$$

The fuzzy decision matrix is normalized as follows ($R = (r_{mn})_{M \times N}$)

$$r_{mn} = \begin{cases} \frac{x_{mn}}{\max_n d_{mn}} & if \quad n \in C_{ben} \\ \frac{\min_n a_{mn}}{x_{mn}} & if \quad n \in C_{cost} \end{cases}, \tag{3}$$

where C_{ben} is the set of benefit criteria (max value is preferable), and C_{cost} is the set of cost criteria (min value is preferable).

In the analysis we also use the numerical weights of criteria w_n $(w_n > 0, n = 1, \ldots, N)$ which satisfy the condition: $\sum_{n=1}^{N} w_n = 1$. The consecutive steps in the calculation of the total evaluation of the alternatives depend on the fuzzy MCDM method used.

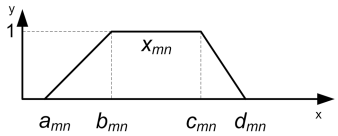


Fig. 1. The evaluation of an alternative in the form of the trapezoidal fuzzy number

2.1 The FSAW Method

The SAW method was used for the first time in [8] as a method for solving the portfolio selection problem. Under uncertainty and/or when the evaluations of alternatives are difficult to measure, the fuzzy SAW method [22] is also used. The main procedures to find the scores of the alternatives using FSAW are described in Table 1.

Table 1. Procedures of the FSAW method

Stage	Description of procedure
1	Construct the weighted normalized fuzzy decision matrix $V = (v_{mn})_{MxN}$ using the importance values $(w_n,\ n = 1, \ldots, N)$ where $v_{mn} = w_n \cdot r_{mn}$
2	Aggregate the fuzzy total relative importance of mth alternative: $Q_m = \sum_{n=1}^{N} v_{mn}$
3	Determine the total relative importance Q_m^* of mth alternative by using the Center-Of-Gravity (COG) defuzzification method

2.2 The FWASPAS Method

WASPAS is a relatively new method which uses an aggregation operator on Weighted Sum and Weighted Product Models (WSM and WPM). Zavadskas et al. [9] first

suggested WASPAS as an approach whose accuracy is stronger than that of WPM or WSM. The fuzzy version of WASPAS is proposed for decision making in an uncertain environment [23]. The main procedures of FWASPAS are described in Table 2.

Table 2. Procedures of the FWASPAS method

Stage	Description of procedure
1	Using the Weighted Sum Model (WSM), aggregate the total relative importance of mth alternative: $Q_m^{(1)} = \sum_{n=1}^{N} w_n \cdot r_{mn}$
2	Using the Weighted Product Model (WPM), aggregate the total relative importance of mth alternative: $Q_m^{(2)} = \prod_{n=1}^{N} (v_{mn})^{w_n}$
3	Determine the total importance of mth alternative [9]: $Q_m^* = \lambda \cdot Q_m^{*(1)} + (1-\lambda) \cdot Q_m^{*(2)}, \lambda \in [0,1]$, where $Q_m^{*(1)}\left(Q_m^{*(2)}\right)$ is the crisp value obtained from the fuzzy number $Q_m^{(1)} = (a_m\, b_m\, c_m\, d_m)$ by using the Center-Of-Gravity (COG) defuzzification method. The value λ is calculated as follows [23]: $\lambda = \frac{\sum_{m=1}^{M} Q_m^{*(2)}}{\sum_{m=1}^{M} Q_m^{*(1)} + \sum_{m=1}^{M} Q_m^{*(2)}}$

2.3 The FTOPSIS Method

The TOPSIS method, proposed by Hwang and Yoon [10], calculates the total importance of alternatives by measuring simultaneously their distances from the positive ideal solution and the negative ideal solution. The positive ideal solution is the alternative (solution) that is most preferred by the decision maker; the negative ideal solution is the least preferred alternative. The steps of FTOPSIS are shown in Table 3.

The last stage of FSAW, FWASPAS and FTOPSIS is the ranking of the alternatives according to their calculated value Q_m^*. The best alternative is the one with the largest Q_m^*.

The methods presented above are used in the next section for the control of a transport trolley in a manufacturing system.

3 Application of the FSAW, FWASPAS, and FTOPSIS Methods to the Control of a Transport Trolley

3.1 Problem Statement and Its Solution

These three fuzzy MCDM methods are used to control a transport trolley in a Poly (Vinyl Chloride) (PVC) window production system (Fig. 2). The system contains three concurrent and independent welding and cleaning lines (WCLs) and three assembly and treating lines (ATLs). The trolley, located between WCLs and ATLs, transports work pieces from one of the production lines (WCLs) to the appropriate ATL. The problem in question consists in the development of a flow control algorithm for the

trolley, which specifies the trolley's destination (the appropriate ATL). The three ATLs, denoted ATL1–ATL3, as the trolley's destinations, are the alternatives. The following criteria are assumed in the evaluation of each ATL [1]:

- C1 – the estimated waiting time for the release of an ATL;
- C2 – the ATL workload; it is calculated as the ratio of the sum of processing times on machines and workstations of the ATL (expressed in seconds) to the sum of processing times on machines and workstations of the ATL and breaks during the analyzed period; the maximum line workload is 1, and the minimum 0;
- C3 – the arithmetic mean waiting time of an ATL (for a work piece); it is the arithmetic mean waiting time of the first assembly table on the ATL for the work pieces;
- C4 – the arithmetic mean waiting time of a work piece; it is the arithmetic mean waiting time of a work piece in the buffer just before the first assembly table on the ATL.

Table 3. Procedures of the FTOPSIS method

Stage	Description of procedure
1	Construct the weighted normalized decision matrix $V = (v_{mn})_{M\times N}$ using the importance values $(w_n, n = 1, \ldots, N)$ where $v_{mn} = w_n \cdot r_{mn}$
2	Determine the positive ideal solution S^+: $S^+ = \left(v_1^+, v_2^+, \ldots, v_N^+\right) = \left\{\max_m v_{mn}\right\}$
	Determine the negative ideal solution S^-: $S^- = \left(v_1^-, v_2^-, \ldots, v_N^-\right) = \left\{\min_m v_{mn}\right\}$
3	Calculate the distances of each alternative from the positive ideal solution $S^+\left(d_m^+\right)$ and from the negative ideal solution $S^-(d_m^-)$ $d_m^+ = \sum_{n=1}^{N} d\left(v_{mn}, v_n^+\right)$ and $d_m^- = d\left(v_{mn}, v_n^-\right)$, where the distance d between two fuzzy numbers $A = (a_A\, b_A\, c_A\, d_A)$ and $B = (a_B\, b_B\, c_B\, d_B)$ is calculated as $d(A,B) = \sqrt{\frac{1}{4}\left[(a_A - a_B)^2 + (b_A - b_B)^2 + (c_A - c_B)^2 + (d_A - d_B)^2\right]}$
4	Determine the relative closeness of mth alternative to the ideal solutions $S^+$and S^-: $Q_m^* = \frac{d_m^-}{d_m^+ + d_m^-}$

The only criterion C3 is of benefit type. It is associated with the requirement to minimize downtime, hence an ATL with a higher mean waiting time and standby duty time is selected first. The other criteria are of cost type. This is appropriate from the perspective of time efficiency and equal line load.

To verify and compare the presented methods as algorithms of flow control, the PVC window manufacturing system with three production lines and the proposed solutions has been simulated in Matlab Simulink with SimEvents (see Fig. 2). The information from the assembly tables and the CNC machines in ATLs is recorded to

calculate the signals according to criteria C1–C4. Details of the simulation of a similar model of a manufacturing system can be found in [1].

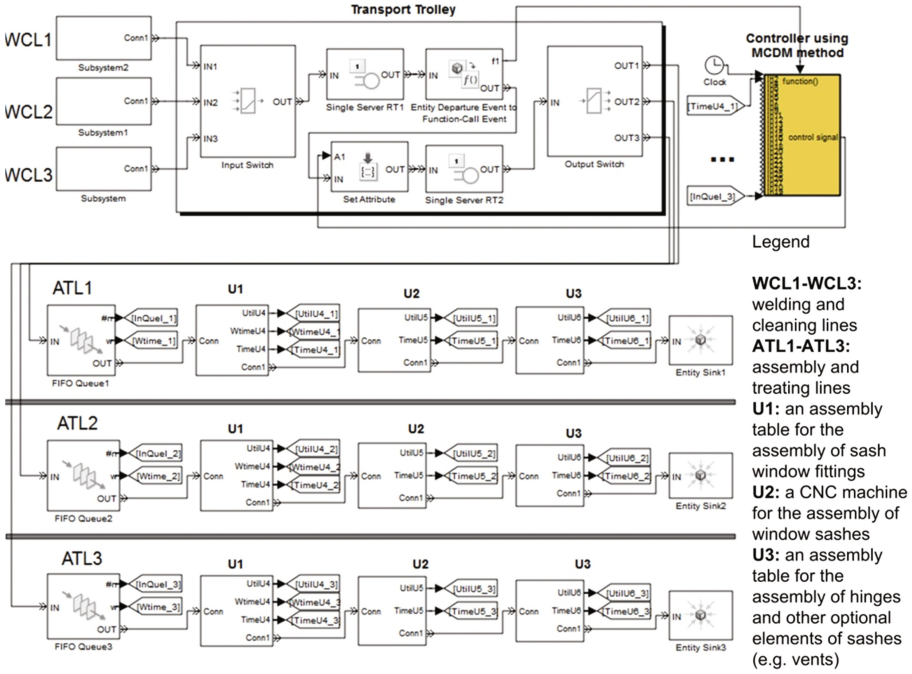


Fig. 2. The simulation model of the manufacturing system with the transport trolley controller

The numerical data for the simulation (such as window sizes, processing times on the workstations and machines, etc.) have been obtained from an interview with experts working with real-life PVC window manufacturing systems. The time of the simulation is 16 h (two shifts). The order of the arrival of window sashes to the production line is random. The processing time of a work piece on each machine (workstation) is the mean of the actual processing times on this machine (workstation).

The evaluations of the alternatives (production lines) based on the criteria set constitute data (parameters), collected during the simulation of the manufacturing system. Due to the uncertainty of the estimation, the crisp evaluation values $x^*_{mn} \in \langle x^L_{mn}, x^U_{mn} \rangle (m = 1, \ldots, M;\ n = 1, .., N)$ are fuzzified into trapezoidal fuzzy numbers of the form (2), where $a_{mn} = \max\left(x^L_{mn}, x^*_{mn} - 2 \cdot \sigma\right), b_{mn} = \max\left(x^L_{mn}, x^*_{mn} - \sigma\right), c_{mn} = \min\left(x^U_{mn},\ x^*_{mn} + \sigma\right), d_{mn} = \min(x^U_{mn}, x^*_{mn} + 2 \cdot \sigma)$. 2.5% of the width of empirical data has been assumed as the imprecision bound σ.

3.2 Results and Discussion

In the simulation, the parameters are calculated according to criteria C1–C4. These parameters can be used at the same time as criteria for the evaluation of the control method. The results of the simulation depend on the crisp weights w_n ($w_n > 0, n = 1, \ldots, 4$) for production line evaluation criteria. The analysis indicated that when the fuzzy MCDM methods are used, a change in the weights does not affect the result, as opposed to the case of the non-fuzzy MCDM methods. For example, workloads of production lines are more divergent and the waiting time is larger for the weight vector $W_1 = \{0.1,\ 0.4,\ 0.4,\ 0.1\}$ which indicates that balancing the workloads of a production line is more important than minimizing the waiting time on it, than for the weight vector $W_2 = \{0.4,\ 0.1,\ 0.1,\ 0.4\}$.

Figure 3 presents the results of the simulation using the three fuzzy MCDM methods (FSAW, FWASPAS, FTOPSIS methods) for the weight vector W_2. In the simulation we calculate both the workloads of the ATLs and the standard deviation of the workloads, for all three ATLs (Fig. 2). The value of the standard deviation indicates workload divergence among the ATLs. The desired value of this parameter is close to 0, but this occurs only when the round robin method is used for control. In that case, however, the control is not flexible and in case of changeover or failure the allocation of the lines is not changed. This can result in longer waiting times and longer lead time.

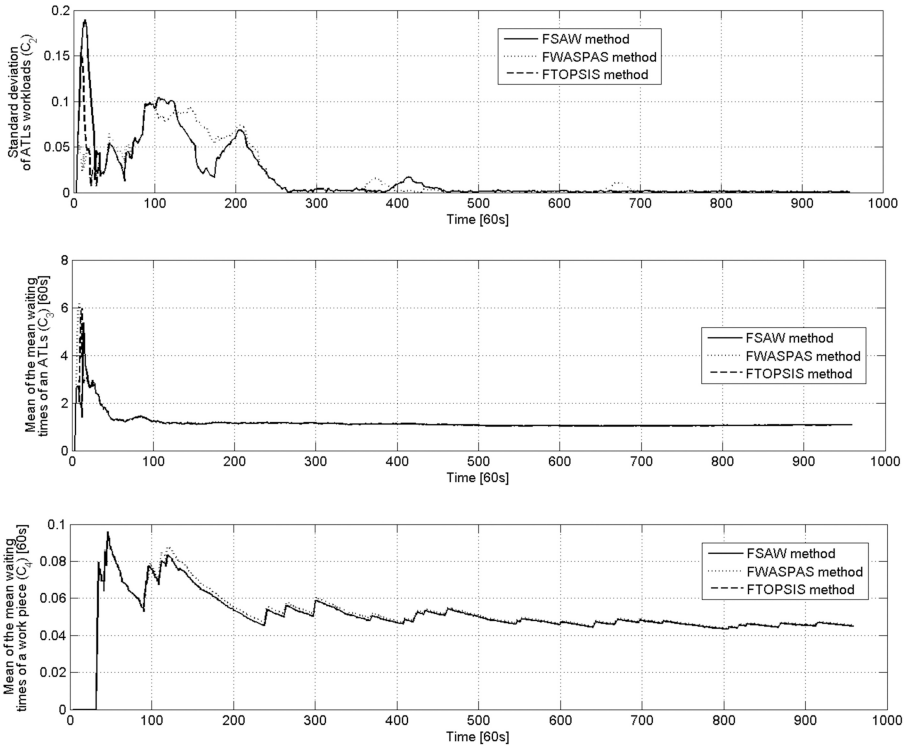


Fig. 3. The comparison of fuzzy MCDM methods

Simulations using these methods indicate that their results are similar. Slightly better production parameters are those obtained with FSAW and FTOPSIS (in Fig. 3 the lines overlap). In those methods, the standard deviations of the line workloads are more stable for a longer time during the simulation and the means of mean waiting times of a work piece in ATLs are lower than for FWASPAS.

The FSAW, FWASPAS and FTOPSIS methods have been compared also with their non-fuzzy versions. In the analysis, W_2 is also used as a vector of criteria weights. Figure 4 shows the comparison of the parameter values which are aggregations of ATL parameters. In the case of the non-fuzzy methods, the best production parameters are those obtained with SAW. However, simulations using the non-fuzzy methods indicate that their results are much worse than for the fuzzy methods. The workloads of the production lines are more divergent. We cannot generalize these conclusions, because for another weight vector the situation may be different.

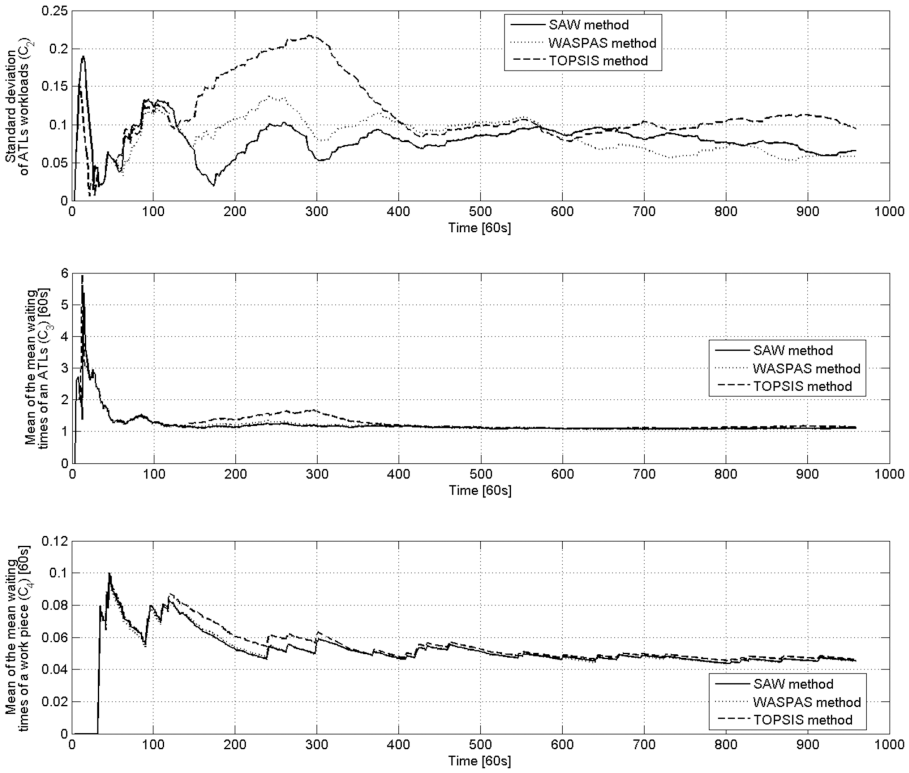


Fig. 4. The comparison of MCDM methods

4 Conclusions

The case study shows that the older fuzzy MCDM methods (FSAW, FTOPSIS), as well as the new FWASPAS method can be used with success as flow control methods for various problems, including the selection of the destination for a transport trolley. It can

also be applied at other decision-making stages of a manufacturing process (route selection, machine selection etc.). The method presented here is not computationally complex, hence it can be easily used in PLC programing. The application of the multicriteria approach allows to suboptimize the flow in the manufacturing system with respect to several criteria simultaneously (not only one dispatching rule). At the same time, this approach is expected to improve certain parameters of the manufacturing system, such as time efficiency and equal workload of machines during the entire time of the simulation (and not only at the time of decision making). The fuzzy methods deal with imprecision and uncertainty involved in the evaluations of the alternatives. Another advantage of this approach is the flexibility in the design of the control. If the project of the manufacturing system is modified (e.g., the number of production lines is changed), the procedure of the selection of the production line remains the same, and only the number of alternatives and/or the calculations of the evaluation criteria parameters change.

The analyzed methods have been also compared with their non-fuzzy versions. We cannot state unambiguously which method will turn out to be the best in the manufacturing system analyzed here, since this depends on the vector of criteria weights. For the non-fuzzy MCDM methods, the flow control is more advantageous when balancing the workload of a production line is more important than minimizing the waiting time on it (criteria C2 and C3 are more important than criteria C1 and C4), while for the fuzzy MCDM methods it is the opposite.

The proposed approach has also a drawback. It is difficult to obtain a vector of the criteria weights for which flow control will be the best with respect to the proposed set of criteria. Further research on this problem would be of interest. The determination of the appropriate weight vector will allow to choose the most advantageous MCDM method, which time efficiency and equal workload of machines throughout the entire simulation.

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Virtual Reality Production Training System in the Scope of Intelligent Factory

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Abstract. The paper presents a prototype Virtual Reality system for learning of operation in an intelligent factory, working according to the concept of Industry 4.0. The SmartFactory laboratory—example of part of intelligent factory—is described. The VR prototype system and process of its building is also presented, starting from digitalization of the real smart factory, through logic programming and connection of peripheral VR devices. Functions of the training system are presented, along with directions of future studies and development.

Keywords: Industry 4.0 · Smart factory · Virtual reality training system

1 Introduction

A concept of intelligent factory is a vision of a highly automated, but flexible cyber-physical production system, characterized by capability of quick reaction to requirements of clients'. It requires innovative and smart solutions not only in terms of objects (e.g. Internet of Things), but also regarding processes (e.g. Knowledge Based Engineering) [1]. That is why smart design and production control should be necessary elements of an intelligent factory of the future, able to realize a strategy of mass customization [2, 3]. Only then it will be possible to fully utilize manufacturing potential of a company owning modern technical resources, according to the concept of Industry 4.0 [4].

Cyber-physical systems, which are key components of an intelligent factory, are presented with very different requirements, dependent mostly on characteristics of a realized process. However, it can be assumed, that each of them should be as flexible as possible, meaning easy adjustment of their structure. Moreover, an important factor is their easiness (user-friendliness) and intuitiveness of operation. It cannot be forgotten, that a key element of the most cyber-physical systems is still a human being [5–7]. In these cases, the smart production systems are enriched with technologies within scope of Virtual Reality (VR) and Augmented Reality (AR) [3].

Necessity of constant adjustment of production systems to variable requirements of clients enforces implementation of new methods in scope of process organization or production control [8]. In this context, having in mind implementation of solutions for automation and computerization of data flow in the production processes, particular

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attention should be paid to training of employees in new conditions. There is no doubt that VR systems contribute to realization of these tasks without intervention in the real production processes and bearing too high or unjustified financial investments.

2 Literature Overview

The VR systems are computer-based solutions, which today are used to aid not only the military industry, medicine or entertainment, but also production processes of different types [9]. The most important component of each Virtual Reality system is the application, which should be understood as programmatically and logically enclosed unity, containing virtual three-dimensional models of objects, placed in an appropriate environment, with ensuring of interaction and immersion to the user [10]. The most popular engineering VR applications are, among others, virtual simulations of operation [11], servicing, assembly and disassembly, virtual workplaces [12] or product configurators [13]. Depending on the phase of the product lifecycle, at which the VR application is created and used, it can be applied for design and testing of a product, visualization of a production process or training of staff.

The VR systems are currently readily used, especially for education and training [14]. Nowadays, there is a very broad scope of various equipment, allowing not only to obtain near-photorealism in visualization (VR goggles—Head Mounted Devices), but also allowing user directly interact with elements inside a visualization (haptic devices, systems for tracking and gesture recognition), intensifying feelings of immersion [12]. By integrating specific hardware with a properly prepared VR application, a specialized simulation environment can be obtained, in which the training is performed according to conditions present in reality. The training VR applications allow increasing effectiveness of transfer and access to procedural knowledge, especially for inexperienced employees. It is far easier to perform trained activities repeatedly in VR, as well as presentation of undesired or dangerous situations. VR applications are also flexible and easily scalable, which is a clear advantage. The VR application can be created in a way to adjust presented content to a specific user and changing conditions of a simulated process.

The training VR applications found their use in many different branches. Gorecky and his team presented a training VR application in scope of the VISTRA project [15]. This solution was presented on example of a process of assembling of car parts, using different techniques and methods. It needs to be emphasized, that the whole system was enriched with a specially prepared base of knowledge and design of user interface assumed intuitive interaction known from computer games (game-based user interaction). Abate and coauthors presented the ViRstperson system, dedicated to trainings in scope of technical servicing of airplanes, with use of haptic devices [16]. Angelov and coauthors described a training VR system for the energy branch [17]. The paper by Fast and others presents an application for learning of a welding process [18]. Lin and coauthors developed a VR app for learning of operation of an NC machine tool [19], while Wasfy and his team used a virtual environment for training of operation of an aerodynamic tunnel in NASA [20]. It is therefore clear, that VR is present everywhere, where there is a need for a flexible training solution, reducing costs and time of training in real conditions.

3 Aim of the Work

This paper presents a process of building a virtual training system, for operators of production (assembly) workplaces in an intelligent factory. The application was prepared on the basis of a real assembly line, which is physically operating in a smart factory laboratory of Poznan University of Technology. The following assumptions were taken in the work:

- Neccessity of visual representation of elements of the SmartFactory laboratory,
- Building functional models in a virtual environment (with possible detailed interaction in the virtual assembly process),
- Integration with a system controlling a real assembly line.

The main aim of the work was to obtain and test a working prototype of a training system for new employees in order to allow them to prepare for flexible changes in the assembly sequence and scope of manufactured products.

4 SmartFactory Laboratory

The production system, which is an equipment of a SmartFactory laboratory at Poznan University of Technology, consists in an automated production line. It consists of four transporting loops, by which there are production stands. Transport of products is realized by small pallets, which can be directed to any production stand. Their automated identification in the system is realized with use of the RFID technology. The whole production system is controlled by an author-made computer program, named 4Factory. Structure of the system is presented in Fig. 1.

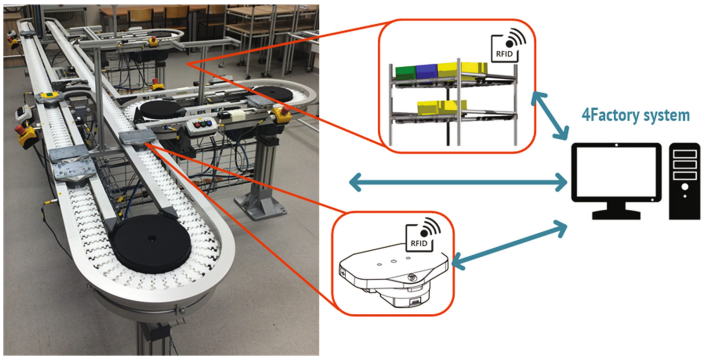


Fig. 1. Structure of the SmartFactory system

The 4Factory system is built out of modules dedicated for supervision of material flow and control of work of a production line. The system contains the following modules:

- Resources—information about resources of a production system,

- Indexes—characteristics of products and their components,
- Orders—data of orders for ready products,
- Technology—definition of processes,
- Production planning—tasks related to setting course of production orders in a production schedule,
- Production control—controlling and analyzing realization of the production flow,
- Magazine—tasks related to material traffic in magazines of resources and ready products.

The production system of the SmartFactory laboratory was built to represent real production (assembly) processes, aimed at realization of customized orders, according to the Industry 4.0 concept.

A production process realized in the SmartFactory laboratory, analyzed in this paper, consists in assembly of parts at subsequent production stands. The parts, subassemblies and ready products are transported through an automated line, using small pallets. Production stands are equipped with flow racks, that allow storing containers with parts and subassemblies for assembly of customized products. The racks are additionally equipped with heads reading RFIDs, allowing their identification.

A base for launching the production process is a schedule developed in the 4Factory software. It supplies information about order of manufacturing of products and sequences on particular stands. Operators present at a particular stand must first identify a product after a pallet stops, to properly set scope of assembly tasks.

The tasks realized by the operators consist in:

- Getting familiarized with an assembly instruction, which is displayed on a tablet computer or supplied in a printed form,
- Realization of a sequence of assembly tasks, compatible with the instruction, consisting in taking appropriate parts from a stand rack and assembling them in the product in a correct order,
- Confirmation of realization of the assembly operation.

Number of assembly activities, as well as activities related to taking parts from the material racks is obviously related to the scope described in the manufacturing instruction.

Considering possibility of realizing orders of variable configuration, operators must constantly check the required scope of work. Both in the SmartFactory laboratory and in industrial conditions, it requires maintaining high focus. It is easy to make a mistake, leading to delays in realization of the whole production process. To maintain proper efficiency of this process, it is therefore necessary to properly prepare operators, by frequent trainings. Performing them in real conditions is often related to stopping the production, which in turn may cause delays in realizing orders of the clients. This means that training in real conditions is economically unjustified. Using VR systems for training purposes makes it possible to study reactions and capability of realization of tasks by the operators without pausing the production, thus being significantly cheaper and enabling more flexible training scenarios, at cost of lower realism and lack of physical interaction with the production line. It was decided to build a VR training system for the SmartFactory line, in order to improve effectiveness of work of operators. The next chapters present the process of building this solution.

5 Virtual Reality Training System Development

The prototype of a virtual training system built for the needs of the SmartFactory is dedicated to use by inexperienced operators of particular stands (the operators are mostly students). It is a proof of concept application with basic functionalities and it was developed in form of an integrated computer system, consisting of an application (virtual environment, user interface, logical connections between objects) and specific peripheral devices (the VR goggles—the Oculus Rift CV1 device, integrated with a system for tracking user position and orientation in space). Particular stages of building the system are presented in Fig. 2.

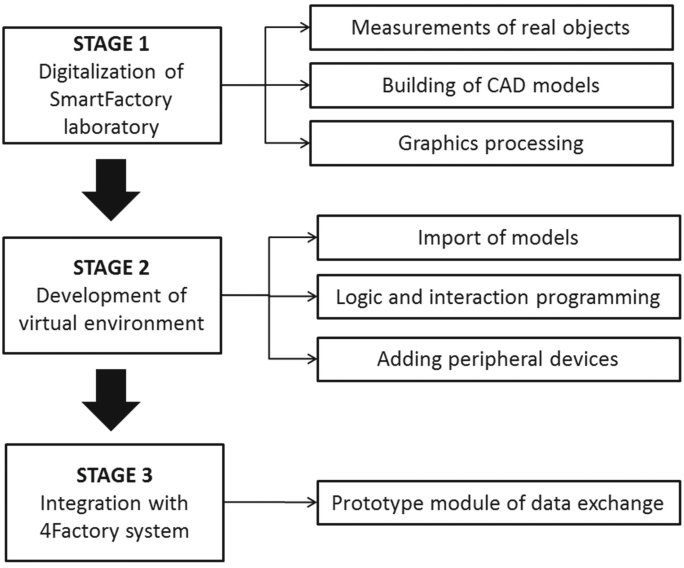


Fig. 2. Stages of building the VR training system

First stage of building the system consisted in digitization, meaning measurement of real objects needed for the virtual training and preparation of their digital, CAD 3D models, using Autodesk Inventor software (no digital documentation was available, so the reverse engineering approach was used). A complete digital 3D model of the production line was prepared, along with racks and parts of manufactured products. The authors cared about faithful representation of real conditions, to make the VR-trained person utilize the obtained knowledge in practice more efficiently, that is why the CAD models were transformed and processed in a computer graphics software Autodesk 3DS Max for better visual effect (Fig. 3).



Fig. 3. Digitalization of the production line, A – CAD model, B – graphics processing

Aim of the next stage of work on the VR system was preparing of a virtual, interactive environment, representing the real SmartFactory laboratory. To build the application, the Unity3D engine (version 5.5) was used. The prepared 3D models were imported (Fig. 4) and adjusted visually by setting up lights, environment, shading, texturing and reflections. Then, appropriate logical connections were programmed to build a usable, digital model of a production line. Finally, the application was connected to the selected peripheral devices (Oculus Rift Head-Mounted Display, tracking system and joystick). C# language was used to write all the scripts in Unity3D, some logical connections were programmed without coding, using the event system with object references (this applies e.g. to object selection by gazing at it).

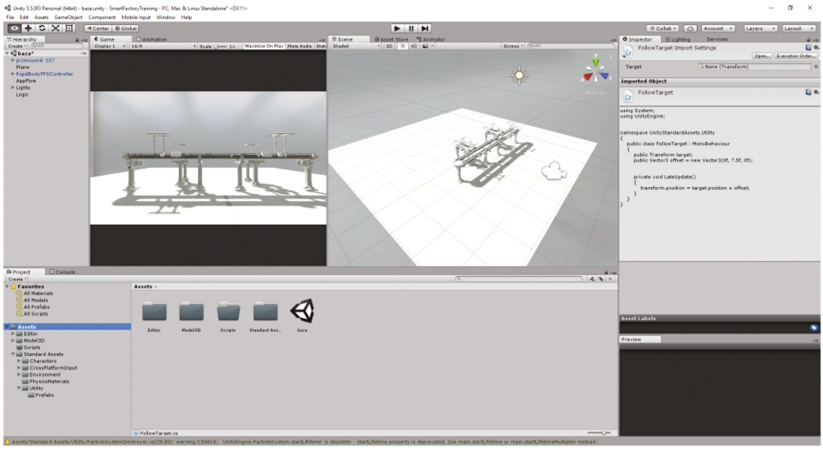


Fig. 4. Building virtual reality application in the Unity3D engine

In the last stage of building the system, a special dedicated module was developed to import production plans from the 4Factory system. The selected production schedule

and sequences on particular stands are possible to launch on a digital production line. It is a prototype functionality and requires manual correction by the operator, but it will be fully utilized in next versions of the application. Thanks to this, a virtual production system reaches a level of a simulator representing the real SmartFactory lab. At the present stage of system development, this is realized by export-import mechanism of plain text files. A script written in Unity reads the assembly sequence from the generated text file and sends appropriate information to virtual production line elements, as well as to user interface components, in order to maintain appropriate logic and information sent to user.

6 Virtual Reality Prototype Training Environment

There are several solutions of operation of the presented application. The image can be displayed both on a computer monitor and VR Head Mounted Device. The second option obviously brings much high level of immersion. Interaction with virtual objects can be realized using a standard joystick, but there is a future possibility of including manipulators for free hand movement.

The VR training application allows the user to perform the following activities:

- Free movement and exploration of the virtual production line, by walking in area of 1,5 × 1,5 m (tracking space of Oculus Rift HMD), movement over a greater area is realized by a gamepad analog stick (part of the Oculus Rift system),
- Familiarizing with the assembly instruction, displayed in text and image form in the graphical user interface of the application; GUI is bound to the physical space of a specific production stand,
- Taking parts for assembly from a virtual rack—the part to take is indicated by gaze (virtual cursor controlled by user head movement), action of grasping a part requires the user to be in its proximity, gazing at it and pushing an appropriate button on a gamepad,
- leaving taken parts in the assembly space – a small pallet transported around the production line – it is done by pushing the same button, the part is then released from user's grasp,
- Performing an assembly operation – indicating two parts by gaze while staying in their proximity, then pushing an appropriate button to perform assembly,
- Confirming the assembly operation by pushing another button on a gamepad.

It is possible to train certain activities at all production stands. User's actions correspond with behavior of the production line—the transport movements are simulated and synchronized with confirmations of assembly. The parts for assembly are marked as rigid bodies and all the 3D objects in the scene have colliders attached to them, which allows simulation of basic physics, like gravity and pushing. Specific animations are attached to parts, meaning that the user does not perform the assembly movements by himself, he just indicates which parts should be connected at this stage. There is a possibility of performing certain activities incorrectly (e.g. putting down subassembly on an inappropriate rack or taking a wrong part in a given sequence), to allow learning by trial

and error. It will result in an appropriate message from the application and necessity of performing the assembly sequence again.

Prototype of connection with the 4Factory system is still being tested, but at full capability it will allow full simulation of the process according to reality. The virtual pallet moves between particular stands according to the production cycle assigned to it, just as the real pallet does by the RFID technology.

7 Conclusions

The built prototype VR system was prepared to realize basic training of employees/operators of a production system functioning according to the Industry 4.0 concept. Dynamics of production changes in an intelligent factory, due to readiness of manufacturing customized products, is currently very high. A human being is still very important in the production cycle, that is why so much depends on his preparation and training. The proposed solution, using the VR technologies, seems a good way of training the employees, as there is a potential of its full integration with a real production system and the costs are generally low. The main contribution of the presented paper is faithful representation of a real assembly line realizing the intelligent factory concept, according to the Industry 4.0 idea.

Further work on the system will comprise of improving interaction mechanisms, in order to obtain higher realism by enabling users to perform specific movements during the assembly process, training not only their comprehension abilities, but also manual skills. The concept will be validated with participation of persons, who operate the SmartFactory production line on a daily basis (the system has been currently tested only in a very basic way by the authors). It will be necessary to perform a comparative analysis of traditional education methods with the new system, to evaluate effectiveness of the proposed solution.

As for now, there are certain limitations of the system, because it is only a prototype. Scope of simulation of products of any configuration is limited. Right now, the system can only simulate production of hard-coded configurations (certain animations need to be attached to the parts, meaning that the assembly mechanism should be known earlier). In the future, there will be an integration with a design system, to simulate new (meaning future, never launched before) production processes, with simultaneous training of employees. Such a task requires development and implementation of a certain base of knowledge, meaning that the full version of the presented system will be a KBE class solution.

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Water Consumption Prediction for City Pumping Station Using Neural Networks

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Abstract. In this article, the ways to improve the efficiency of water supply in urban areas are considered and the need for water consumption prediction at the pumping stations output is shown. 58 models of artificial neural networks for prediction of the city water supply were built using the experimental data. As a result of the analysis of their performance, for future research, the one artificial network was chosen. Its absolute error of prediction does not exceed 3% in 35 h that fits the requirements. Based on the model of the artificial neural network, it was developed software for short-term prediction of water consumption at the output of the pumping station "Novyj Dvir", Rivne city, Ukraine, for water supply of the city districts.

Keywords: Artificial neural network · Prediction · Water supply · Time series

1 Introduction

City water supply systems are one of the most important sectors of the urban economy. These systems provide drinking water to people, support their sanitary safety, make significant influence on the level of social security of the city population and determine the scale of industrial development [8]. However, urban water supply systems require substantial and increasing amounts of energy, that's why various utilities should be used to reduce energy consumption [4].

Sustainable management of a city water supply system is a complex task requiring careful planning and analysis [11].

The water supply of urban areas in Ukraine is not ideal and also has a lot of problems. Among them is obsolete equipment, which increases the costs for electricity and maintenance, but it is gradually replaced by new. One of the biggest problems is the lack of comprehensive data analysis and search for new ways to improve the management of water supply. It leads to water quality decreasing, appearance of leaks and irrational consumption of energy resources.

Water pumping is the most energy-consuming chain in water supply system. Therefore the main idea of our research is finding new ways to increase the efficiency of water supply on the basis of data analysis and prediction of water consumption on pumping stations.

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2 The Basis for Water Consumption Prediction

A centralized water supply system of a city should provide water extraction from the source in a necessary quantity, water treatment, transmission and supply consumers under the required pressure. For this purpose, a typical water supply system includes the following elements: water intake structures, pumping stations, water purification units, reservoirs (tanks) and water towers, plumbing and water distribution networks. Mutual arrangement of water supply installations and their structure can vary depending on the destination, local environmental conditions and consumption requirements or based on economic considerations.

In western Ukraine, water for the population is mostly extracted from groundwater or reservoirs [6]. This process can be schematically represented as on Fig. 1 [8].

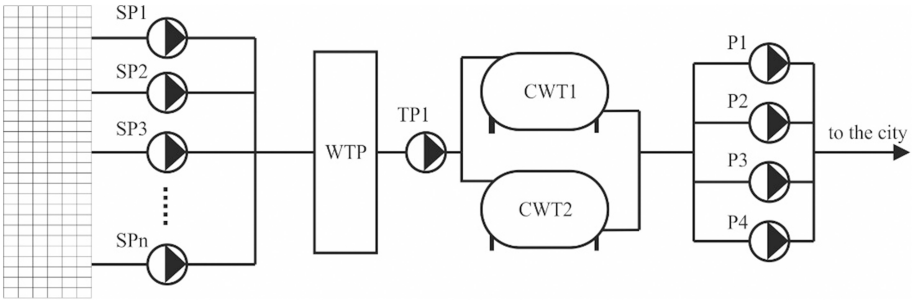


Fig. 1. The simplified diagram of water supply to the city

Water from the ground or from reservoirs is pumped to the water treatment plant (WTP) by means of submersible pumps (SP1–SPn). After purification, iron removal and chlorination, water is pumped into the clean water tanks (CWT1, CWT2) by the transportation pump (TP1). After all, water is supplied to the city through the three pumps (P1–P3). Two of them work with the constant performance, and the third is controlled by changing the rotation frequency of its drive. The pump P4 is a reserve and normally is powered off.

Water supply systems typically are quite distributed over the wide area. For example, most of the wells from which water is obtained in Rivne, Ukraine, are located more than 30 km away from the city. Sometimes, this distance can be up to 110 km, for example, city of Lviv, Ukraine. Thus, most of the consumption of energy resources are used for water transport. To save costs of electricity, water transportation from the treatment plants to the clean water reservoirs on the final pumping stations is carried out at night, when the load on the electrical networks is minimal.

So, the overage of water daily supply in CWT causes to the longer stay of water in the system, respectively, reducing its quality. Lack of water in CWT leads to additional costs of transportation and increase the load on the electrical networks during peak hours.

The main factor determining the operation of all elements of the water supply system is the mode of water consumption by consumers for which the system is intended. Therefore prediction of water consumption on the end pumping stations is extremely important in these water supply systems.

3 Prediction of Water Consumption

A lot of different type methods for water consumption prediction were developed during the last decades [1, 7, 11]. One of the powerful instruments for this purpose is using of artificial neural networks (ANN) [1, 7].

Our research is based on data of water consumption on the pumping station "Novyj Dvir" which provides water to one of the districts of Rivne city in Ukraine. The dataset consists of 1415 of water consumption values per hour in the city for 59 days from June 9, 2016 to August 6, 2016. A fragment of the dataset with 5 days of hourly water consumption is represented in Table 1.

Table 1. Fragment of water consumption dataset for analysis

Time	Date				
	Water consumption by date, m^3				
	02.07.2016	03.07.2016	04.07.2016	05.07.2016	06.07.2016
0:59:59	8.87548	30.3487	18.0911	19.00054	15.95595
1:59:59	−1.12826	−2.43765	−3.21292	−3.42873	−2.86611
2:59:59	−2.3857	−2.93869	−2.32418	−2.4545	−2.14854
3:59:59	−2.47653	−3.17312	−2.3531	−2.44545	−2.10516
4:59:59	−2.50764	−3.32859	−2.44997	−2.32834	−2.06207
5:59:59	−2.41428	−3.21724	−2.43578	−2.24506	−2.09458
6:59:59	−2.37903	−3.16653	−2.4528	−2.34486	−2.07705
7:59:59	53.98334	52.63786	40.14723	48.66577	52.86267
8:59:59	159.21419	166.7738	142.41747	167.25377	162.36104
9:59:59	177.20436	187.9173	170.75992	175.51184	180.44154
10:59:59	169.60143	167.65437	149.92578	154.93822	149.99922
11:59:59	152.89029	131.31335	113.26371	143.2397	123.90472
12:59:59	126.17338	123.4966	103.32559	118.72707	116.42657
13:59:59	107.84072	123.72973	107.56012	111.36655	117.29706
14:59:59	103.19717	105.78876	112.38662	102.60563	120.13999
15:59:59	91.58302	87.13496	84.07536	69.32848	97.58523
16:59:59	87.2248	86.02344	88.28444	67.40788	95.34911
17:59:59	87.12555	89.34766	102.26497	76.49239	112.51418
18:59:59	98.69015	111.06331	106.52007	87.13872	100.38322
19:59:59	122.80792	123.54944	113.03066	106.38371	89.47705
20:59:59	135.50461	125.65942	129.90796	110.72307	93.57647
21:59:59	169.55901	163.38864	172.17166	145.54677	135.09674
22:59:59	200.72923	189.1368	185.01546	171.55283	159.90216
23:59:59	140.1474	146.43333	132.69691	122.29097	115.44331

The dataset was divided into two parts. The first part contains 1368 points for learning, validation and testing (divided as 70, 15 and 15% accordingly) artificial neural network, and the second part—47 points, which were used to check the neural network performance on data, that was not used during the modeling process.

Nonlinear autoregressive (NAR) artificial neural networks with delays are one of the suitable means for use in tasks of time series prediction [2, 3, 5, 9]. In our case, the data is presented in the form of dynamic time series and next time steps depend on past ones. That is why the ANN includes delays and feedback.

Construction, training and testing of neural networks were carried out in the Matlab software. During this process it has been analyzed 58 models of artificial neural networks with a different number of layers, delay and amount of neurons. It was also used different activation functions of neurons (*tansig, purelin, logsig*). The ANN training was carried out using the Levenberg–Marquardt backpropagation [10] algorithm.

Analysis of the results showed that the most effective in terms of accuracy was a two-layer artificial neural network with one hidden layer (Fig. 2).

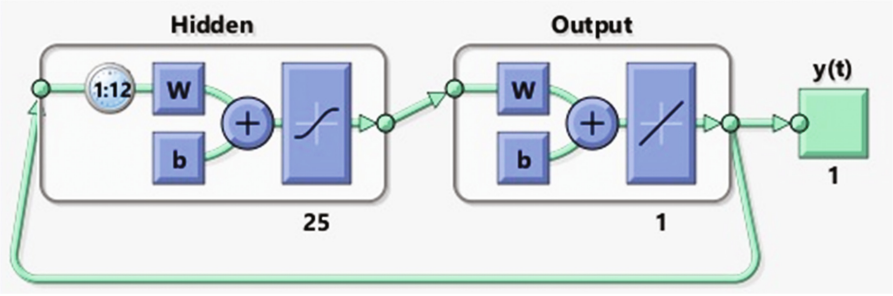


Fig. 2. The nonlinear autoregressive artificial neural network for water consumption prediction

This is the artificial neural network with feedback. The first hidden layer has 12 delays, 25 neurons with hyperbolic tangent sigmoid transfer functions. The second, the output layer has one neuron with a linear activation function. Thus, due to delays and feedback, the prediction for the next point is based on the previous 12. So, this artificial neural network can predict 1 next hour of water consumption based on previous 12 h by 1 cycle of its algorithm. In case of using "closed loop", when output of ANN is connected to input, the predicted value shifts input values by one time step. That is how we can "predict on predicted" initializing ANN as many times as needed. But we must consider that too many prediction cycles with "closed loop" can lead to loss of accuracy.

Test results of the artificial neural network for predicting of water consumption at the output of pumping station at 47 time points (August 5 and 6, 2016) that were not used during the training process are represented in Table 2. Considering that 12 points are used to initialize the network, the comparison was carried out by 35 points.

Table 2. The results of water consumption prediction for 35 h

Date	Time	Original data	Predicted data	Date	Time	Original data	Predicted data
05.08.2016	0:59	−2.7696	Used for initialization	06.08.2016	0:59	−2.95863	−2.074665
05.08.2016	1:59	−2.56702		06.08.2016	1:59	−2.26161	−1.56727
05.08.2016	2:59	−2.66184		06.08.2016	2:59	−2.52331	−5.75762
05.08.2016	3:59	−2.65807		06.08.2016	3:59	−2.65193	0.3529791
05.08.2016	4:59	−2.735		06.08.2016	4:59	−2.65407	2.5316805
05.08.2016	5:59	-2.70431		06.08.2016	5:59	−2.54037	−2.654089
05.08.2016	6:59	−2.64825		06.08.2016	6:59	−2.3274	3.6136934
05.08.2016	7:59	−3.45603		06.08.2016	7:59	27.44921	12.437406
05.08.2016	8:59	5.89295		06.08.2016	8:59	133.93108	138.23013
05.08.2016	9:59	79.34109		06.08.2016	9:59	163.1394	154.79181
05.08.2016	10:59	103.0998		06.08.2016	10:59	150.58586	160.26798
05.08.2016	11:59	99.92608		06.08.2016	11:59	135.3416	137.65059
05.08.2016	12:59	78.42645	84.8027	06.08.2016	12:59	116.58499	116.56787
05.08.2016	13:59	67.7475	64.62024	06.08.2016	13:59	118.02037	107.99495
05.08.2016	14:59	51.90541	57.06114	06.08.2016	14:59	114.52831	108.7247
05.08.2016	15:59	44.29541	56.83908	06.08.2016	15:59	89.46127	91.607467
05.08.2016	16:59	31.45682	40.06653	06.08.2016	16:59	76.85092	83.682884
05.08.2016	17:59	30.92835	38.43922	06.08.2016	17:59	75.76114	88.46241
05.08.2016	18:59	42.41803	38.42495	06.08.2016	18:59	81.42107	77.600329
05.08.2016	19:59	40.58853	47.26279	06.08.2016	19:59	100.11924	86.295569
05.08.2016	20:59	44.93685	44.95009	06.08.2016	20:59	101.70833	94.109566
05.08.2016	21:59	93.95483	73.18898	06.08.2016	21:59	144.53282	116.24018
05.08.2016	22:59	116.7907	119.1402	06.08.2016	22:59	168.67673	165.53815
05.08.2016	23:59	53.93374	62.80709				

The visualization of comparative analysis is shown on Fig. 3

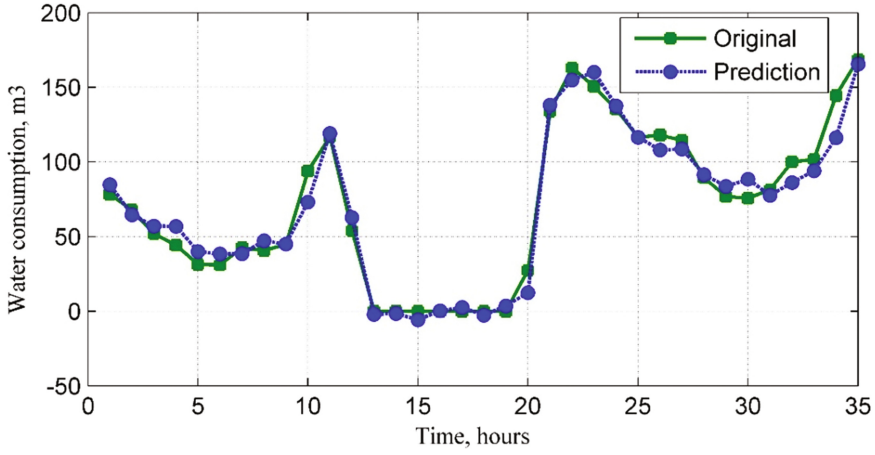


Fig. 3. Comparative analysis of original data with predicted values

As a result of the comparative analysis, it was pointed out that the average absolute error does not exceed 627 m^3/h. Considering that the upper limit of consumption is 220 m^3/h, and the lower is −30 m^3/h at overpressure in the network when the pumps are powered off during the night, it is easy to see that the absolute error does not exceed 3%.

4 Practical Results

Among the usual ways to implement neural network algorithms (including hardware, software, and hardware–software), the software-based has been selected because of its simplicity and absence of strict requirements for speed. This method is also called as the program simulation of neural network on a PC, because the parallel processes are executed sequentially.

It was developed a software application, based on the model of the ANN for water consumption prediction for up to 35 h. The main window of the application is shown in Fig. 4.

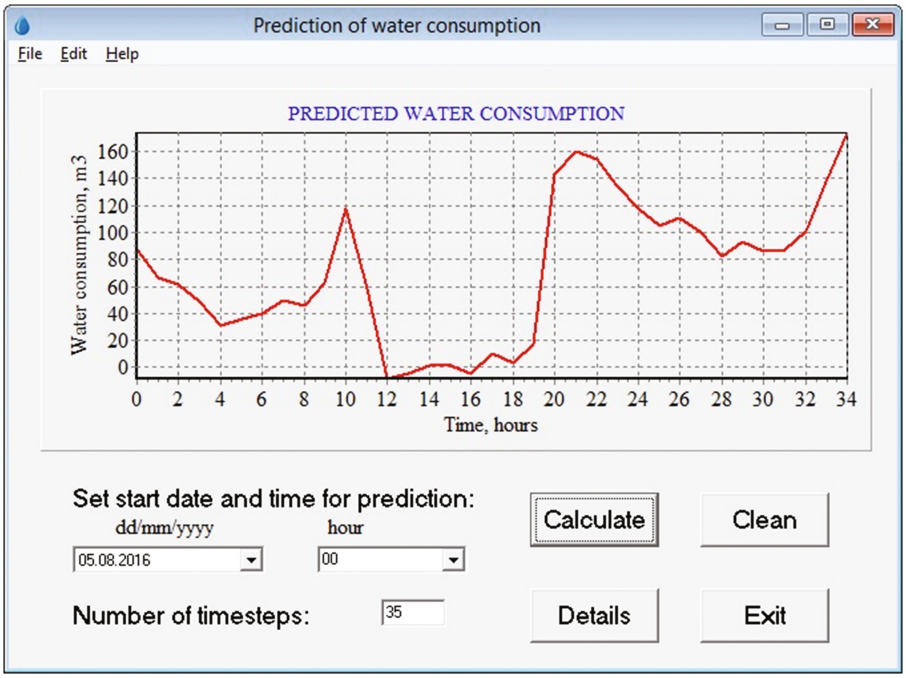


Fig. 4. Main window of software for water consumption prediction

The data of water consumption are allocated in a database on an operator`s automated workplace PC. Our software connects to the database using Open Database Client (ODBC) technology, where twelve points of time series of water consumption are selected according to the time and date entered by the user manually or by using the Date picker. By clicking the “Calculate” button the neural network algorithm (Fig. 5) is processing with a user-specified number of times.

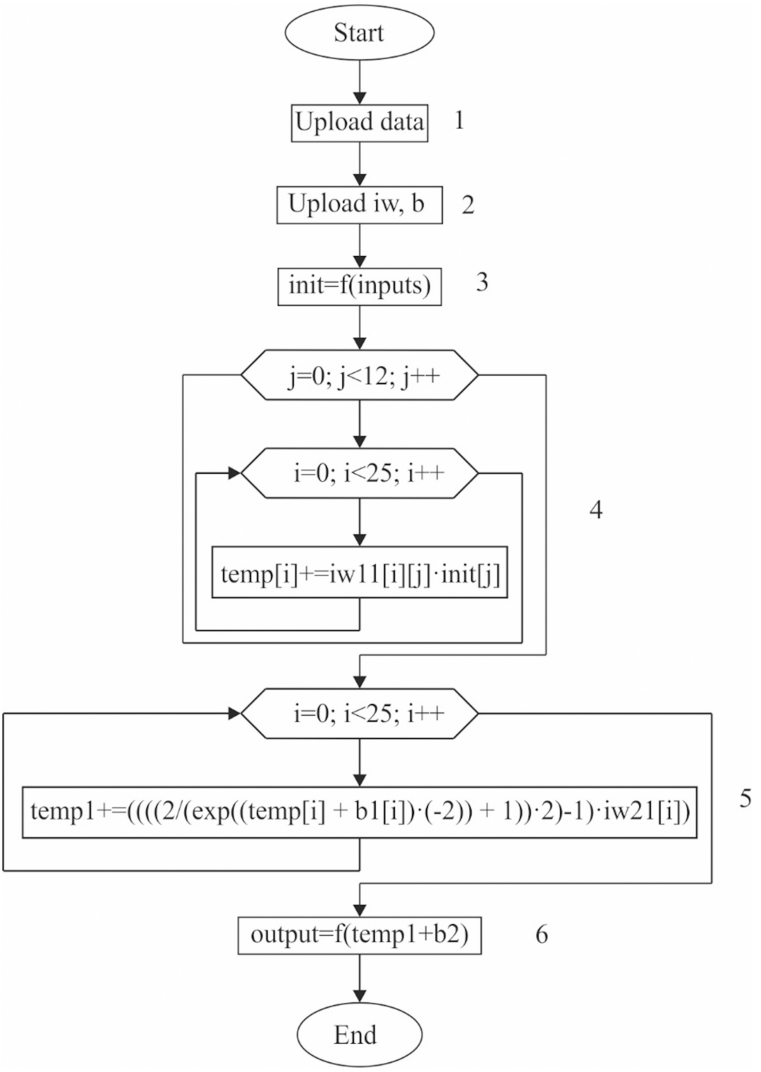


Fig. 5. Algorithm of program for data processing with ANN

First of all we have to upload initialization data from database (step 1) and values of weight coefficients (*iw*) and biases from files (*b*), on second step. The third step is to process input (*inputs*) data to the range from −1 to 1 and store the result into variable *init*, for future process the signal with *tansig* transfer function. On the 4th step we have cycle, layered into cycle to calculate a temporary variable temp, which is a sum of multiplications of every normalized initial value multiplied by weights (*iw11*) of hidden layer 1 neurons. On epy 5th step we calculate a cycled sum (*temp1*) adding biases (*b1*) to the values of previous calculation, processing the result with tansig transfer function which result is multiplied by weights (*iw21*) of output neuron. After adding

biases (*b2*) of output neuron we process output with function, which is inversed to process input on step 3 to normalize signal on step 6. At the result we have a variable output with the predicted value of water consumption stored in it.

At each step of initializing of this algorithm, the time interval for the neural network delays initialization is shifted by one time step forward using the predicted values of water consumption. As a result, a new predicted value of consumption becomes the last in the time series for the next prediction, and the first one is rejected. Finally, the predicted values are displayed on the chart. By clicking on the button "Details" an additional window opens. It contains a reporting table with the specific predicted numeric values matched with time and date, and the total water consumption for the period of prediction.

The weights and biases of the artificial neural network are allocated in a text file. They are read out every time the program starts. So there is no need to change the code after their modification.

5 Conclusions

Analysis of water supply in western Ukraine showed the need to develop systems for prediction of water consumption by the population. The artificial neural networks were selected as the main tool for the prediction. Using experimental data, it has been built a model of ANN for water consumption prediction at the output of the pumping station that matches the requirements of accuracy. The software application was developed based on the simulated ANN. The application provides to perform short-term predictions of water consumption with sufficient accuracy. The applied technique could be used for a long-term prediction in the future. Further modeling of neural networks with external inputs using the additional parameters such as temperature or rainfall, or information about their forecast, season and time of day can significantly improve the accuracy of prediction.

It is planned to further upgrade the developed software with addition of new modules for long-term prediction and networks relearning system to modify their weights and biases for the accuracy prediction improvement during their use.

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Author Index

A
Abramovici, Michael, 33
Antosz, Katarzyna, 13, 23

B
Backes, Bianca, 324
Bonci, Andrea, 249
Bracke, Stefan, 324
Brodny, Jarosław, 74, 151
Brzeziński, Wiktor, 306
Burduk, Anna, 179, 336, 347

C
Chlebus, Maciej, 392
Chlebus, Tomasz, 179
Ciechanowicz, Bartosz, 306

D
Davidrajuh, Reggie, 109
Diakun, Jacek, 306
Diering, Magdalena, 407
Dostatni, Ewa, 306
Drevetskyi, Volodymyr, 459

F
Felka, Dariusz, 151
Fertsch, Marek, 140

G
Gladysz, Bartlomiej, 238
Gola, Arkadiusz, 260, 358
Górnicka, Dagmara, 336
Górski, Filip, 450
Grajewski, Damian, 306
Grzybowska, Katarzyna, 227
Gwiazda, Aleksander, 316

H
Hamrol, Adam, 168
Herok, Anna, 99
Hetman, Łukasz, 407
Hoffa-Dąbrowska, Patrycja, 227

J
Jakubczyk-Gałczyńska, Anna, 161
Jankowski, Robert, 161
Jurdziak, Leszek, 189, 418

K
Karwasz, Anna, 306
Kawalec, Witold, 189, 418
Kleapch, Marko, 459
Kłos, Sławomir, 85, 131
Kłosowski, Grzegorz, 260
Korytkowski, Przemyslaw, 209
Kosicka, Ewelina, 54
Kotowska, Joanna, 347
Kowalska, Beata, 199
Kowalski, Dariusz, 199
Kozłowski, Edward, 54, 199, 260
Krenczyk, Damian, 99
Krinidis, Stelios, 43
Kristowski, Adam, 161
Król, Robert, 189, 418
Kujawińska, Agnieszka, 168, 407
Kutia, Vitalii, 459

L
Longhi, Sauro, 249
Loska, Andrzej, 64, 428
Lysiak, Cezary, 238

M
Malachowski, Bartlomiej, 209
Markowski, Marcin, 336, 347
Mazurkiewicz, Dariusz, 54, 199
Michlowicz, Edward, 271
Midor, Katarzyna, 3

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N
Neges, Matthias, 33
Nowakowski, Tomasz, 392

O
Olender, Małgorzata, 316
Oleśków-Szłapka, Joanna, 140

P
Paszkowski, Waldemar, 64, 428
Patalas-Maliszewska, Justyna, 85, 131
Pawłowski, Grzegorz, 140
Pérès, François, 284
Pirani, Massimiliano, 249

R
Rogalewicz, Michał, 168, 407
Rojek, Izabela, 168
Rudnik, Katarzyna, 440

S
Saniuk, Anna, 217
Saniuk, Sebastian, 217
Santarek, Krzysztof, 238
Sękala, Agnieszka, 316
Skolud, Bozena, 99
Sobaszek, Łukasz, 358
Stadnicka, Dorota, 13, 23, 249
Steculа, Kinga, 74
Studziński, Jan, 296
Świć, Antoni, 358
Szczęśniak, Bartosz, 3
Szeląg, Bartosz, 296

T
Tchangani, Ayeley, 284
Tubis, Agnieszka, 368
Tutak, Magdalena, 74
Tziroglou, Giorgos, 43
Tzovaras, Dimitrios, 43

V
Vafeiadis, Thanasis, 43
Voutetakis, Spyros, 43

W
Waszkowski, Robert, 179
Werbińska-Wojciechowska, Sylwia, 392
Wichniarek, Radosław, 306
Więcek, Dariusz, 380
Więcek, Dorota, 380
Wolf, Mario, 33

Z
Zasadzień, Michał, 3
Zawadzki, Przemysław, 450
Ziogou, Chrysovalantou, 43
Zwolińska, Bożena, 121
Żywicki, Krzysztof, 407, 450