THESIS ON MECHANICAL ENGINEERING E92

Dynamic Management Framework for Continuous Improvement of Production Processes

JEVGENI SAHNO

TUT PRESS

TALLINN UNIVERSITY OF TECHNOLOGY
Faculty of Mechanical Engineering
Department of Machinery

The thesis was accepted for the defence of the degree of Doctor of Philosophy in Engineering Sciences at Tallinn University of Technology on: 07.05.2015.

Supervisor:
Eduard Shevtshenko, PhD, Senior Research Scientist, Faculty of Mechanical Engineering, Department of Machinery, Chair of Production Engineering, Tallinn University of Technology, Estonia.

Opponents:
Ph.D. Stipe Čelar, Assistant Professor, Department of Computer Architecture and Operating Systems, University of Split, Croatia.

Double Dr.sc.ing. Aleksandrs Boiko, ("Railway Transport", field "Transport and Traffic Engineering", subfield "Land Transport and Infrastructure" and "Applied Mechanics", field "Mechanics and Machine Science"); Lecturer, Riga Technical University, Institute of Railway Transport; Chief Technologist, L-Ekspresis Ltd, Latvia.

Defence of the thesis: 30.06.2015.

Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for any degree or examination.

ISSN 1406-4758
ISBN 978-9949-23-792-0 (publication)
ISBN 978-9949-23-793-7 (PDF)

MEHHANOTEHNIKA E92

Tootmisprotsesside pideva parenduse dünaamiline juhtimisraamistik

JEVGENI SAHNO

TTÜ KIRJASTUS

CONTENTS

INTRODUCTION

Background

Internal issues that many manufacturing companies face today are often surrounded by the idea that companies are aware of the problems they have, for instance, unreliable production processes, low product quality, financial losses, delay in product delivery, but they do not often understand the root causes of these problems. The Pareto principle states that roughly 80% of the problems are arise from 20% of the causes (Koch et al., 2004). Problems in manufacturing start from various causes, e.g., low labour qualification, unbearable working conditions and old technologies applied that lead to low quality product. As a result, these causes may lead to the loss of customers' expectations and consequently, to loss of the market position. To survive in the competitive market, companies should be expedient in technological resources, they should be able to demonstrate innovativeness, proof of their functional quality system and on time delivery of highly qualified products (Lõun et al., 2011; Riives et al., 2012).

Customer Satisfaction (CS) is a superb feeling that emerges when a company meets expectations of a customer. There is a relationship between customer value and CS. The goal of a company is to provide the most competitive value to a customer. In order to provide value to a customer, a company should know what the value for the customer is. CS levels can be measured using survey techniques and questionnaires. The question is - what exactly is important for the customer: if it is product Quality, Cost or Delivery, which could indicate the Key Performance Indicators (KPIs). Quality products and services of a company are considered as the most important factor leading toward competitiveness and success (Hennig-Thurau & Klee, 1997). A quality improvement effort will lead to a higher product and service quality, which will lead to improved CS (Torbica & Stroh, 2001). Achieving high levels of CS is important for a business because satisfied customers become loyal and can make repeat orders. A customer who is satisfied by the first buying experience needs to be satisfied again. Most customers care about quality, willing to pay more than an average market price and see "the extras" that are worth the additional expense (Matzler et al., 1998; Phillips et al., 1990; Deng et al., 2010). A company that succeeds on meeting and exceeding customers' expectations is guaranteed to have substantial Return On Investment (ROI).

Today's companies are using various well-known methodologies like PDCA, 8D, Six Sigma DMAIC and 4Q (Sahno & Shevtshenko, 2014) for continuous improvement of their business processes and product quality, but these methodologies are intended to reduce variations and wastes in the processes rather than defect detection and prevention. Furthermore, companies utilize different lean tools like FMEA, Swimline process diagram, Pareto chart for waste detection and reduction. In addition, they use different Information System (IS) tools to facilitate and support business processes. All these methodologies and tools are very successfully used to reach appointed goals and improve business success; but in most cases they are used independent of each other and bring no consolidated results. Therefore, the aim in this research is to present a framework that integrates various methodologies and tools into one general environment and shows what benefits a company can gain after its implementation.

Figure A shows the structure of the thesis. Chapter – *"Introduction"* describes the background, objective and tasks of the research. Chapter 1 presents the literature review of the basic concepts, methodologies and tools applied in the research. The main contribution of this research is described in Chapter 2 where the new framework is created and in Chapter 3 where the Data Mart is developed for the new framework and connections with IS sources are presented. In Chapter 4 the computational experiment of the framework is demonstrated. Chapter – *"Conclusions"* presents the summary of the thesis. The new framework is applied in the structure of the problem solving methodology such as Six Sigma DMAIC but it can also be applied in the PDCA, 8D and 4Q methodology (Sahno & Shevtshenko, 2014).

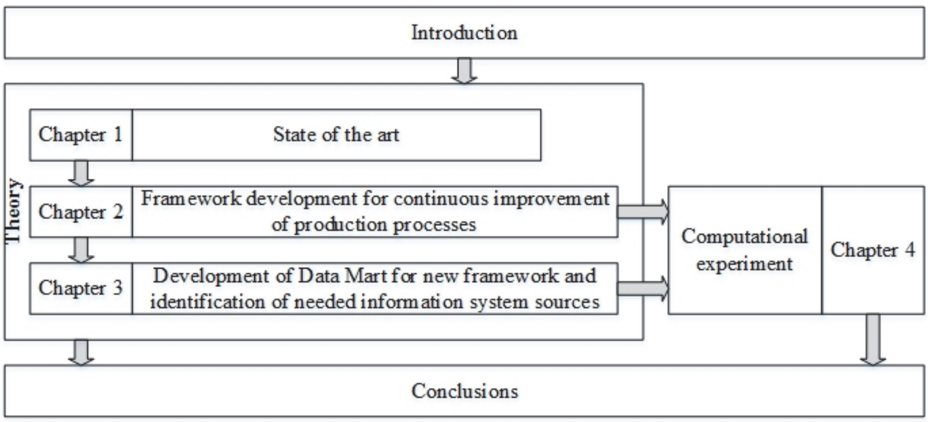

Figure A. Structure of the thesis

Research objectives and tasks

The objective of this research is to develop a framework for continuous improvement of the production processes that allows improvement of product quality, cost and delivery. This framework should integrate various quality improvement tools, methodologies, which are introduced into the Data Mart and connected with IS sources. The new framework will be applied in the rigorous Six Sigma DMAIC methodology that enables one to define, measure, analyse, improve and control the problematic production process.

This framework will help engineers find out problematic operations and make decisions for elimination of the problems to improve product quality, cost and delivery. The framework should play the role of a *"dashboard"* like in a cockpit, which allows monitor **production process KPIs** such as Process/Product Sigma Performance Level (PSPL), Cost Weighted Factor for RPN (CWFRPN) and Throughput (TH) (further in the text these notions will be expressed as follows: CWF_{RPN}, *PSPL*, *TH,* not only as abbreviations but also as values) in an up-to-date way due to the constant renewal data from the production floor, for example, data from the Enterprise Resource Planning (ERP) system (Umble et al., 2003). These KPIs in turn influence **product KPIs** (KPIs that are measured based on feedback from a customer) such as Quality, Cost and Delivery. The framework is oriented on the improvement of production processes in the production floor; it is suitable for Small and Medium Enterprises (SMEs) and can be applied in large enterprises which have batch production. In addition, the current framework can be applied to various industries, where production process exists, such as machining, electronics, automotive etc. For this purpose, a company needs to develop own Failure Classifier (FC) and to adapt their production processes to current framework.

The new framework enables:

- Detection of failures in the production process, which mostly influence product Quality, Cost and Delivery KPIs;
- Priority determination for product Quality, Cost and Delivery KPIs improvement;
- Access to data required for analysis and decision making.

LIST OF ABBREVIATIONS

AHP	– Analytic Hierarchy Process
BOM	– Bill Of Materials
C_M	– Cost of Material
C_O	– Cost of Operation
CS	– Customer Satisfaction
CT	– Cycle Time
CTQ	– Critical To Quality
CWF_{RPN}	– Cost Weighted Factor for Risk Priority Number
DBMS	– Database Management System
DPMO	– Defects Per Million Opportunities
DMAIC	– Define, Measure, Analyse, Improve, Control
DW	– Data Warehouse
ERP	– Enterprise Resource Planning
ETL	– Extraction Transformation Loading
FCC	– Failure Cost Calculation
FC	– Failure Classifier
FMEA	– Failure Mode and Effect Analysis
IS	– Information System
IT	– Information Technology
I_O	– Index of Occurrence
KPI	– Key Performance Indicator
PC	– Process Constraint
PDCA	– Plan Do Check Act
PDM	– Product Data Management
PR	– Production Route
PSPL	– Process/Product Sigma Performance Level
PY	– Process Yield
QCD	– Quality-Cost-Delivery
ROI	– Return On Investments
RPN or RPN_{Real}	– Risk Priority Number or Real RPN
$RPN_{Theoretical}$	– Theoretical Risk Priority Number
SME	– Small and Medium Enterprise
TH	– Throughput
TOC	– Theory Of Constraints
TQM	– Total Quality Management
WIP	– Work In Process
4Q	– 4 Quadrants
8D	– 8 Disciplines

1. STATE OF THE ART

This section provides the background of the basic concepts and the definitions used in this research.

1.1 Basic concepts applied in the research

1.1.1 Key Performance Indicators

Measurement of any performance in business is an essential principle because it shows gaps between current and desired performance, it shows indication where it is necessary to move to close the unwanted gap. "Therefore, carefully selected Key Performance Indicators (KPIs) indicate precisely where to take action to improve performance" (Weber and Thomas, 2005).

KPIs help an organization define and measure progress toward appointed goals. If an organization has defined its goals, then it is necessary to measure the progress toward appointed goals. A business organization may have its own KPIs that are based on customer's feedback, for example product delivery on time (Reh, 2005). KPIs are used for evaluating of the company current status or for foreseeing the possible benefits after implementation of some modifications in the system. KPIs are quantifiable dimensions that are agreed on beforehand, they reflect the critical success factors of an organization and depend on the particular company where they should be evaluated. In addition, they vary depending on the organization (Barchetti et al., 2011). Nowadays KPIs are used in most business areas for monitoring of the performance of production, procurement and management of supply chains and in other areas. The importance of KPIs lies in presenting the company's performance in terms of overall understanding how effectively a company competes in the marketplace. For that purpose, company needs to measure its own performance and compare it with competitors (Morphy, 1999).

The KPI metrics can be categorized into the following sub-categories (Stéen, 2006):

- Quantitative – presented as a number
- Qualitative – presented as a number
- Leading – predict the outcome of a process
- Lagging – present the success or failure after the event
- Input – measure the amount of resources consumed during the generation of the output
- Process – represent the efficiency or the productivity of the process
- Output – show the results of the process
- Practical – interact with existing company processes
- Directional – show whether or not an organization is improving
- Actionable – show organizational changes
- Financial – used in performance measurement and when looking at an operating index

Based on the literature review, three important KPIs were found: **Quality**, **Cost** and **Delivery** (Stewart, 1995; Morphy, 1999; Jacoby, 2005), which will be considered in this research.

Quality. A set of properties that determines its ability to meet the specific needs of a customer. If a product fulfils customer's expectations, then it is considered that product is acceptable or even high quality. If a product does not fulfil customer's expectations, then it is considered that product is not acceptable or low quality. Other words, product quality may be defined as "its ability to fulfil the customer's needs and expectations". Quality should be agreed beforehand in terms of what the customer wants and it can vary from product to product. (UNIDO, 2006).

Cost. "The amount of money that a company spends on the creation or production of goods or services. It does not include the profit" (Cost definition, 2015). The cost has some definitions presented in Figure 1.1. In this research direct labour and direct materials costs called the prime cost or also the direct cost (costs that can be identified directly with a particular process, project or program) (Wild, 1995) will be discussed. In case the investments are required (purchase new equipment), the overhead cost should be considered and the period how soon the investment starts to pay off (when the break-even point starts) (Badiru, 2005).

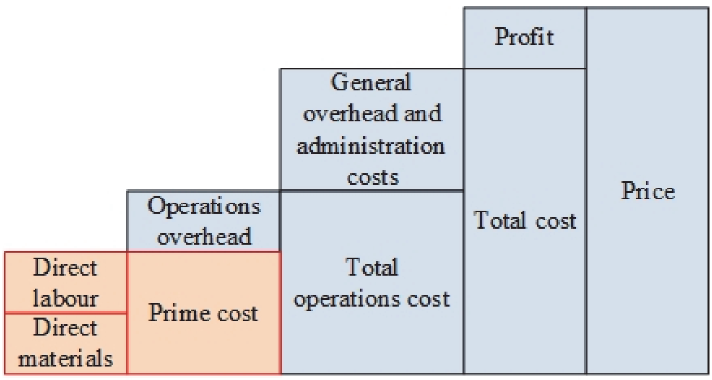

Figure 1.1 Operations and total costs

Delivery. This notion is quite broad (it can be measured from order receiving until the physical order delivery to a customer), therefore this study considers only the manufacturing part of this notion, i.e., production lead time (e.g., the time from physical production start of the first sub-assembly/part until the finished product is ready for delivery) (Lead Time Terminology in Manufacturing, 2014). During this time, manufacturing line should release a specified amount of products and the ability of production line release needed for an amount of units is called **Throughput** (Pritsker et al., 1969; Johnson, 2003). The Throughput or Little's Law (which shows the relationship between WIP, CT and TH) can be calculated using Equation (1.1).

$$TH = \frac{WIP}{CT} \tag{1.1}$$

where:

TH – Throughput – “the average output of a production process (machine, workstation, line, plant) per unit time”,

WIP – Work In Process – “the inventory between the start and end points of a product routing”,

CT – Cycle Time – “the average time from release of a job at the beginning of the routing until it reaches an inventory point at the end of the routing (i.e., the time the part spends as WIP)” (Little and Graves, 2008).

Purpose of usage in this research: Continuously improve production process KPIs (*PSPL*, CWF_{RPN} and *TH*) that influence the product KPIs (Quality, Cost and Delivery).

1.1.2 Analytic Hierarchy Process

In our everyday life, people have to make various choices concerning which tasks and when to fulfil or not to fulfil, and whether to fulfil them at all. “There are many challenges, such as buying the most cost effective personal computer, a car, or a house, choosing a university or a job, investing money, deciding on a vacation place, or even voting for a political candidate, are common everyday problems in personal decision-making” (Saaty, 1988). In addition, local and national governmental decisions, such as where to build a road or a school, how to make funds within a country, are made. Similar challenges are met in business decisions, such as equipment purchasing, marketing a product, labour recruiting. All these problems are very essential and complex regarding choices. They need a logical decision. The human mind is incapable of considering all the factors and their effects simultaneously. Today people solve problems using mathematical models that draw conclusions which may not be clearly useful or even make decisions intuitively. Therefore, the Analytic Hierarchy Process (AHP) based on linear algebra was developed. Until recently, its connection to decision making has not been adequately studied. Today by help of personal computers, using the AHP software we can solve basic linear algebra problems. The difference of the AHP from conventional decision analysis techniques lies in the requirement that its numerical approach to priorities conforms to scientific measurement. If appropriate scientific experiments are carried out using the scale of the AHP for paired comparisons, the scale derived from these should yield relative values that are the same or close to what the physical law underlying the experiment dictates according to known measurements in that area. The AHP is of particular value when subjective, abstract or non-quantifiable criteria are involved in the decision (Saaty, 1988).

“The AHP is a structured technique for organizing and analysing complex decisions developed by Thomas L. Saaty in the 1970s. The AHP breaks down a problem into a hierarchy in which each decision element is considered to be independent; thus, it cannot accommodate interrelationships among elements”

(Chung et al., 2005; De Ambroggi and Trucco, 2011; Tseng et al., 2009; Wu and Lee, 2007).

"AHP approach consists of three major components and one of them, which is applied in this research, is *"measurement methodology"* used to establish priorities among the elements within each stratum of the hierarchy. This measurement is accomplished by asking the participants to evaluate each set of elements in a pairwise comparison with respect to each of the elements in a higher stratum. The task of the respondent is to evaluate each pair separately as to the degree to which one item of a pair dominates the other with respect to the elements from the next level in the hierarchy. In this case an illustrative instruction to the respondent would be: *"which option is more important in helping achieve the corporate profit objectives and how important is it?"*" (Wind and Saaty, 1980; Saaty, 1987). In order to provide numerical pairwise comparisons, a reliable and workable scale is needed. Table 1.1 presents the 9-point scale.

Table 1.1. The 9-point scales of the AHP (Wind and Saaty, 1980)

Importance	**Definition**	**Explanation**
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one element over another
5	Strong importance	Experience and judgment strongly favour one element over another
7	Very strong importance	An activity is favoured very strongly over another
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Used to express intermediate values	

Using this scale, the participants assess the dominance of each element over the others with respect to each element of the higher levels of the hierarchy. The individual judgements are made in a group setting, involving the relevant decision maker, and serve as a basis for discussion on the reasons for specific judgements. Such discussions often result in agreement and in those cases in which agreement cannot be reached, a sensitivity analysis can be conducted to assess to what extent the divergent judgement leads to significantly different results (Wind and Saaty, 1980; Saaty, 1987).

The basic premise of the AHP is that measurement evolves out of comparisons, particularly pairwise comparisons. Suppose that there are n objects $A_1, \ldots, A_n$ whose vector of corresponding weights $w = (w_1, \ldots, w_n)$ is known. From here the Matrix/Equation (1.2) of pairwise comparisons of weights can be formed (Saaty, 1990).

$$\begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_n \end{matrix} \begin{pmatrix} A_1 & A_2 & \cdots & A_n \\ w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ \vdots & \vdots & \vdots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{pmatrix} \times \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix} = n \times \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix} \quad (1.2)$$

Purpose of usage in this research: Compare various KPIs and identify the most important one for improvement.

1.2 Basic concepts applied in dynamic management framework

1.2.1 Bill Of Materials

Bill Of Materials (BOM) or product structure is a list of the assemblies, sub-assemblies, materials, components and the required quantities to manufacture a finished product. The content of the BOM may vary from company to company, depending on business needs and processes. In industries, the BOM is also known as the recipe or ingredients list, which usually contains the following information:

- BOM Level (the hierarchy of BOM level starts from level 0 – finished product and so on until the level 1, 2, 3 and N, which includes sub-assemblies and materials),
- Part Number,
- Part Name/Description,
- Quantity,
- Unit of Measure,
- Procurement Type,
- BOM Notes,
- Other information required for business needs.

BOM can be specific to engineering (used in the design process), production (used in the manufacturing process), and to other areas. A production BOM is important in Materials Requirement Planning (MRP) and Enterprise Resource Planning (ERP) systems; it is used to calculate the direct cost of a product, as well as to order parts from suppliers (Bill Of Materials, 2015).

Purpose of usage in this research: Direct product cost calculation and production route creation per BOM level.

1.2.2 Production Route Card

Production Route (PR) card is a card that gives the details of an operation to be performed in a production line. It is used to instruct the workers to take up the production work. The content and formats of the PR card can vary from a company to a company. In general, it contains: an item and the number of quantities to be produced; production time; dimensions; any additional information that may be required by the worker. PR card traces the route to be taken by a job during a production process (Production Route Card, 2014).

Purpose of usage in this research: Describe production process steps (product/component name, work centres, operation name, time, sequence).

1.2.3 Failure Classifier

Reliability engineering deals with an analysis of the causes of the faults in factories. In this research, a Failure Classifier (FC) based on DOE-NE-STD-1004-92 standard was developed for a machinery company presented in Figure 1.2. There are seven major cause categories, and each of them has its subcategories. The basic goal of using this standard is to define the problems or causes that can occur for each operation during the production process, in order to further correct them (DoE, U. S., 1992). This standard was adapted and modified for the machinery enterprises (Karaulova et al., 2012).

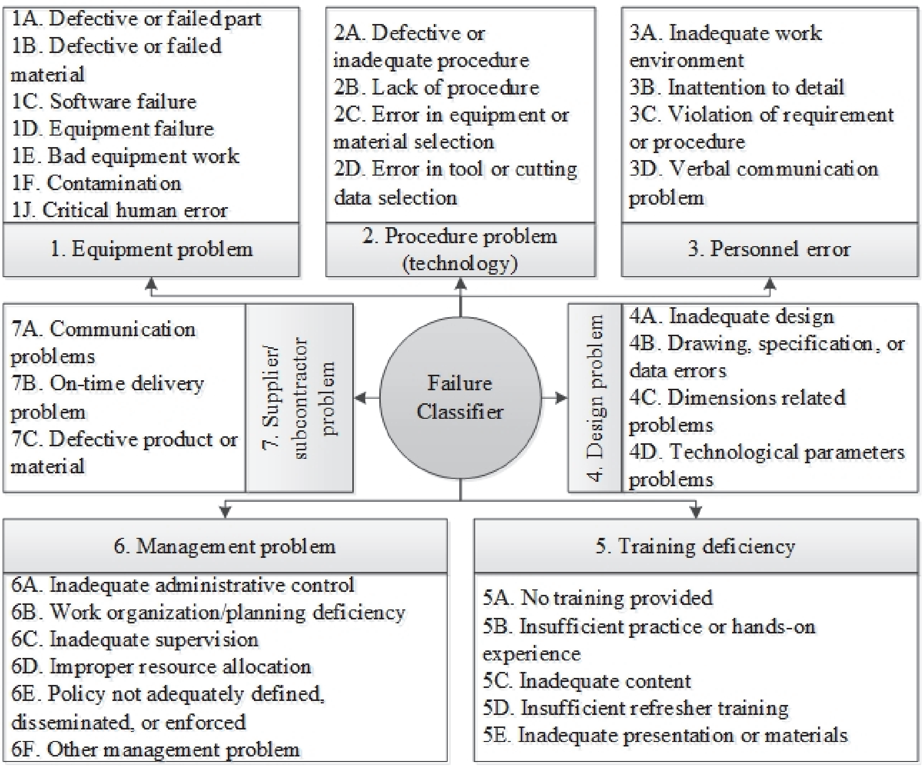

Figure 1.2. Failure Classifier for a machinery company

Purpose of usage in this research: Assign the failure group and the failure cause to the problem operation during the production process; then use assigned and measured failures for process analysis.

1.2.4 Failure Mode and Effect Analysis Methodology

Failure Mode and Effect Analysis (FMEA) is a reliability procedure that provides an evaluation of potential failure modes for processes and their likely effect on outcomes and/or product performance. “It determines by the failure mode analysis the effect of each failure on system operation and identifies single failure points that are critical to mission success or crew safety. FMEA is suitable especially when the effects of faults of basic materials, parts and equipment on the next functional level of higher order are examined, and which fault mechanism can be established at this level” (Stamatis, 2003). “FMEA can be applied to equipment and facilities and might be used to analyse a manufacturing operation and its effect on the product or process. The output/results of FMEA can be used as a basis for design or further analysis or to guide resource deployment” (ICH Q9 Quality Risk Management, 2006).

Nowadays, companies are working to enhance the reliability of their products to open an opportunity for business development. Therefore, the FMEA was born. “It is a systematic method of identifying and preventing product and process problems before they occur. FMEA has focused on preventing defects, enhancing safety and increasing a customer’s satisfaction” (Johnson, 1998).

All FMEAs are team based and the purpose of an FMEA team is to bring a variety of perspectives and experience to the project. A person is appointed responsible for making of an FMEA; however, collection of FMEA data should be performed within a team. The team should be made of five to nine members. All team members must have some knowledge of group behaviour, they must be cross-functional and multidiscipline to handle the problem to be discussed. The team should consist of experienced members, for instance of engineers from the design, quality, supply chain, production and testing (Stamatis, 2003).

FMEA is presented in the form of a table (see Figure 1.3). Every row is a single failure mode described by a number of characteristics: how it must be, what can fail, effect and cause of this failure and current control.

Row Number	Process Name	Process Description	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause of Failure	Occurrence	Current Control Prevention	Detection	RPN	Recommended Action(s)	Corrective Action Results			
			Failure Description			Description						Severity	Occurrence	Detection	RPN

Figure 1.3. An FMEA form

“Every potential failure mode and effect is rated in three factors by Severity (S), Occurrence (O) and Detection (D) on a scale ranging from 1 to 10 presented in Tables 1.2, 1.3, and 1.4. By multiplying the rating for the three factors (S×O×D), a Risk Priority Number (RPN) will be determined for each potential failure mode and effect using Equation (1.3). The RPN will range from 1 to 1000 for each failure mode or operation. It is used to rank the need for corrective actions to eliminate or reduce the potential failures" (MacDermott et al., 1996).

$$RPN = S \times O \times D \tag{1.3}$$

Severity (S) – "criticality of a failure, the consequence of the failure that should occur during the process. It is an estimation of how serious the effect can be if a failure occurs. In some situations it is clear because of past experience how serious the problem is. In other situations, the severity rating can be estimated based on the knowledge and expertise of the team members. Every failure may have several different effects and each effect can have a different level of severity. Therefore, for every effect, its own severity rating should be given, even if there are several effects for a single failure mode" (MacDermott et al., 1996).

Occurrence (O) – "how often the failure happens, the probability or frequency of the failure occurring. The best method for determining the occurrence rating is to use actual data from the process. For example, the data from the production floor can be used. When actual failure data are not available, the team should estimate how often a failure occurs and at what frequency failures happen. Once the potential causes are identified for all of the failure modes, an occurrence rating can be assigned" (MacDermott et al., 1996).

Detection (D) – "what kind of control is required in a process to detect the failure before the impact of the effect is realized. The detection rating looks at how likely a failure or the effect of a failure to be detected is. It is started by identifying current controls that may detect a failure or an effect of a failure. If there are no current controls, the likelihood of detection will be low, and the item would receive a high rating, such as 9 or 10. The current controls should be listed first for all of the failure modes, or the effects of the failures and the detection ratings assigned" (MacDermott et al., 1996).

Advantages of the FMEA could be summarized as follows:

- Finds relations between reasons and cause effects,
- Shows previous unknown event reasons,
- Allows systematic analysis.

Disadvantages of FMEA could be summarized as follows:

- Amount of data can be huge,
- Data analysis can be very complicated,
- Environment conditions, maintenance respects cannot be examined (Lendvay, 2004).

Table 1.2. Ranks for severity estimation (MacDermott et al., 1996)

Severity effect on product	**Rank**	**Severity effect on process**
Potential failure mode affects safe item operation without warning	10	May endanger operator/machine without warning
Potential failure mode affects safe item operation with some warning	9	May endanger operator/machine with warning
Loss of primary function (item inoperable, but does not affect safe item operations)	8	100% of production may be scrap. Stop production or stop shipment
Degradation of primary function (item still operates, but at a reduced level of performance)	7	Portion of production run may be scrapped. Decreased line speed or additional manpower required
Loss of secondary function (item still operable, but comfort functions do not work)	6	100% of production run may require off-line rework
Degradation of secondary function (item still operates, but comfort functions perform at reduced level)	5	Portion of production run may require off-line rework
Appearance item or audible noise (annoys more than 75% customers)	4	100% of production run may require rework in-station before it can be processed
Appearance item or audible noise (annoys 50% customers)	3	Portion of production run may require rework in-station before it can be processed
Appearance item or audible noise (annoys less than 25% customers)	2	Slight inconvenience to process, operation or operator
No discernible effect	1	No discernible effect

Table 1.3. Ranks for occurrence estimation (MacDermott et al., 1996)

Likelihood of Failure	**Occurrence of Causes**	**Occurrence Index %**	**Occurrence Rank**
Very High	>1 per 10	> 10	10
High	1 in 20	5	9
	1 in 50	2	8
	1 in 100	1	7
Moderate	1 in 500	0,2	6
	1 in 2000	0,05	5
	1 in 10 000	0,01	4
Low	1 in 100 000	0,001	3
	1 in 1000 000	0,0001	2
Very Low	Failure eliminated by preventive control		1

Table 1.4. Ranks for detection estimation (MacDermott et al., 1996)

Detection by process control	Detection rank
No current process control; cannot detect; is not analysed	10
It is not easy to detect failures and errors (e.g. random audits)	9
Post-processing failure mode detection by operator using visual, tactile or audible means	8
In-station failure mode detection by operator using visual, tactile or audible means or by attribute gages	7
Post-processing failure mode detection by operator via variable gages or in-station by operator using attribute gages	6
In–station failure mode or cause detection by operator via variable gages, also gauging on set up; first piece inspection	5
Post-processing failure mode detection by automated controls that detect nonconforming parts and prevent further processing	4
In-station failure mode detection by automated controls that detect nonconforming parts and prevent further processing	3
In-station cause detection by automated controls that detect an error and prevent bad parts from being made	2
Error prevention via fixture design, machine or part design, bad parts cannot be made	1

FMEA is criticized for the RPN meaning used. Although it is a measure of the risk of a failure mode or fault, it is the product of three rankings, and as such, it has no meaning as a number: it is only useful in comparisons. Additionally, the number of products that are designed and/or produced with this RPN is not taken into account (Gilchrist, 1993). Furthermore, the FMEA process identifies a large number of failure modes and faults, providing insight in the way in which reliability can be improved.

Although the FMEA is very successful and useful, as a tool it has most valuable as a management tool (rather than as a technical prediction tool), the effectiveness of which is dependent on the extent to which it is carried out. First of all, the composition of the team that has to identify all potential failure modes and effects determines very much the extent to which all potential failure modes and faults will be identified. Since the identification of the failure modes as well as their RPN is based on experience and imagination, it is important to obtain many different viewpoints in the first step of the FMEA process (hence, it is recommended to include many different participants in the FMEA process). Secondly, the identification of the RPN for the different faults is only one part of the FMEA process. At least as important as the identification of the RPNs, is defining and executing the actions that have to be taken in order to reduce the RPN of high-ranking faults (Houben, 2010).

Reasons for use of the FMEA in the current research are as follows (Kostina, 2012):

- FMEA is a relatively low-tech method, which can be understood and used by many practitioners.
- FMEA is a very widespread method; many enterprises are using it.
- FMEA shows relationship between the failure mode and the cause of this failure.

During assessment of Severity and Detection ratings in the FMEA (Occurrence should be calculated more precisely based on data from the production floor), differences in opinions between experts can arise; therefore, when the expert opinions do not match, the assessment may be made using Kendall's coefficient of concordance (Kendall and Babington, 1939), which was presented in the work of Kostina (Kostina, 2012). "Kendall's coefficient of concordance is a measure of the agreement among several quantitative or semi-quantitative variables assessing a set of objects of interest" (Legendre, 2005).

"The coefficient of concordance varies in the range of:

$0 < W < 1$: 0 – the total incoherence, 1 – complete unanimity.

If $W \geq 0{,}6–0{,}9$ opinions are consistent; If $W < 0{,}1–0{,}5$ opinions are inconsistent" (Legendre, 2010).

If during the FMEA parameters estimation, expert opinions are in the range of 0,6–0,9, it is advisable to find one common solution, i.e., one rank. If opinions are in the range of 0,1–0,5, activities which can help to estimate a rank are required: for instance, examination of the question directly in the production, operators' or maintenance personnel inquiry.

Purpose of usage in this research: It gives an opportunity to analyse the production process and eliminate failure causes that consequently allow improve production processes reliability.

1.2.5 Theory Of Constraints

Theory Of Constraints (TOC) is a multi-functional methodology that was primarily developed by Dr. Eliyahu M. Goldratt to help people and organizations to think about system problems, develop breakthrough solutions and implement them successfully. TOC has been popularized through business novels such as "The Goal" (Goldratt and Whitford, 1992), "It's Not Luck" (Goldratt, 1994), "Critical Chain" (Goldratt, 1997), and "Necessary But Not Sufficient" (Goldratt, 2011).

The purpose of the TOC is system improvement. A system may consist of many interdependent processes. It is similar to a chain: a group of interdependent links working together toward the overall goal. The constraint in the chain or in the process is a weak link. The performance of the entire chain or process is limited by the strength of the weakest link. In the production processes, TOC concentrates on the process that slows the speed of product throughput. It consists of five steps:

1. Identify the system's constraints. Find weak element/chain of the process.

2. Decide how to exploit the system's constraints. Use maximum throughput of the weak element/chain that constrains the system.

3. Subordinate everything else to the above decision. When the constraint element is identified and a decision is made what to do with the constraint, it is necessary to run the system with the speed or the capacity of the constraint. It may be necessary to slow down and/or speed up other elements of the system. In other words, it is necessary to subordinate system elements to the constraint element. The system should work with the speed of the constraint.

4. Elevate system's constraints. In case the results of the overall system are not satisfactory, the improvements should be proceeded. Continuous improvement is performed by investing into new facilities, process reorganization or other major expenditures of time or money. In other words, whatever actions that are necessary to eliminate system constraint should be taken.

5. If a constraint has been broken in the previous steps, go back to step one, but do not allow inertia to cause a system constraint. Once the first constraint is removed, in another part of the system or process a new constraint can arise. It is necessary to repeat the cycle of the first four steps in order not to allow inertia to cause system constraint again.

In summary, this methodology shows that reduction of waste in the constraint decreases the lead time and increases the product *TH*. When the constraint is improved, variation is reduced, the process reliability is improved (Goldratt, 1990; Goldratt and Whitford, 1992; Goldratt, 1994; Dettmer, 1997).

Purpose of usage in this research: Elevate production process constraint by eliminating failures in the process/operation that influence *CT* that in turn increases *TH*, which consequently influences product Delivery KPI.

1.3 Review of methodologies and tools for continuous improvement

1.3.1 Total Quality Management

Total Quality Management (TQM) is a philosophy that was successfully launched many years ago in Japan and the United States. This philosophy focuses on the continuous improvement of three main levels:

- Quality of product,
- Quality of organizational processes,
- Quality of human resources.

The TQM principle can be compared with the retention of the ball on the inclined plane. In order the ball does not roll down, it is necessary either to prop up it or push it up. The following two TQM mechanisms allow to *"keep the ball in play"* that enables constant improvement and business development:

- Quality Assurance (QA) – supports the required level of quality and gives certain guarantees to the customer about the confidence in the quality of the product or service.
- Quality Improvements (QI) – suggests that the level of quality should be not only maintained but also increased (continuously improved), which allows the level of guarantees to be raised.

The word *"Total"* in the concept of TQM means that everyone in the organization should be engaged in the process, the word *"Quality"* means care of customer satisfaction, and the word *"Management"* refers to the people and processes required to achieve a certain level of quality (Mansir and Schacht, 1989).

In order to understand the evolution of the TQM, it is useful to look at the philosophies of notable individuals who contributed into its evolution. These persons and their main contributions are presented in Table 1.5.

Purpose of usage in this research: The TQM philosophy describes the background, evolution and history of quality improvement standards and methodologies, such as ISO 9000, Six Sigma and other options.

Table 1.5. Concepts of the TQM philosophy (Reid and Sanders)

Quality Guru	**Main Contribution**
Walter A. Shewhart	Contributed to the understanding of process variability. Developed the concept of statistical control charts.
W. Edwards Deming	Stressed management's responsibility for quality. Developed *"14 Points"* to guide companies in quality improvement.
Joseph M. Juran	Defined quality as *"fitness for use"*. Developed the concept of cost of quality.
Armand V. Feigenbaum	Introduced the concept of total quality control.
Philip B. Crosby	Coined the phrase *"quality is free"*. Introduced the concept of zero defects.
Kaoru Ishikawa	Developed cause-and-effect diagrams. Identified the concept of *"internal customer"*.
Genichi Taguchi	Focused on the product design quality. Developed the Taguchi loss function.

1.3.2 ISO 9000 Standards

ISO 9000 is a standard which consists of the requirements for a quality management system in the organization. The ISO 9000 was not created from scratch, it summarizes the whole experience of quality management whose origins are in the 1930s of the last century which was based on the ideas and principles of the TQM. The first version of the standard was released by the International Organization for Standardization (ISO) in 1987. There are many ISO standards most of which have nothing to do with the quality, many of them related to such things as material resistance, safety, etc. To receive ISO 9000 certification, companies have to demonstrate that they have met the standards described by the ISO. The standards are applicable to all types of companies and have gained global acceptance. The ISO 9000 standard does not guarantee the quality of goods and services. This standard helps to companies to establish a quality management system designed to achieve product and service quality. Nowadays, the ISO certification in many industries has become a requirement for doing business. To obtain the ISO 9000 certification, it is necessary to document production technology, processes and procedures which are aimed at the qualitative needs of consumers and to ensure the quality of goods and services is in accordance with requirements. (Reid and Sanders; ISO 9000 Standards, 2015).

Using the TQM philosophy, such quality and process improvement methodologies as PDCA, 8D, Six Sigma DMAIC, 4Q (that will be described in the next section) (see Table 1.7) and ISO 9000 Standards were developed, which today allow companies continuously improve the quality of products, processes and human resources. The implementation of such philosophy, methodologies and standards enables companies to satisfy customers and sustain competitiveness on the market place.

Purpose of usage in this research: The ISO 9000 standard based on the TQM philosophy is used now by companies to demonstrate that all the requirements described in the standards are met.

1.3.3 Six Sigma

"The lowercase Greek letter sigma "σ" stands for standard deviation. In statistics, it is used to describe how much variation exists in a set of data, a group of items, or a process. The first step in calculating sigma or in understanding its significance is to grasp what your customers expect. In the language of Six Sigma, customer requirements and expectations are called CTQs (critical to quality)" (Pande, 2002).

"From the statistical point of view, the term Six Sigma is defined as having less than 3,4 Defects Per Million Opportunities (DPMO) or a success rate of 99,9997% where sigma is a term used to represent the variation about the process average. If a company is operating at three sigma levels for quality control, this is interpreted as achieving a success rate of 93,32% or 66 807 DPMO" (Antony and Banuelas, 2002). "The Six Sigma methodology is a very rigorous quality control concept where many organizations still perform at three sigma levels" (McClusky, 2000). To calculate DPMO and define sigma process yield, the following Equation (1.4) (Seemer, 2010) is used. After calculating DPMO and or sigma process yield; further, sigma performance level according to the sigma scale table presented in Table 1.6 can be defined.

$$DPMO = \frac{\sum D \times 1000000}{\sum U \times \sum O} \qquad (1.4)$$

where:

$DPMO$ – sum of Defect Per Million Opportunities,

$\sum D$ – sum of real defects occurred,

$\sum U$ – sum of units produced/tested,

$\sum O$ – sum of opportunities for defects per unit.

Sigma level measurement is used to show how well or poorly a process performs and show a common understanding of that measure to every person in an organization. Table 1.6 presents the sigma performance scale, showing how many defects would occur for every million opportunities or activities.

Table 1.6. Sigma performance scale (Watson, 2004)

Sigma Performance Level	Defects per Million Opportunities (DPMO)	Process Yield (PY)
1,0 σ	670 000	33%
2,0 σ	308 537	69,2%
2,78 σ	100 000	90%
3,0 σ	66 807	93,32%
4,0 σ	6 210	99,38%
5,0 σ	233	99,9767%
6,0 σ	3,4	99,99966%

It can take a long time for a company to produce a million of items, but it is not so important; this scale is just a projection of the number that would happen if a company produces this amount. To define on what sigma performance level a company operates, the percentage of the Process Yield (PY) can be identified and the corresponding sigma level in the sigma scale table can be defined.

The *PY* in Six Sigma is calculated using Equation (1.5): subtract the sum of real defects that occurred ($\sum D$) from the sum of opportunities for defects per unit ($\sum O$) and divide it to the sum of opportunities for defects per unit ($\sum O$), and finally, multiply the result by 100 (Process Sigma, 2015).

$$PY = \frac{\sum O - \sum D}{\sum O} \times 100 \tag{1.5}$$

"Six Sigma is a project management methodology intended to improve the organization's products, services and processes by reducing defects" (United States Patent, 1998); "it focuses on improving customer requirements, productivity and financial performance" (Kwak and Anbari, 2006; Snee, 1999). "The main objective of the Six Sigma is focused on process improvement and variation reduction" (Antony, 2004). "Utilizing analytical tools and processes to measure quality and eliminate variances in the processes allows the company to produce near perfect products and services that will satisfy customers" (Stephens & McDonald, 2007). "Six Sigma efforts target three main areas: improve *CS*, reduce *CT*, and reduce defects. Improvements in these areas usually represent cost savings to businesses, as well as opportunities to retain customers, capture new markets and build a reputation for top performing products and services. Reaching Six Sigma means that process or product will perform with almost no defects" (Pande et al., 2002).

"Motorola was the first company who developed a Six Sigma project in the mid1980s that allowed many organizations to sustain their competitive advantage by integrating their knowledge of the process with statistics, engineering and project management" (Rancour and McCracken, 2000; Anbari, 2002). The original focus of Six Sigma was on manufacturing (Nonthaleerak and Hendry, 2008) but today it has been widely accepted in healthcare (Van den Heuvel et al., 2006; Koning et al., 2006), finance (De Koning et al., 2008), service (George and George, 2003), and education (Antony et al., 2012).

1.3.4 Lean Six Sigma

Lean and Six Sigma were developed as the most successful tools for reducing cost and cycle times, improving quality and service, designing products and services that meet customer expectations. The goal of Lean is to eliminate wastes, while Six Sigma focuses on eliminating process variations. Their common goal is to make the process more efficient and effective. Lean Six Sigma is an integration of Six Sigma and Lean Manufacturing, both quality improvement programs that come from industry. Today, these powerful tools are successfully combined into a single integrated toolkit (Aon Management Consulting, 2003). Lean Six Sigma promotes continuous improvement of processes by both analysing sources of waste and reducing waste (Stephens & McDonald, 2007). Lean and Six Sigma contain a complementary range of tools and techniques that in reality will inevitably require a range of both of them. DMAIC is an effective problem solving a structure that helps to be clear about what you are trying to achieve. For that reason, it is recommended to combine these techniques within a DMAIC structure (Brook, 2010).

1.3.5 Six Sigma DMAIC

Six Sigma's DMAIC structure offers a thorough roadmap for problem solving. The steps of Six Sigma DMAIC are described in Figure 1.7.

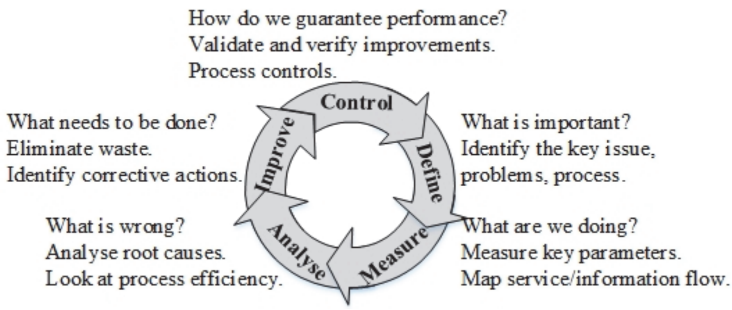

Figure 1.7. Six Sigma DMAIC structure

Define is the first step of the Six Sigma process. During this step, a problem is identified and quantified in terms of the perceived result. The product and/or process to be improved is identified, resources for the improvement project are put in place, and expectations for the improvement project are set. The focus of the problem-solving strategy is kept on the customer's primary requirements.

Measure step enables an organization to understand the present condition of its work process before it attempts to identify where they can be improved. It provides the substance for the problem statement. During this step, the critical to-quality (CTQ) characteristics are defined, as well as the defects in the process or product and a physical model of the process is developed through graphical analysis. All the factors of the outputs are evaluated, and potential effects they have on failure modes are identified. The Measure step is based on valid data, so it eliminates guesswork about how well a process is working.

Analyse step adds statistical strength to problem analysis. Statistical analysis identifies a problem´s root cause by determining which factors contribute to the observed variation and how much of the total variation is explained by these factors. It can be used to calculate how much variation each dominant factor contributes to the overall problem. Interaction effects among the process variables can be observed through statistical testing.

Improve step aims to develop, select and implement the best solutions with controlled risks. The effects of the solutions that are then measured with the Key Performance Indicators (KPIs) are developed during the Measure step.

Control step is intended to design and implement a change to influence improvements based on the results demonstrated during the Improve step. The human element of the process is engaged to implement and manage changes in daily work activities required to achieve the targeted result of the change project. The Control step involves monitoring the process to ensure it has the discipline required to implement the change, capture the estimated improvement benefits, and maintain performance gains over a long term (Watson, 2004).

Purpose of usage in this research: Based on comparing various methodologies, it was decided that the widely used and popular structured Six Sigma DMAIC methodology will be applied in this research. The reason for selection of the Six Sigma DMAIC methodology is the following: it is based on the TQM philosophy; focus is on the reduction of process variability, cycle time, costs, defects and increase of customer satisfaction and company profit; targeted to continuous improvement; option to measure process (in order to improve something, firstly it should be measured); option to apply Six Sigma with Lean Manufacturing tools (Lean Six Sigma); structural approach to solve problems using the DMAIC structure; it is mostly applied to solve large problems where much data are available and where statistical tools should be applied. However, every company can apply the presented framework in another well-known methodology like PDCA, 8D or 4Q. Table 1.7 presents a brief summary of the process improvement methodologies and their evolution (from left to right) and correlation (Sahno and Shevtshenko, 2014).

PDCA cycle is the problem solving approach used in Lean Manufacturing and mostly in the automobile industry. It is a concept for continuous improvement of processes that is embedded into the culture of an organization. PDCA is used for medium sized problems (Sahno and Shevtshenko, 2014).

8D is an effective approach to find the root causes to develop proper actions to eliminate the causes and to implement the corrective actions. The goal of 8D is to provide fast reaction to customer complaints. Usually, the first three steps should be performed and reported to the customer during three days (Sahno and Shevtshenko, 2014).

4Q process is a problem solving method that is similar to the above mentioned methodologies intended for continuous improvement of the processes. It was developed by the ABB company to help to solve 90% of all issues (Sahno and Shevtshenko, 2014).

Table 1.7. Evolution, correlation and summary of quality improvement methodologies (Sahno and Shevtsenko, 2014)

Steps	**PDCA**	**8D**	**Six Sigma DMAIC**	**4Q**
	Plan	D0: Plan	Define	Pre 4Q
		D1: Identify team		
		D2: Define problem		
		D3: Contain symptom	Measure	Measure
		D4: Identify root causes	Analyse	Analyse
	Do	D5: Choose corrective action	Improve	Improve
		D6: Implement corrective action		
	Check	D7: Make change permanent	Control	Sustain
	Act	D8: Recognize the team		
Comparison of methodologies for continuous improvement application				
Year	1939	1940´s	1980	2009
Industry	Automobile	Automotive	Manufacturing of all type, healthcare, finance, service	Automotive, electrical,
Project / problem size	Medium sized, up to 3 months	Small, some weeks	Large, up to 12 months and even more	Small and medium, 1 week up to 2 months
Used / Applied	For continuous improvement of small problems	For automotive industry and focused on fast reaction to customer complaints	For large problems where huge amounts of data and statistics are used	For continuous improvement of various problems (allowed solution of 90% of all issues in ABB company)

1.4 Tools applied in the Information System framework

"Information System (IS) is an organized combination of people, hardware, software, communication networks, data resources, policies and procedures that stores, retrieves, transforms and disseminates information in an organization. People use modern IS to communicate with each other using various physical devices, information processing instructions and procedures, communication channels and stored data. In other words, today ISs are considered to be associated with computers" (O'Brien and Marakas, 2008).

Purpose of usage in this research: Apart from creation of the framework for continuous improvement of reliability of production processes in this research, another goal is to adapt the developed framework into the IS environment that includes various systems and tools, which are described in the following sections below.

1.4.1 Product Data Management

"Product Data Management (PDM) system is the software that manages product data of design files generated by Computer Aided Design (CAD) systems. This system enables standardization of items, storing them into repository and controlling document files, maintaining Bills Of Materials (BOM) and document revision levels and displaying relationships between parts and assemblies. It gives a quick access to standard items, BOM structures and files for reuse, reduces the risk of using incorrect design versions and increases the reuse of existing product information" (Saaksvuori and Immonen, 2008; Peltonen et al., 1996; Lebovitz, 1997).

Purpose of usage in this research: Used as an initial data source where the product BOM is created. Further, this BOM will be used as the basis for the next steps of the research.

1.4.2 Enterprise Resource Planning

"Enterprise Resource Planning (ERP) system is an enterprise cross-functional software driven by an integrated suite of modules that supports the basic internal business processes of a company" (Koudsi, 2000). It is the IS backbone of e-business, an enterprise framework that integrates various data: sales, purchasing, inventory management, production planning, finance, human resource (De Geus, 1988; Markus, 2000). "ERP system helps organizations integrate their information flow and business processes. It supports the different departments and functions in the organization by using a single database that collects and stores data in real time. When the ERP system is implemented in a business organization, it can yield many benefits: reduce cycle time, enable faster information transactions, facilitate better financial management and generate new knowledge (tacit to explicit)" (Davenport, 2000).

Purpose of usage in this research: Receive data from the PDM system, process them and use for product production. Further, transfer results/data from the production floor to the Data Mart.

1.4.3 Extraction-Transformation-Loading

"Extraction-Transformation-Loading (ETL) system is the tool/software responsible for the data *extraction* from different sources (operational data), *transformation* (conversion, cleaning, normalization, etc.) and *loading* into a Data Warehouse (DW)" (Vassiliadis et al., 2002).

The creation of an ETL process is usually composed of six tasks:

1. Select the data sources for data extraction (several different data sources).

2. Transform the data from the data sources or derive new data (filtering data, converting codes, calculating derived values, transforming between different data formats, automatic generation of sequence numbers etc.).

3. Join the different data sources to load the data together into a unique target.

4. Select the target to load the needed data into the targeted place.

5. Map source attributes: extract data from the data sources and map to the corresponding target ones.

6. Load the transformed data to the target.

An example of the ETL system is PDM-ERP middleware – a standardized communication interface between the PDM and ERP systems that allows designing and managing of easily adaptable workflows to exchange data and integrate processes between these two systems (Teamcenter Gateway for SAP Business Suite (T4S), 2014).

Despite the power of an ETL solution, a new ELT (Extraction-Loading-Transformation) system is available on the market today. "This system offers superior performance and scalability compared to traditional ETL system; for example, better performance leveraging database technology; leverages DBMS engine hardware for scalability less network traffic due to data movement; simple transformation specification using SQL Extract and Load processes are isolated from Transform, helping make the process more manageable; data cleansing is done at the staged area, thereby ensuring only the checked data is loaded for transformation" (ELT system, 2015).

Purpose of usage in this research: Apply ETL to integrate various systems and tools, such as PDM. ERP, Data Mart into one general IS environment.

1.3.4 Data Warehouse and Data Mart

Data Warehouse (DW). Today Information Technology (IT) plays an important role in the business of a company. During last years, advances in IT, such as networks and databases allowed businesses to store huge amounts of internal and external data needed for analysis and decision-making. Through an effective decision-making system that means effective and flexible DW systems any company can become competitive and successful on today's market place (Watson and Gray 1997; Barquin and Edelstein, 1997; Inmon, 2005).

"DW is a database that provides a single source of management information for reporting, analysis of data across the organization and for decision-making. It was proposed as a main solution to the problem of satisfying organizational management information needs at the beginning of the 1990s" (Inmon, 1996).

"A significant part of IT investments in most organizations is devoted to DW developments. High levels of user satisfaction and ROI have been reported in the literature for such developments" (Graham et al., 1996). The DW can collect much useful data about the business processes, such as production, purchasing, sales, marketing etc. "These data show customer patterns and trends, the effectiveness of business strategies and other characteristics that are important for business success" (Watson et al., 2001). Today companies use and maintain a number of operational data sources that include the databases and other repositories utilized to support the everyday operations (Inmon, 1996).

Data Mart. "Data Mart follows the same principle as the DW but on a small scale. It provides access to the data faster than the DW, it allows business managers to initiate business intelligence strategies and receive useful reports" (Houari and Far, 2004). "Data Mart is the part of the DW process where data are accessed directly by end users. The data are extracted from the central DW into Data Mart to support particular analysis requirements" (Moody and Kortink, 2000). The example of DW architecture is presented in Figure 1.4.

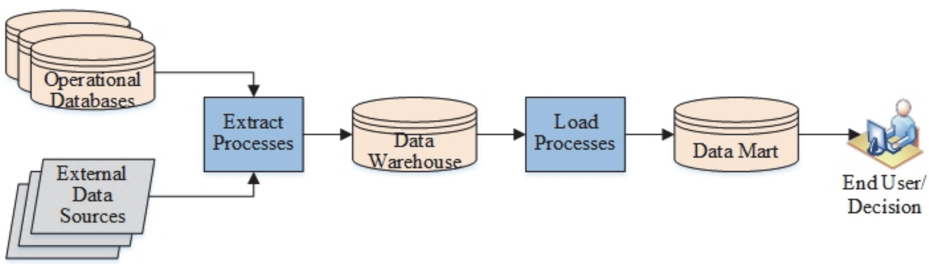

Figure 1.4. Architecture of a Data Warehouse

"Companies can create a DW using a top-down or a bottom-up approach and each has its advantages and disadvantages. When a DW is created with the top-down approach, it combines data across the organization and end-user applications are developed after the DW is implemented. This strategy is time consuming, expensive, and may fail to deliver benefits within a reasonable time span. With the bottom-up approach, a project team creates a Data Mart with a limited set of data sources that meets very specific user requirements. After the Data Mart is finished, subsequent marts are developed and they are conformed to data structures and processes that are already in place. The Data Marts are integrated into an enterprise DW that meets the needs of company's users. The advantage of the Data Mart strategy is that a mart can be created quickly, at relatively low cost and risk" (Watson et al., 2001).

"Kimball proposed a new approach for data modelling specifically for designing a DW, which he called *dimensional modelling*. The method was developed based on the observations of practice and in particular, of data vendors who are in the business of providing data in a *"user-friendly"* form to their customers. Dimensional modelling has been adopted as the predominant approach to designing DWs and Data Marts in practice, and represents an important contribution to the discipline of data modelling and database design" (Kimball, 1996; Kimball, 1997; Kimball, 1998).

Star Schema. "The basic building block used in dimensional modelling is the *star schema* that consists of one large central table called the *fact table*, and a number of smaller tables called *dimension tables* that radiate out from the central table, as shown in Figure 1.5. The fact table forms the *"centre"* of the star, while the dimension tables form the *"points"* of the star. A star schema may have any number of dimensions. The fact table contains *measurements*, which may be aggregated in various ways" (Kimball, 1996; Chenoweth et al., 2003). "The advantage of using star schemas to represent data is that it reduces the number of tables in the database and the number of relationships between them and therefore the number of joins required in user queries. Kimball (1996) claims that use of star schemas to design DWs results in 80% of queries being single table browses" (Kimball, 1996).

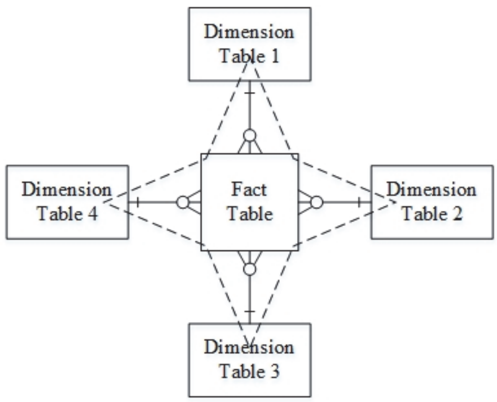

Figure 1.5. Star schema

Purpose of usage in this research: Develop Data Mart for dynamic management framework that enables improvement of product quality, cost and delivery based on the priorities of a decision maker. In the development of Data Mart, the ISO/IEC/IEEE 42010:2011 standard for systems and software engineering for architecture description can be used (International standard ISO/IEC/IEEE 42010:2011, 2011).

1.4.5 ISA-95 Standard

ISA-95 (Industry Standard Architecture) or ANSI/ISA-95 is the international standard that defines the interfaces between business and manufacturing operations and control systems. This standard was developed by the international association of specialists in the field of ISA automation for use in all kinds of industries and processes (continuous and repetitive). The main goal of the standard is to ensure a smooth, accessible information flow throughout the enterprise, between various functions, departments and systems. It facilitates enterprise-wide communication and mutual understanding among all of the constituents involved, everyone can use it, from IT to engineering, quality, operations and finance. This standard also allows reducing the risk, cost and errors related to implementation. For example, it shows the way of integration of ERP and Manufacturing Execution System (MES)/Manufacturing Operations Management (MOM). The ISA-95 standard consists of five levels: Level 0 to Level 4 – each representing a level of manufacturing from the production floor to corporate planning. Two above mentioned levels (ERP and MES/MOM) are referred to as Level 4 and 3. The standard provides a framework for developing requirements for information system functionality and data flow that allows enterprise systems and control systems to inter-operate and be easily integrated. ISA-95 has no reference on where the *"right"* location is, so companies must decide on what level their business and control systems (ERP, MES, etc.) are located. Figure 1.6 shows ISA-95 standard levels and functions (Brandl, 2002; Dassault Systems & DELMIA, 2012).

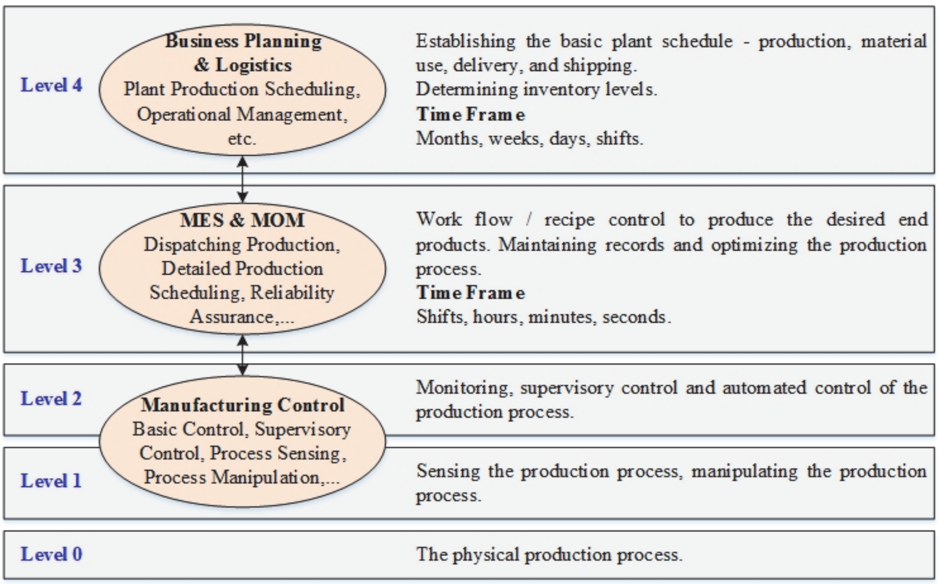

Figure 1.6. ISA-95 standard levels and functions

Purpose of usage in this research: Application of this standard allows understanding the level that every tool/component of the new framework for continuous improvement of production processes is located on.

1.5 Summary of the Literature Review

Based on the literature review covering FMEA, Six Sigma and TOC, it can be summarized that these methodologies are mainly focused on continuous improvement of business processes. Initially, these methodologies were used separately to achieve their goals, when the researchers started to combine them, more efficient results were achieved.

As already mentioned above, initially the Six Sigma methodology was developed to eliminate variability and lean manufacturing to eliminate wastes in business processes. Then, these methodologies were combined with the DMAIC structure for the structural approach of problem solving. Later this combination became known as Lean Six Sigma. Many different tools are used in Lean Six Sigma, such as FMEA, Value Stream Mapping, Cause & Effect, Design of Experiments (DOE), SIPOC/COPIS, QFD/House of Quality and other tools (Brook, 2010; Six Sigma Tools & Templates, 01.02.2015), which have been developed for various purposes, such as measurement, analysis and improvement of business processes. But the most suitable Lean Six Sigma tool that will be used in this research is the FMEA that is intended to improve the reliability of business processes. Common application of Six Sigma and FMEA to attain specific goals has been discussed in many research papers. For example, Table 1.8 presents a list of authors whose research is close to the topic of the current thesis (FMEA and Six Sigma).

In addition to the above, in the current research, TOC is applied to identify and elevate system constraints. Much literature related to the description of Lean Six Sigma and TOC common application is available. The main focus of this tandem is on finding a system constraint using the TOC approach, and then, with the help of Lean Six Sigma and its tools, elevate this constraint. Thus, the references presented in Table 1.8 (Six Sigma and TOC) describe how to use these methodologies together to find and elevate system constraints. However, no similar studies are available which describe how to use a particular tool from Lean Six Sigma with TOC to elevate system constraints. Table 1.8 also shows that such researches are not available (FMEA and TOC). Therefore, in the present thesis, this gap will be filled. Neither are any studies available covering combination of FMEA, Six Sigma and TOC that will also be discussed in this thesis.

In summary, based on the results of the comprehensive literature review, to discover possible accomplishments **not yet been achieved** by combining these methodologies together.

- How to calculate Sigma performance level that shows the level of the process or product quality based on the data from FMEA?
- How to calculate the financial impact of failure on the process, which influences the direct cost of the final product using the data from FMEA?
- How to identify process constraint and factors which influence the process *TH* and make decisions for improvement using the data from FMEA, failure classifier, and the data that show the financial effect of a failure?

Such approaches can enable the engineers to determine more efficiently failures which influence the KPIs and improve them. All these proposals will be discussed further in the current thesis.

Table 1.8. Summary of FMEA, Six Sigma and TOC integration

Authors	**FMEA**	**Six Sigma**	**TOC**
Baek et al., 2006; Mekki, 2006; Das et al., 2006; Krishna and Dangayach, 2007; Sarkar, 2007; Krishna et al., 2008; Myszewski, 2010; Yang et al., 2010; Bhanumurthy, 2012; Chiarini, 2012; Kumaravadivel and Natarajan, 2013; Mazumder, 2014; Bubshait and Al-Dosary, 2014; Kumar et al., 2014.	×	×	
Nave, 2002; Ehie and Sheu, 2005; Yang, 2005; Jacob et al., 2009; Jin et al., 2009; Sproull, 2012; Pacheco, 2014; Lean Six Sigma, 30.01.2015.		×	×
No results	×		×
No results	×	×	×

2. FRAMEWORK DEVELOPMENT FOR CONTINUOUS IMPROVEMENT OF PRODUCTION PROCESSES

The main goal of this research is to present a new dynamic management framework for continuous improvement of production processes and KPIs. This framework enables the number of defects/failures in the process to be reduced, thus decreasing their RPN_{Real} value that in turn increases production process KPIs, such as *PSPL*, CWF_{RPN} and *TH* that influence the product KPIs, such as Quality, Cost and Delivery, customer satisfaction and company revenue. Figure 2.1 shows the QCD framework in the Six Sigma DMAIC structure.

In the Define step, the problem and main KPIs for improvement are identified.

In the Measure step, the modified FC standard, i.e. DOE-NE-STD-1004-92, is applied, which enables the types of failures to be specified for each operation during the production process. In addition, the FMEA is applied to assess the weight of each failure by Severity, Occurrence and Detection rating and then calculate the RPN_{Real} value. Based on the FMEA results, the *PSPL* KPI that indicates the general level of quality is calculated for the process/product that influences the product Quality KPI. Using the RPN_{Real} values from the FMEA, the variability of the process by failures, operations work centres and the BOM level can be observed. In addition, the direct costs of the components and/or the BOM level should be calculated in FCC, in order to further define the financial impact of failure (CWF_{RPN}) on the final product. This KPI shows where improvements should be made to increase the product Cost KPI. In the TOC phase, the process constraint of the production process should be identified and further elevated by reducing the number of failures or RPN_{Real} values in the constraint that in turn decreases the process *CT* and increases the process *TH* and affects the product Delivery KPI.

In the Analyse step, the KPIs should be compared using the AHP and various charts and diagrams created (Pareto chart, Chart for CWF_{RPN} and Swimline diagram) based on the data from the Measure step. Then, by analysing various charts and data, failures necessary to improve or eliminate to increase specified KPI for the specified process/product should be identified.

The first three steps of the DMAIC process (Define, Measure, Analyse) characterize the nature of the problem to be solved. Upon completion of these steps, the problem and its root cause(s) are known and further based on these steps the Improve and Control steps should be applied where appropriate changes and corrective actions in the production process are implemented and sustained. Below the framework in Six Sigma DMAIC methodology is described in detail.

2.1 Actions in Define step

The problematic process should be defined and the required KPI metric(s) for continuous improvement must be evaluated and indicated.

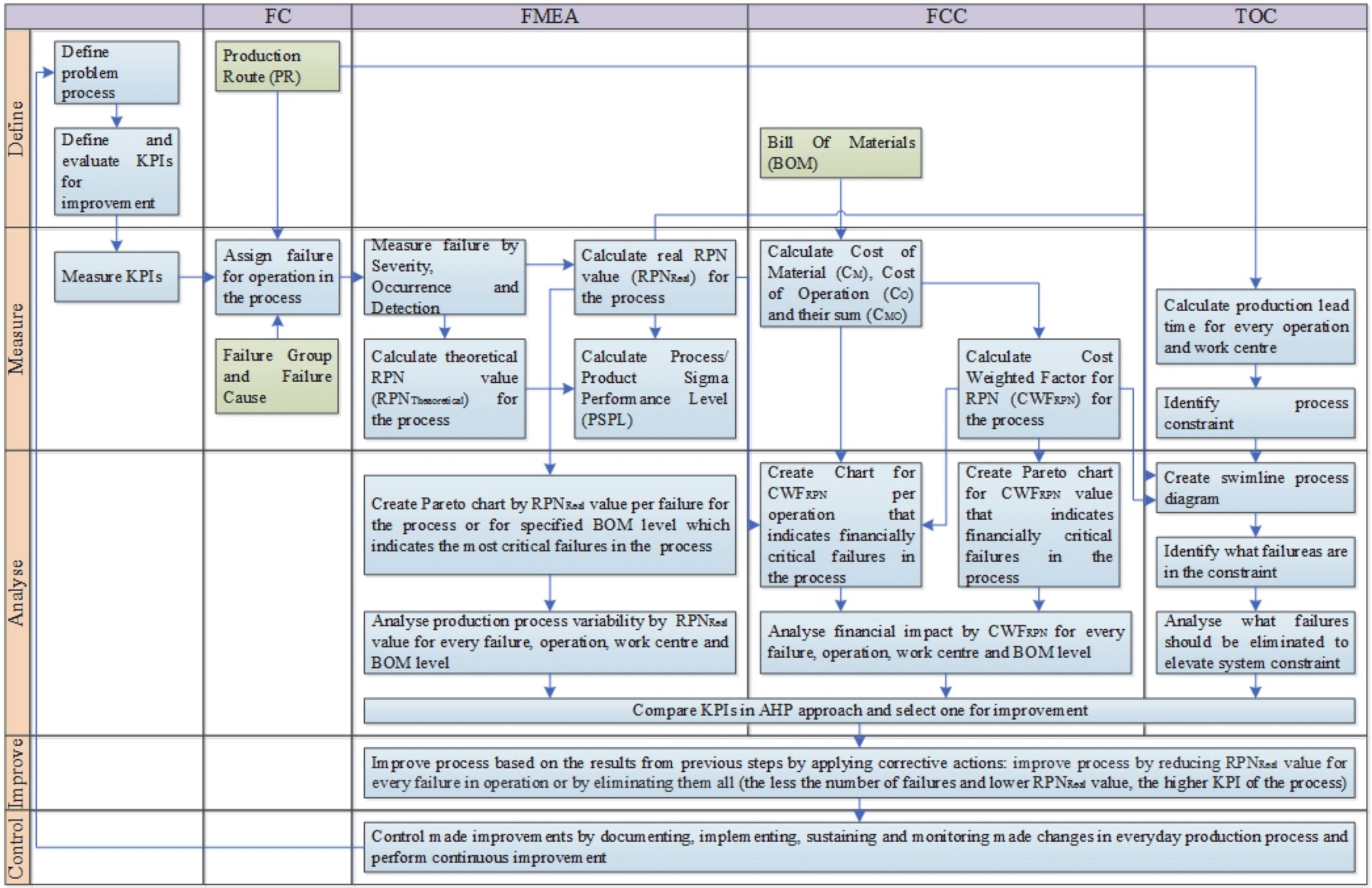

Figure 2.1. QCD framework for continuous improvement of production processes in the Six Sigma DMAIC structure

2.2 Actions in Measure step

In the Measure step, four different tools/methods are applied: 1) FC where failures are assigned for every problematic operation in the process; 2) FMEA where every failure type is assessed by Severity, Occurrence and Detection rating, and *PSPL* KPI (Sahno et al., 2013; Sahno et al., 2015) is calculated; 3) FCC where the direct cost of the BOM level and financial impact of failure on the final product – CWF_{RPN} KPI (Sahno et al., 2015) is calculated. 4) In the TOC, the *TH* KPI is identified. The applications of these four tools/methods are described below.

2.2.1 Measure in FC

During the production process, an operation may have a failure, therefore the Failure Group/Cause should be assigned to the problematic operation from the FC. This step is the basis for the next three steps in FMEA, FCC and TOC.

2.2.2 Measure in FMEA

One of the purposes of the FMEA is to assess the risks of the production processes that influence product quality. Therefore, the purpose of the FMEA in this research is to monitor the product **Quality KPI** by reducing the RPN_{Real} value of failures or eliminating them in the production process.

Usually the Severity, Occurrence and Detection ratings in the FMEA are assessed in a team. In order to attain more precise results in the FMEA that correspond to the data of real production, it is proposed in this research to assess the Occurrence rating based on the production data from the production floor. As for Severity and Detection ratings, they will be assessed in a team using the FMEA rank tables. The techniques of assessing these ratings are described below.

Severity assessment: The goal of this rating is to assess how critical the effect of a potential failure mode is on the overall system or process. In some cases, it is clear from past experiences. In this research the rating of Severity is defined from the Severity ranks table (Table 1.2) and it is based on the knowledge and experience of the team members.

Occurrence assessment: This rating is based on the assessment of failure frequency in the production process. Occurrence is assessed according to the statistical data collected from the production floor for the specified period of time (e.g., for one month). Equation (2.1) below shows the calculation of the Index of Occurrence (I_O). Further, based on I_O, the Occurrence rating can be defined using Table 1.3.

$$I_O = \frac{\sum S_Q}{\sum P_Q} \times 100\% \qquad (2.1)$$

where:

ΣS_Q – scrap (non-qualified components/products) quantity for a specified period,

ΣP_Q – produced product quantity for a specified period.

When the **percent value** for the Occurrence is calculated, this rating should be defined according to the ranks table presented in Table 1.3. For example, when 100 units are checked and 10 units have scrap, the rating will equal to 10 points.

Detection assessment: The assessment of Detection is related to the performance of the measurement tool that should check the required parameters in the product and detect failures before a product goes to a customer. In the current research, the rating of Detection is defined from the Detection ranks table (Table 1.4), based on the knowledge and experience of the team members.

RPN real (RPN_{Real}) value per failure calculation: By multiplying the three factors (S×O×D), the RPN_{Real} value is calculated for each failure ((Equation (1.3)).

RPN real (RPN_{Real}) value per operation, work centre, BOM level and process calculation: To calculate the sum of RPN_{Real} value per operation, work centre, BOM level and process, all RPN_{Real} values per failure should be summed up.

Theoretical RPN ($RPN_{Theoretical}$) value per failure calculation: The maximum RPN_{Real} value for Severity, Occurrence and Detection rating may equal to 10 points, subsequently the maximum $RPN_{Theoretical}$ value per failure is 1000 points.

Theoretical RPN ($RPN_{Theoretical}$) value per process calculation: To calculate the sum of $RPN_{Theoretical}$ value per process/product, the number of failures in the production process should be counted and multiplied by 1000 points using Equation (2.2). This $RPN_{Theoretical}$ value shows the scope of the process or the maximum RPN value, which can be reached or failed.

$$\sum RPN_{Theoretical} = \sum F \times 1000 \tag{2.2}$$

where:

$\sum F$ – sum of failures in the production process,

1000 – theoretical RPN value per failure.

RPN_{Real} percent calculation: To calculate the *PSPL*, RPN_{Real} percent value should be calculated first using Equation (2.3).

$$RPN_{Real}\% = \frac{\sum RPN_{Real}}{\sum RPN_{Theoretical}} \times 100\% \tag{2.3}$$

where:

ΣRPN_{Real} – sum of real RPN for a particular product,

$\Sigma RPN_{Theoretical}$ – sum of Theoretical RPN for a particular product, (S_{Max}×O_{Max}×D_{Max} = 10×10×10 = 1000).

Process Yield (PY) calculation: Having calculated RPN_{Real} percent, now the Process Yield *(PY)* can be calculated, using Equation (2.4).

$$PY = 100\% - RPN_{Real}\% \tag{2.4}$$

where:

100% – maximum percent value of $\Sigma RPN_{Theoretical}$

Process/Product Sigma Performance Level (PSPL) definition: The *PSPL* in this research shows the level of process/product quality that can be defined using the RPN_{Real} per failure, operation, work centre, BOM level and common process, and $RPN_{Theoretical}$ values calculated in the previous steps. Having calculated *PY* and according to the sigma performance scale in Table 1.6, the *PSPL* can be defined.

Average PSPL calculation: In the current research, the *PSPL* is calculated for a finished production process (process that includes various production operations to produce a final product). However, general production system (which includes various production processes/products) may have some products being produced and they may have their own *PSPL*, therefore, an average *PSPL* for a general production system may be calculated by summing up all *PSPLs* and dividing by the number of product types. Equation (2.5) should be used for that purpose.

$$PSPL_{Average} = \frac{\sum_{i=1}^{n} PSPL_i}{n} \tag{2.5}$$

where:
$PSPL_{Average}$ – average *PSPL* for a general production system,
$PSPL_i$ – observation *i*, $i = 1,\ldots, n$,
n – number of observations.

2.2.3 Measure in FCC

The purposes of the FCC approach in this research is to calculate the Cost Weighted Factor for the RPN (CWF_{RPN}) that shows financial impact of the failure (calculated in FMEA) on the final product. In the present research, this KPI should be improved by eliminating the RPN_{Real} values of failures in the FMEA that influence the product **Cost KPI**. To calculate CWF_{RPN} for failure, operation and work centre, the direct Cost of Material and Operation (C_{MO}) should be calculated first and to calculate CWF_{RPN} for the BOM level, the Cost of BOM Level (C_{BOML}) should be calculated too.

Cost of Material and Operation (C_{MO}) calculation and conversion into percent value: To calculate C_{MO}, the Cost of Material (C_M) and the Cost of Operation (C_O) should be summed using Equation (2.6).

$$C_{MO} = C_M + C_O \tag{2.6}$$

In the current research, a product and its component cost are assessed in percent value. The total cost of a product equals 100%, which is the cost of BOM level zero – C_{BOML0}. The material and operation cost can be converted from currency into percent value using Equation (2.7).

$$C_{MO}\% = \frac{C_{MO} \times 100\%}{C_{FP}} \tag{2.7}$$

where:
$C_{MO}\%$ – product or component cost in percent value from the final product cost,
C_{FP} – cost of the finished/final product.

Cost of BOM Level (C_{BOML}) calculation: Figure 2.2 shows an example of the product BOM structure that consists of BOM levels and other sub-levels and subsequent lower levels. The cost of C_{BOML0} equals the sum of the operation cost ($\sum C_{O0}$) and the sum of the material cost ($\sum C_{M1}$) from BOM level 1 (C_{BOML1}). Further, the cost of C_{BOML1} equals the sum of the operation cost ($\sum C_{O1}$) and the sum of the material cost ($\sum C_{M2}$) from BOM level 2 (C_{BOML1}) and so on until the lower level of a product is reached. To calculate the C_{BOMLN}, Equation (2.8) should be used.

$$C_{BOMLN} = \sum_{y=1}^{m}\sum_{i=1}^{n} C_M yi + \sum C_O yi \qquad (2.8)$$

where:
$y = 1 \div m$ – number of BOM levels,
$i = 1 \div n$ – number of components in the BOM level,
C_M – material direct cost of the BOM level,
C_O – operation direct cost of the BOM level.

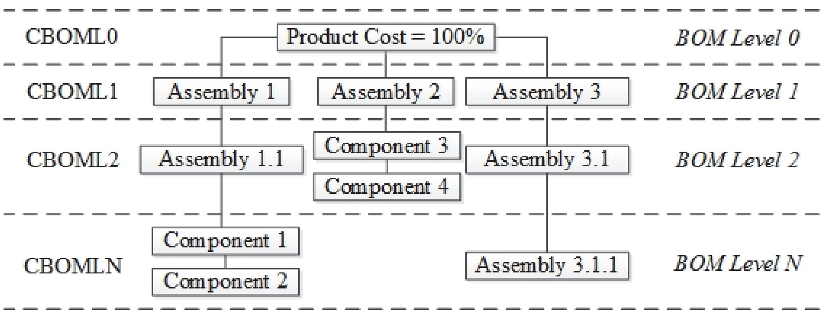

Figure 2.2. Product BOM structure

Cost Weighted Factor of RPN (CWF_{RPN}) calculation: Based on the previous step where C_{MO} and C_{BOMLN} were calculated, next, CWF_{RPN} per every failure, operation, work centre and BOM level should be calculated that shows the financial impact on the final product. To calculate CWF_{RPNFOW} per failure, operation, work centre Equation (2.9) should be applied. To calculate $CWF_{RPNBOMLN}$ per the BOM level, Equation (2.10) should be used.

$$CWF_{RPNFOW} = \frac{C_{MO}}{C_{BOML0}} \times \sum RPN_{Real} \qquad (2.9)$$

$$CWF_{RPNBOMLN} = \frac{C_{BOMLN}}{C_{BOML0}} \times \sum RPN_{Real} \qquad (2.10)$$

where:
CWF_{RPNFOW} – CWF of RPN per failure, operation and work centre,
$CWF_{RPNBOMLN}$ – CWF of RPN per BOM level N,
C_{MO} – direct Cost Of Material and Operation,
C_{BOMLN} – Cost of Bill Of Materials (BOM) of level N,
C_{BOML0} – upper BOM level that equals 100% of the product direct cost,
$\sum RPN_{Real}$ – sum of real RPN per failure, operation, work centre and the BOM level.

2.2.4 Measure in TOC

The purpose of the TOC phase in this research is to elevate system constraint by eliminating failures that enables a decrease in operation *CT* and an increase in production orders *TH*. As a result, this improvement will increase product **Delivery KPI**.

In the TOC phase the Process Constraint (PC) of the production process should be identified, for instance, the PC of the specific product type or a general production system. The PC can be identified, for example, by identifying high *CT* of operations. It can be identified by applying simulation software using the real data from the production floor or by experience observations of production managers and engineers. Further, the PC should be elevated by decreasing the operation *CT* by reducing the RPN_{Real} values of failures or eliminating them all in the operation. This improvement, as mentioned earlier, increases the process/product *TH* (see Analyse in TOC) (Sahno et al., 2015). To calculate the *TH*, Equation (1.1) should be used.

2.2.5 Comparison of KPIs in AHP

In order to define which KPI is more important for improvement of some particular product and/or customer, the AHP approach can be employed. The AHP nine-scale approach is used to compare KPIs in a pairwise way. Every pair of KPIs is compared to define the relative importance with respect to others. Table 1.1 shows the AHP assessment scale of every level from 1 to 9. Figure 2.3 presents an example of the AHP assessment scale where various KPIs should be compared.

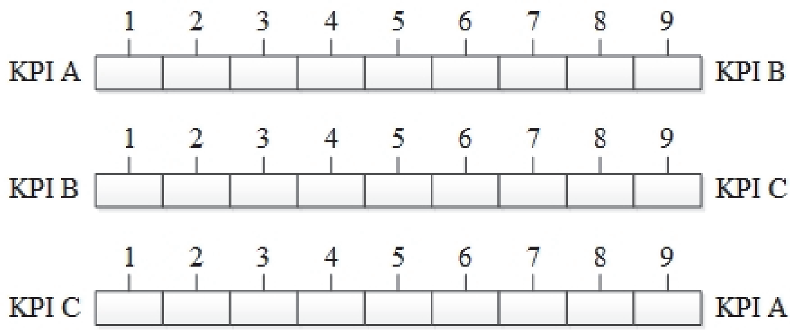

Figure 2.3. An illustration of the AHP comparison scale for KPIs

2.2.6 Summary of Measure Step

Figure 2.4 shows the summary of the Measure step where the new framework process is shown that depicts the inputs of the product production process and the failures that can occur. For example, a product contains components and sub-components and until the lower level is reached. The components are processed in work centres, which have inputs – materials and operations. The operations have failures assigned from the FC and are assessed by RPN_{Real} values in the FMEA that enables calculation of the *PY* and definition of the *PSPL*. In addition, the FMEA is the place for monitoring of the Quality KPI and it is the basis for the next phases: FCC and TOC.

To improve the Quality KPI and increase *PSPL*, the RPN_{Real} values of failures should be decreased or eliminated. To improve the direct Cost KPI, the RPN_{Real} value of failure in the FMEA that influences CWF_{RPN}, the latter should be decreased or eliminated. To improve the Delivery KPI, the *TH* should be increased by decreasing or eliminating RPN_{Real} values of failures in the FMEA that influence the *CT* in the process constraint. In other words, the lower the RPN_{Real} value and/or number of failures, the higher the KPIs are. Further, in the AHP, the KPIs should be compared and identified where it is necessary firstly to improve the production process to improve a specified KPI.

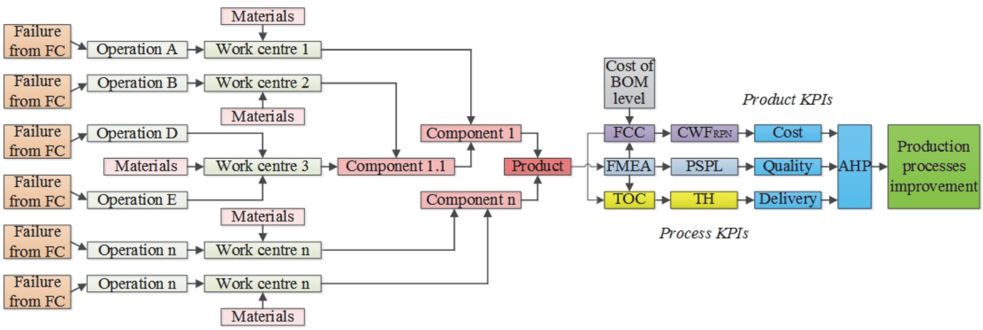

Figure 2.4. Summary of the Measure process

2.3 Actions in Analyse step

The outcome of the Measure step enables to perform the analysis of the production process/product and the general production system in a different way in FMEA, FCC and TOC phases as described below.

2.3.1 Analyse in FMEA and FCC

Based on the received results in FMEA and FCC from the Measure step, a Chart for CWF_{RPN} and the Pareto Chart should be built and their observation and comparison should be made (Sahno et al., 2015).

Chart for CWF_{RPN}***,*** C_{MO} ***and*** RPN_{Real} ***creation:*** This chart should be built for an operation using CWF_{RPN} and C_{MO} from FCC and RPN_{Real} value from the FMEA. This chart should visually show which operations in the process/product have a high RPN_{Real} value, C_{MO} and CWF_{RPN} compared to other operations.

Pareto Chart creation: This chart should be built based on the calculated RPN_{Real} values from the FMEA and CWF_{RPN} from the FCC that indicates the most critical failures in the production process. Further, these charts can be compared as follows. They indicate that the failures of these charts are located in different sequences. The Pareto chart based on RPN_{Real} from the FMEA shows a failure sequence that influences the Quality KPI. The Pareto chart based on CWF_{RPN} from the FCC shows a failure sequence that influences the direct Cost KPI. As a result of comparison of these charts, an engineer can make a decision which KPI is more important for some specified product type or for a general production system or for some customer (Sahno et al., 2015).

2.3.2 Analyse in FMEA

Using RPN_{Real} values from the FMEA, the process variability of component name, work centres, operations, failure group and failure cause can be observed in the following way (Sahno et al., 2015):

Component Name: A specific component should be selected, which shows in which work centre it is produced, by what operations and what the failures are; it shows minimum, maximum and average RPN_{Real} value for the specific component and which product type is used.

Work Centre: A specific work centre should be selected, which shows which operations and failures it has; it shows minimum, maximum and average RPN_{Real} value for the specific work centre and the BOM level and the product type.

Operation: A specific operation should be selected, which shows which failure types it has and in which work centre, BOM level and product type it was used. In addition, for example, some specific operation in the process can be selected and minimum, maximum and average RPN_{Real} value calculated, or all existing operations selected and most problematic operation with high RPN_{Real} value defined.

Failure Group and/or Failure Cause: Failure Causes (sub-groups) should be grouped according to their main Failure Group. Further, the specific failure variability by RPN_{Real} value it has can be seen. It can be observed in what operation, work centre, BOM level of the product that specific failure exists. In addition, minimum, maximum and average RPN_{Real} value of the failure for the process can be calculated.

2.3.3 Analyse in FCC

The analysis in the FCC should be performed using the following example. A BOM level has 10% of the direct cost of the final product and it has high RPN_{Real} values and at the same time, there is another BOM level, which has 20% of the direct cost of the final product and it has the same RPN_{Real} values or may be even lower, then, a decision for BOM level should be made that has higher direct cost. In other words, the CWF_{RPN} indicates the cost weight of failures, operations and BOM levels of the final product. This kind of cost weighted factor assessment allows engineers to pay attention to more important problems, which have financial impact on the final product. This approach allows decreasing the amount of scrap, as a result, it enables saving money and increasing company revenue.

The example above may have exceptions. For instance, if a direct cost of some BOM level is 10% of the final product cost and it has high RPN_{Real} values, but it does not influence entire product quality, e.g. a scrap component can be replaced or demounted from the design point of view, then, in this case, the financial impact will be low. Another example, if a direct cost of the BOM level is 10% of the final product cost and it has low RPN_{Real} values, but it can influence entire product quality, e.g. the scrap component cannot be replaced or demounted from the final product, as a result, an entire product may go to scrap, so the financial impact will be high. In this case, improvements should be made for the BOM level, which has high financial impact on the final product (Sahno et al., 2013).

2.3.4 Analyse in TOC

In order to identify which department (work centre) is a constraint for the process, it is necessary to build the Swimline diagram with the data of the production process, such as a PR card (work centre, operation name and time), the data from FC (failures), the FMEA (RPN_{Real} value) and the FCC (CWF_{RPN} value) should be presented on the Swimline diagram, as shown in Figure 2.5. The Swimline diagram must show the RPN_{Real} and CWF_{RPN} value per every failure, operation and work centre. According to the operation *CT*, it can be identified by a PC.

This kind of process visualization allows better understanding of which failures should be improved or eliminated, in particular department (work centre) or operation to decrease *CT* that consequently increases the process *TH* and increases the product Delivery KPI (Sahno et al., 2015).

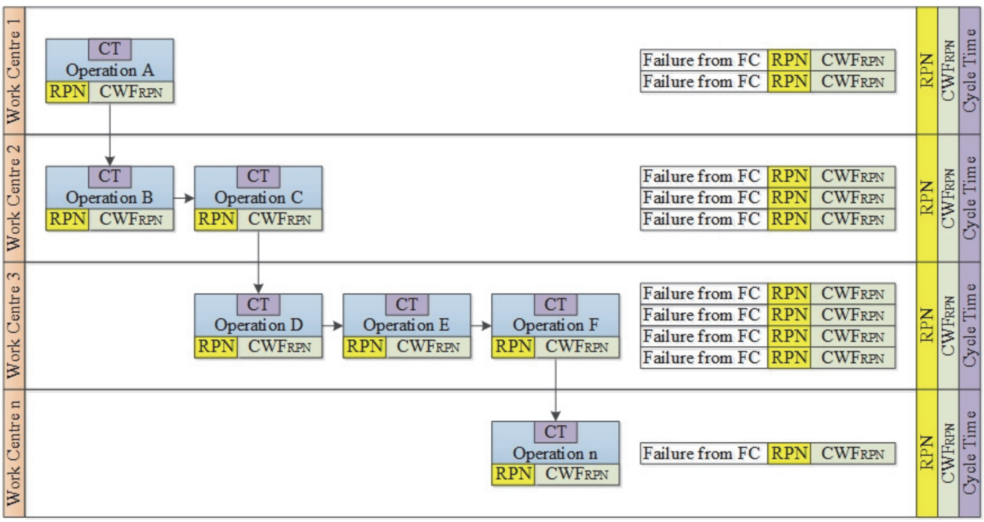

Figure 2.5. Swimline process for TOC

2.4 Actions in Improve step

Perform corrective actions are based on the results from previous steps (measure, analyse): generate various potential solutions and select the best one, assess the effect of the solution (identify which KPI is more important for the particular product or for a general production system or for a customer), implement solution (reduce the RPN_{Real} value for a harmful failure in operation or eliminate them completely). The more reliable the production process, the less process variability, the fewer defects and failures or RPN_{Real} values are in the process. From here, the higher the product quality, the lower the financial losses of the product and the lower the product cost, the higher the product quality, delivery and therefore the higher the KPIs are. In case the improvement requires financial investment, it is necessary to calculate how soon the investment starts to pay off (when the break-even point starts).

When the corrective actions are applied, an engineer should follow them by performing *"mini DMAIC"* process as follows:

- Define the object of study that is something that has been corrected or improved.
- Measure the improved process by assigning failures from the FC and assessing RPN_{Real} in the FMEA.
- Analyse processes and decide where and what corrective actions are necessary to carry out.
- Improve process (if needed).
- Control improvements made in daily processes if the process requires repetition of an improvement, then repeat the *"mini DMAIC"* process again until the changes satisfy.

If the changes made are good enough and do not require any corrective actions, then proceed to the improvements with other processes.

2.5 Actions in Control step

Ensure that the implemented solution is working by applying the *"mini DMAIC"* process. If the changes made are good enough and do not require any more corrective actions, then proceed to the improvements with other processes. Document, apply, sustain and monitor improvements made in the real processes of everyday production.

2.6 Summary of the QCD framework

This section demonstrated the new framework for continuous improvement of production processes using the Six Sigma DMAIC methodology. The framework enables assigning the failure type for an operation during the production process using the FC. Further, these failures are assessed in the FMEA that enables calculation of *PY* and definition of *PSPL* that show the general level of the process/product quality influencing the product Quality KPI. Based on the data from the FMEA and C_{MO} calculation in the FCC, financial impact of failure (CWF_{RPN}) on the final product cost that influences the Cost KPI should be calculated. In the TOC phase, PC should be identified and elevated by reducing operations *CT*, as the result this improvement will influence the product Delivery KPI. Finally, thanks to the received results and the AHP approach, an engineer can make a decision about which the KPI necessary to improve for some specified product in the production processes or which KPI is more important for a general production system, company and customer. Below is a brief summary of the framework:

- Improve the product Quality KPI by eliminating failures in the FMEA, which have high RPN_{Real} values in operations, work centres, semi-products, or final product that do consume needed resources and do not bring value for the customer.
- Improve the product Cost KPI by eliminating failures in the FMEA that cause high CWF_{RPN} values in operations, work centres, semi-products or final product. This approach allows concentrating on the failures that cause unnecessary financial losses.
- Improve the product Delivery KPI by eliminating operation failures in the FMEA that are found in a PC. By decreasing RPN_{Real} value of failure or eliminating them all, the operation *CT* decreases, which in turn increases the process *TH* of the constraint (work centre).

3. DEVELOPMENT OF DATA MART FOR THE NEW FRAMEWORK AND IDENTIFICATION OF NEEDED INFORMATION SYSTEM SOURCES

3.1 Data Mart development and description

One of the purposes of this research is to develop a framework that allows continuously improve production process KPIs, which influence product KPIs. In order to monitor production processes performance (e.g., based on the data for the previous day) the Data Mart was developed for the presented framework that will play the role of a *"dashboard"*. The purpose of this Data Mart is to collect and store product and production data from various sources, e.g., an ERP system, then calculate the needed KPIs (*PSPL*, CFW_{RPN} and *TH*) and analyse them. The developed Data Mart allows data collection from various sources and creating necessary reports for engineers, management and decision makers (Sahno et al., 2011).

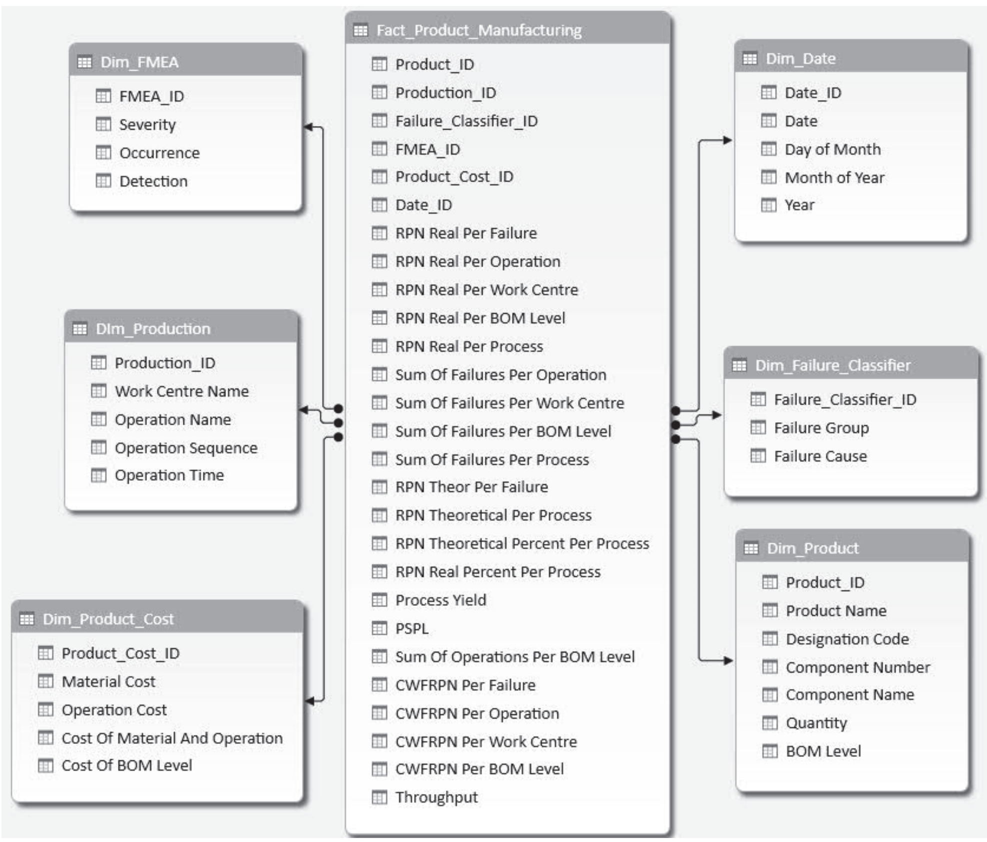

Figure 3.1. Dimensional model of the Data Mart

The functionality of the Data Mart allows analysis of the production processes by creating various charts and diagrams that enable understanding and making decisions of which failures should be improved or eliminated to increase the KPI performance for some specified product, a general production system or a customer.

Figure 3.1 illustrates the dimensional model of the Data Mart structure based on the Kimball bottom-up data warehouse design methodology (Kimball and Ross, 2002) that was created in Microsoft Office PowerPivot for Excel 2013. This dimensional model contains data about concepts that are part of the manufacturing process. The dimensional model consists of the fact table (*Product Manufacturing*) and six dimension tables: *Product*, *Production*, *Failure Classifier*, *FMEA, Product Cost* and *Date*. The dimensional model provides an easily communicable medium between people who understand the manufacturing process and IT workers who develop the software. It also provides the actual database structure of the Data Mart.

3.2 Description of Information System environment for the Data Mart

This section describes how the Data Mart can be applied in the IS architecture with the PDM, ETL and ERP system presented in Figure 3.2. The process starts from a CAD system (not shown in the figure, but is a part of the PDM environment) where a design engineer creates a new product/item. Along with CAD models and drawings, the engineer defines Item Data in the PDM system. The item Data contain different attributes that are *"packed"* under a general Designation Code *("XYZ")*. The ERP system contains templates – Reference Items – that simplify the creation of new items. It contains various ERP-specific parameters – Reference Item Data – that are identified by a unique Reference Item Code *("REFITEM**P/S**XYZ")*. In the current example, this coding is divided into three parts. The first part (prefix) **"REFITEM"** marks that this is a template, not some particular item in the ERP system. The second part implicates the procurement type of the item, where ***"P"*** is for in-house produced items and *"**S**"* for subcontracted or purchased items. The last part – Designation Code, for example ***"XYZ"*** – is an item key that is used to logically connect data between the PDM and ERP systems. Each specific item or a group of items has its own unique Designation Code. When the product design is finished in the CAD system and approved in the PDM, the engineer starts to send the product BOM structure to the ERP system using the specified workflow.

The ETL system transfers the Designation Code and the accompanying Item Data from the PDM (arrows labelled by 1 and 2), finds a Reference Item Code by a matching Designation Code (along with the set of Reference Item Data from the ERP) and copies them into ERP Master Data (arrows 3 and 4) (Sahno et al., 2012; Sahno et al., 2013). The last step (arrow 5) is presented in Figure 3.3 in more detail.

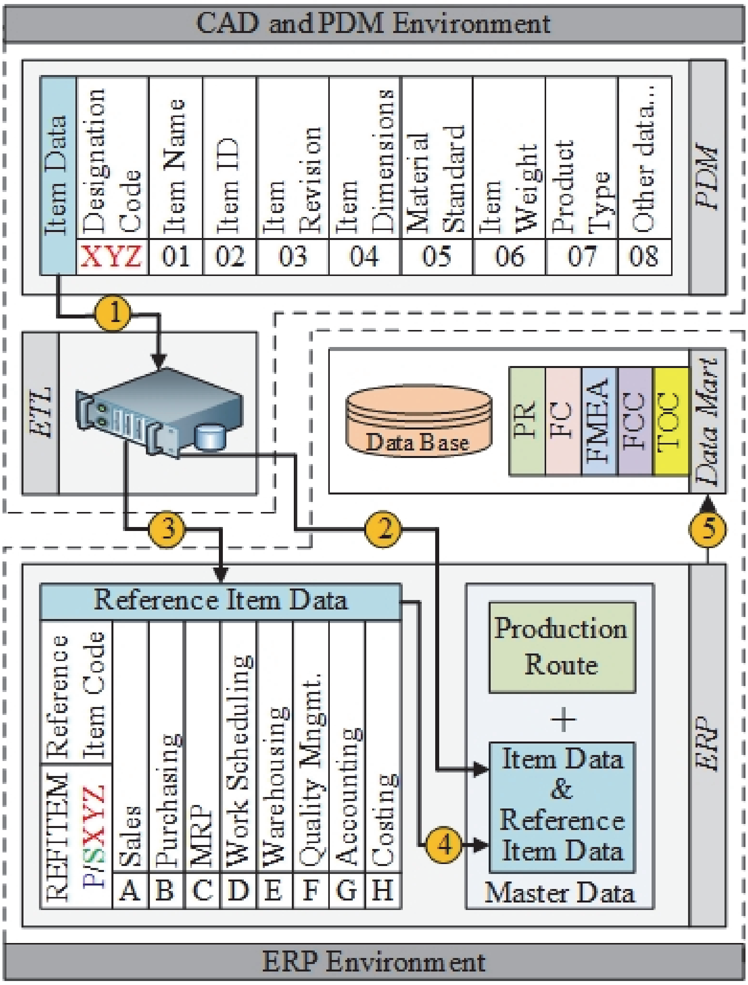

Figure 3.2. Information system architecture

Figure 3.3 shows data flow from the PDM to the ERP system and then to the Data Mart. Such data as PR, FC (failures), scrap (Occurrence), FMEA (Severity, Occurrence and Detection) and product direct cost are transferred. Based on these data, in the Data Mart, the process KPI – *PSPL* in the FMEA, CWF_{RPN} in the FCC and *TH* in the TOC are calculated, which influence Quality, Cost and Delivery KPI. Further, using the AHP approach a comparison of KPIs should be made that enables definition of which KPI is more important for some specific product type or for the customer. When the important KPI is identified, using the functionality of the Data Mart, an analysis of the process should be made and which failures are more harmful for the process identified and what corrective actions should be applied for improvements. When the improvements are made, and they satisfy, the cycle of continuous improvement should be proceeded.

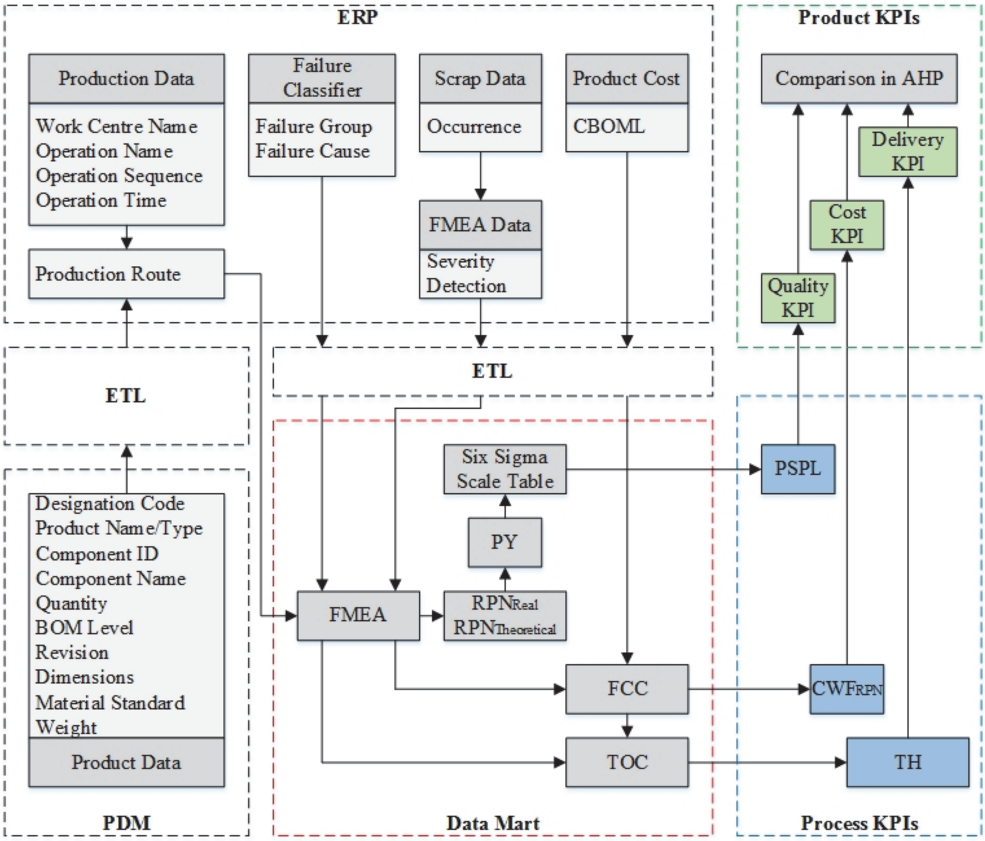

Figure 3.3. Information system architecture and data flow

Figure 3.4 shows the algorithm of the IS architecture where the input data, processing of the data and the output of the process are described. In addition, Table 3.1 shows 17 steps of the Data Mart algorithm that refer to the sections which describe every step in more detail.

According to the ISA-95 standard, the tools/components of the new framework have the following levels:

Level 4 – Data Mart reports,
Level 3 – ERP system,
Level 2 – FMEA data,
Level 1 – missing in the current framework,
Level 0 – the physical production process.

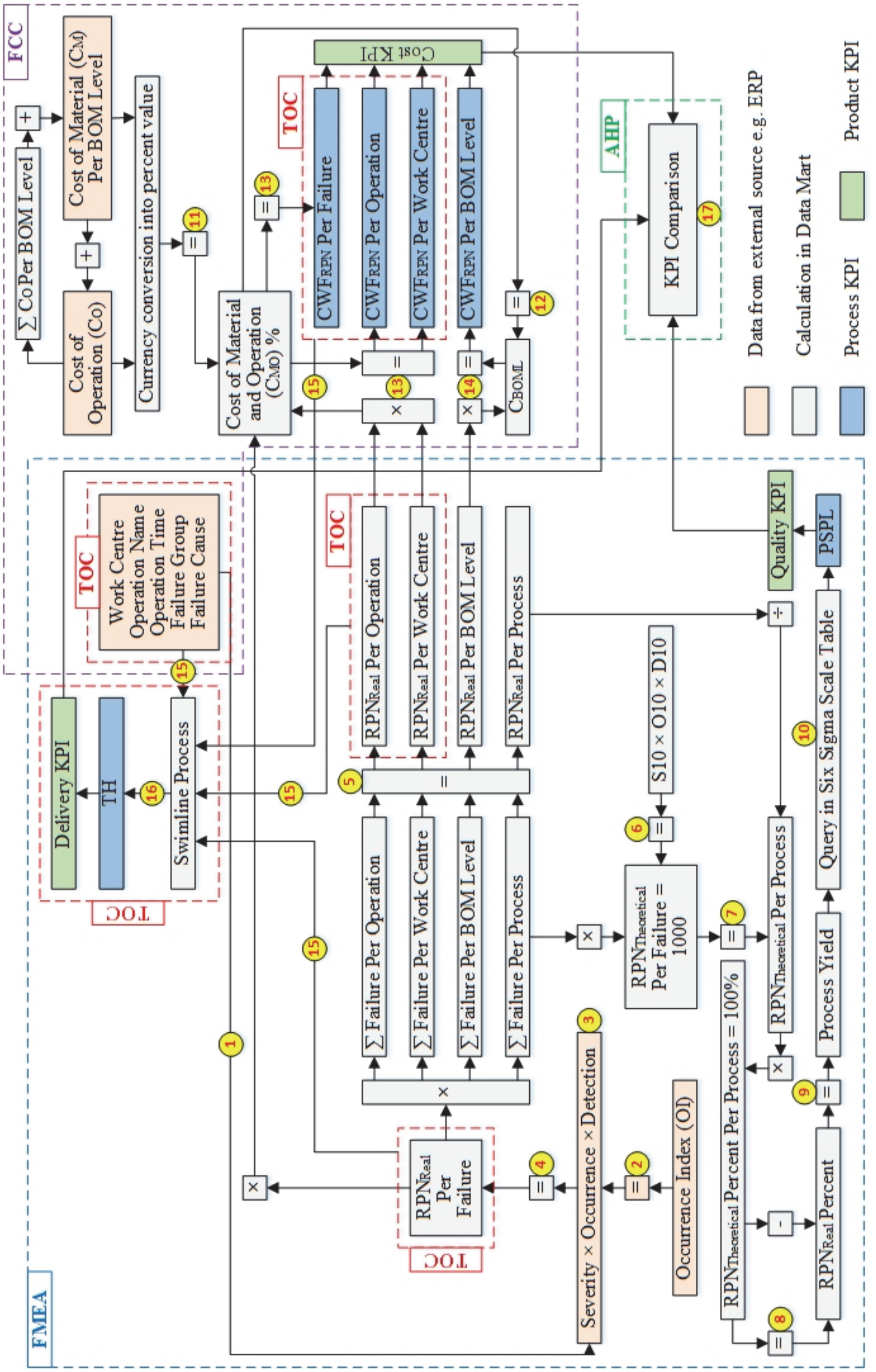

Figure 3.4. Data Mart algorithm

Table 3.1 Summary of the Data Mart algorithm

No.	Activity	Section
1	Problematic process definition Failure assignment and measurement	2.1 Define 2.2.1 Measure in FC
2	Occurrence Index calculation and Occurrence rating assessment	2.2.2 Measure in FMEA
3	Severity and Detection rating assessment in an external source, e.g. in the ERP system	
4	RPN real *(RPN_{Real})* value per failure, calculation	
5	RPN real *(RPN_{Real})* value per operation, work centre, BOM level and process calculation	
6	Theoretical RPN *($RPN_{Theoretical}$)* value calculation	
7	Theoretical RPN *($RPN_{Theoretical}$)* per process calculation	
8	RPN_{Real} percent calculation	
9	Process Yield (*PY*) calculation	
10	Process/Product Sigma Performance Level *(PSPL)* calculation Average *PSPL* calculation	
11	Cost of Material and Operation *(C_{MO})* calculation and conversion into percent value	2.2.3 Measure in FCC
12	Cost of BOM Level *(C_{BOML})* calculation	
13	Cost Weighted Factor of RPN *(CWF_{RPN})* per failure, operation and work centre calculation	
14	Cost Weighted Factor of RPN *(CWF_{RPN})* per BOM level calculation	
15	Create Swimline process based on the data from PR (work centre, operation name, operation time, failure group and cause); from FMEA (RPN_{Real} per failure, operation, work centre); from FCC (CWF_{RPN} per failure, operation, work centre)	2.2.4 Measure in TOC
16	Identify process constraint by operation Cycle Time (*CT*) in the work centre and calculate process Throughput (*TH*)	
17	Compare KPI using AHP and identify which KPI has priority for improvement from the customer point of view	2.2.5 Comparison of KPIs in AHP

A detailed description of that Data Mart algorithm with equations is presented in Appendix.

4. COMPUTATIONAL EXPERIMENT

In this research a computational experiment of the new framework in the Six Sigma DMAIC structure and the Data Mart for continuous improvement of the production processes is checked with the production data from a manufacturing company. The computational experiment was made on a *"Wind Power Generator A"* product that is used in windmills for generation of energy. This product the assembly of which consists of some sub-assemblies is presented in Figure 4.1 in the form of the BOM structure. With reference to this computational experiment, the author indicates Figure 4.12, which shows the report of the presented framework from the Data Mart.

4.1 Actions in Define step

One of the original contributions of this research is to identify a problematic **process** and the main **KPIs** that should be continuously improved.

Process: The problematic process is displayed in the form of Production Route (PR) card with the *"Wind Power Generator A"* product. The PR consists of two parts (see Figure 4.12): Product Data which contain product name to be produced, BOM levels of the product, component ID and name, designation code used for the IS architecture (see Figure 3.2) and quantity to be produced; Production Data which contain work centre name where the component is to be processed, operations name, its sequence, and operation time.

KPI: Today, to find out which KPIs are important for the customer, companies use survey techniques and questionnaires that enable definition of them. In most cases, companies and customers calculate KPI metrics using their own algorithms, for example, based on received reclamations from the production floor or the customer. Taking into account the considerable complexity of the manufacturing sector, this research focused on three KPIs – product Quality, Cost, and Delivery. The calculation of these KPIs is described below.

Quality metric is a calculation of the amount of quality delivered units versus the amount of non-quality units. For instance: Company received 10 units. The order has 2 defect units. The Quality metric for this order is 80%. Calculation: Number of quality units received / Total number of ordered units (8/10 = 80%).

Delivery metric is a calculation of the amount of units delivered on time versus the amount of units ordered. For instance: Customer orders 10 units. The order has a requested delivery date of May 1. The company delivers 7 units on time, the remaining 3 units on May 10. The delivery metric for this order is 70%. Calculation: Number of orders delivered on time (or before the requested date) / Total number of ordered units (7/10 = 70%).

Cost metric is very important for any company that wants to increase their revenue, therefore in this research the goal is to increase company revenue or improve direct cost metric by means of improving reliability of production processes (Quality and Delivery KPIs) that in turn directly influence the Cost KPI.

The product KPI metrics have been identified and evaluated. Further, the application of the new framework is presented with production related data that explain how the **process** KPIs that influence **product** KPIs, are calculated.

4.2 Actions in Measure step

In the Measure step, different tools (FC, FMEA, FCC, TOC and AHP) are discussed.

4.2.1 Measure in FC

The Failure Group and the Failure Cause in FC for each operation during the production process (see Figure 4.12) are defined.

4.2.2 Measure in FMEA

In the FMEA every failure is assessed by Severity, Occurrence and Detection rating, which gives the RPN_{Real} value. The RPN_{Real} value is calculated for every failure, operation, BOM level and process/product. An example of the assessment of Severity, Occurrence and Detection is presented below.

Severity assessment: Severity rating is defined according to the Severity scale that indicates the effect of a failure; it is based on the knowledge and experience of the team members (MacDermott, 1996).

Occurrence assessment: This rating is intended for the assessment of failure frequency in the production process (MacDermott, 1996) and in this computational experiment the following example is applied; the production line passed 500 units of a components during one month on operation *"OpA"* in the work centre *"W1"*. From 500 units, 1 unit has a failure cause – *"7C. Defective material"* that is in the failure group – *"7. Supplier problem"*. To define Occurrence rating, the Index of Occurrence *(I_O)* should be calculated first using Equation (2.1), which shows that 0,2% of failures occur each month. Then, using this index, the Occurrence rating can be defined using Table 1.3, which shows that 1 scrap in 500 units is equal to 6 points of Occurrence rating – moderate (Sahno et al., 2015).

$$I_O = \frac{1}{500} \times 100\% = 0,2\%$$

Detection assessment: The purpose of this rating is to detect the failure before it happens on the customer side. Before the failure happens, parameters of the product to be checked should be specified. The specified parameters of these units should be checked according to the customer needs. Before testing an item, parameters which the customer needs to be tested should be defined beforehand, and if there are flaws, they should be defined and eliminated. If the failure was defined in further production stages or by the customer on his side, the Detection value will increase (MacDermott, 1996).

The following example describes measurement tool rating. For instance, the weld crack detection or Non-Destructive Test (NDT) can be done by magnetic flow detection or ultrasonic test or even by radiography detection; surface measurement can be done by a simple measurement tool, sliding calliper or laser tracker; voltage test can be tested by a voltage tester; or inspection can be done simply visually. If a high level detection tool like a radiography device or a laser tracker is used, then the rating may be equal to 1 point if visual inspection is used, the rating may reach up to 10 points. In other words, the more precise the tool, the lower the Detection rating in the FMEA is.

RPN real (RPN_{Real}) value per failure calculation: By multiplying the three factors (S×O×D), the RPN_{Real} value is calculated for each failure using Equation (1.3) and data from Figure 4.12.

RPN real (RPN_{Real}) value per operation, work centre, BOM level and process calculation: The sum of the RPN_{Real} value is calculated by summing up RPN_{Real} values per failure. For instance, 164 points per operation *"OpB"*; 272 points per work centre *"W1"*; 608 points per BOM level *"1"*; 2000 points per process (Figure 4.12).

Theoretical RPN ($RPN_{Theoretical}$) per process calculation: To calculate the $RPN_{Theoretical}$ per process, the number of failures that occurred in the process should be counted and multiplied by $RPN_{Theoretical}$ per failure (1000 points). Figure 4.12 shows the process of three assemblies or BOM levels – *"1"* (Balanced Rotor, Connected Stator and Frame) and Assembled Generator or BOM level – *"0"* that are processed in work centres. The process has 12 operations with 20 failures that occurred where every failure is equal to 1000 points (10×10×10). The sum of $RPN_{Theoretical}$ value per process for the *"Wind Power Generator A"* can be calculated using Equation (2.2) that is equal to 20000 points. This value is used to define the scope of the common production process that is equal to 100%.

$$\sum RPN_{Theoretical} = 20 \times 1000 = 20\ 000$$

RPN_{Real} percent calculation: After calculating the sum of RPN_{Real} (2000 points) and $RPN_{Theoretical}$ (20000 points) value for the process or product, these values can be used to calculate RPN_{Real} percent per process using the Equation (2.3).

$$RPN_{Real}\% = \frac{2000}{20000} \times 100\% = 10\%$$

Process Yield (PY) calculation: The above results show that RPN_{Real} per process is equal to 2000 points that makes 10% from the $RPN_{Theoretical}$ value of 20000 points. If the RPN_{Real} is equal to 10%, then the *PY* can be calculated using Equation (2.4), extracting the RPN_{Real} per cent (10%) from the $RPN_{Theoretical}$ per cent (100%).

$$PY = 100\% - 10\% = 90\%$$

Process/Product Sigma Performance Level (PSPL) definition: As the *PY* is equal to 90%, according to the sigma performance scale in Table 1.6, the *PSPL* for the current process or product equals **2,78σ**.

Average PSPL calculation: A company produces 5 products and every product has its own *PSPL*, an average *PSPL* for all products can be calculated using the Equation (2.5). The *PSPL*s should be summed up and divided into 5 products. As the result, the average *PSPL* is **2,8σ**.

$$PSPL_{Average} = 2.78 + 2.9 + 2.7 + 3 + 2.6 \approx \mathbf{2{,}8\sigma}.$$

4.2.3 Measure in FCC

The FCC phase in this research is divided into two parts: in the first part C_{MO} and then C_{BOML} are calculated, which is the basis for the second part of CWF_{RPN} calculation.

Cost of Material and Operation (C_{MO}) calculation and conversion into percent value: The direct cost of the finished product is 50 000€, the direct cost of BOM level 1 – *"Balanced Rotor"* is 13 000€ that includes 12 500€ of C_M and 500€ of C_O. In order to calculate C_{MO}, Equation (2.6) should be applied.

$$C_{MO} = 12\ 500 + 500 = 13\ 000€$$

Further, the material cost (12 500€ should be converted from the currency into the percent value using Equation (2.7). It shows that the direct cost of the material – *"Balanced Rotor"* equals 25% (see Figure 4.12). Further, this value is used to calculate CWF_{RPN} per failure, operation and work centre. The same approach should be applied for all materials and operations.

$$C_{MO}\% = \frac{12\ 500 \times 100\%}{50\ 000} = 25\%$$

Cost of BOM Level (CBOML) calculation: Figure 4.1 presents an example of the product BOM structure. From the right side of each BOM level, the value-added operation direct cost *(C_O)* (in per cent value) is defined. For instance, the C_O of the Assembled Generator is 10% from the final product cost, it means that the Connected Stator, Frame and Balanced Rotor assembled together cost 10% of the final product. From the left side, the value-added material direct cost *(C_M)* (in per cent value) is defined, which includes the cost of the BOM of a lower level *($C_{BOMLN-1}$)* because the lower level BOM is the **material/component** (that already has cost) for the upper BOM level. Equation (2.8) and values from Figure 4.1 are used to calculate the direct cost of C_{BOML1} (Connected Stator) and C_{BOML0} (Assembled Generator).

CBOML1: Cost of Connected Stator = Connected Stator *(C_{O1})* + Impregnated Stator *(C_{BOML2})*.

$$C_{BOML1} = \Sigma C_{O1} + \Sigma C_{BOML2}$$
$$C_{BOML1} = 5\% + 45\% = 50\%$$

CBOML0: Cost of Assembled Generator = Assembled Generator *(C_{O0})* + Connected Stator *(C_{BOML1})* + Frame *(C_{BOML1})* + Balanced Rotor *(C_{BOML1})*.

$$C_{BOML0} = \Sigma C_{O0} + \Sigma C_{BOML1}$$
$$C_{BOML0} = 10\% + (50\% + 10\% + 30\%) = 100\%$$

The same approach should be applied for remaining BOM levels and components until the lower level of the product.

Cost Weighted Factor for RPN (CWF_{RPN}) calculation: To calculate the financial impact of failure, operation and work centre on the final product, Equation (2.9) should be used. Below is presented the example for failure cause – 7.C Defective Material; operation – OpA; and work centre – W2.

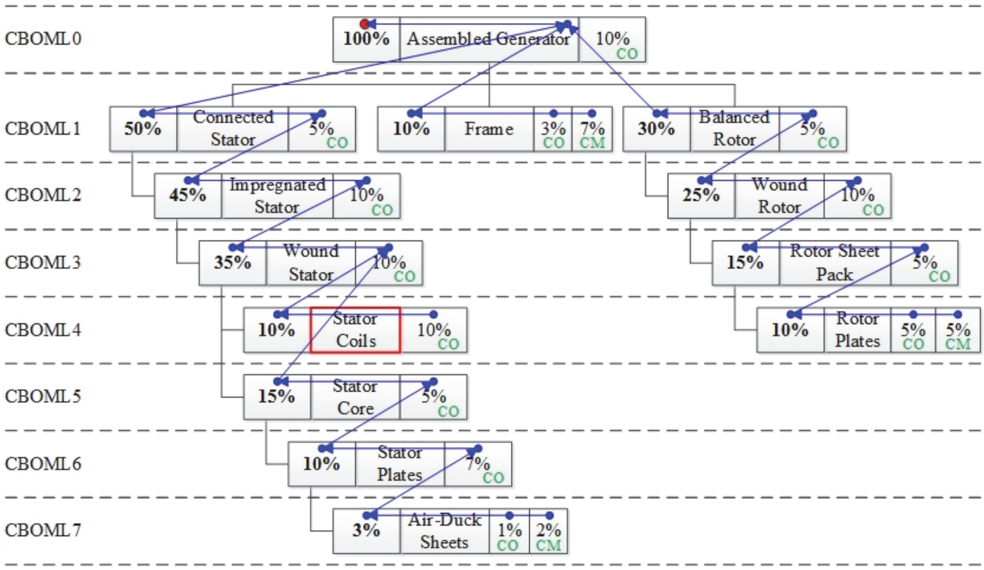

Figure 4.1. Assembled Generator BOM structure

Failure Cause: 7.C Defective material

$$CWF_{RPNFOW} = \frac{26}{100} \times 108 = 28{,}1$$

Operation: OpA

$$CWF_{RPNFOW} = \frac{26}{100} \times (80 + 84) = 42{,}6$$

Work Centre: W2

$$CWF_{RPNFOW} = \frac{28}{100} \times (120 + 120 + 96) = 94{,}1$$

Similarly, applying Equation (2.10) should be used for the BOM level. An example for Balanced Rotor and Connected Stator is presented below.

BOML1: Balanced Rotor

$$CWF_{RPNBOML} = \frac{30}{100} \times (108 + 80 + 84 + 120 + 96) = 182{,}4$$

BOML1: Connected Stator

$$CWF_{RPNBOML} = \frac{50}{100} \times (105 + 72 + 96 + 90 + 128) = 245{,}5$$

4.2.4 Measure in TOC

According to the data from the report of *"Wind Power Generator A"* in Figure 4.12, the Swimline diagram was created in Figure 4.2, which shows that the constraint for the current process is the assembly department (W10). The *CT* in this department is 2 hours (compared with other departments). This department restricts product throughput and it does not allow releasing the required amount of the product (e.g., 6 units) on time. In order to increase the *TH* of this department, for example, additional resources can be added (labour, machines), but in this computational experiment, to increase the *TH* of the constraint, the RPN_{Real} value of failures (at least failures which influence the *TH*) should be decreased or they should be eliminated completely in the constraint. It is first necessary to calculate the *TH* of the constraint using Equation (1.1). The result is: Throughput 5 units. See further explanation in *"Analyse in TOC"* section.

$$TH = \frac{10}{2} = 5$$

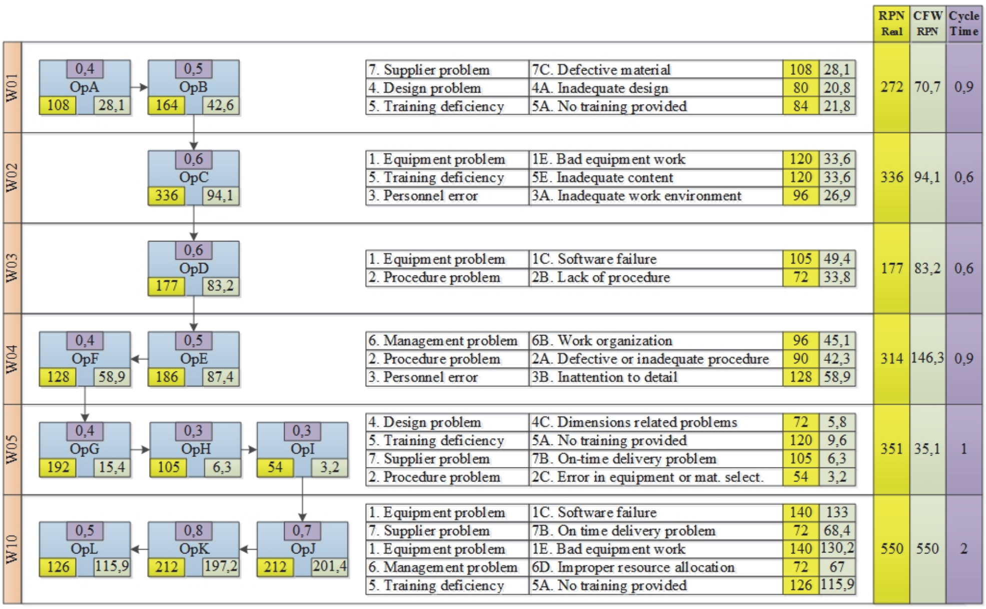

Figure 4.2. Swimline process for "Wind Power Generator A" in TOC

4.2.5 Comparison of KPIs in AHP

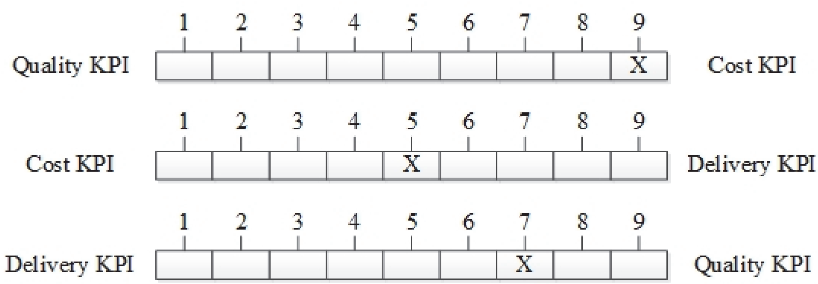

Figure 4.3. AHP assessment scale for Quality, Cost and Delivery KPI

To identify which KPI is more important for *"Wind Power Generator A"*, the AHP approach and Equation (1.2) should be applied. Figure 4.3 presents the scale of the assessment and pairwise comparison of Quality, Cost and Delivery KPI with respect to each other.

The result of the KPI comparison shows that the Quality KPI has a high score (0,9), subsequently this KPI has higher priority for improvement than other factors.

Quality KPI = 9 + 7 = (16 / 18) = 0,9
Cost KPI = 9 + 5 = (14 / 18) = 0,8
Delivery KPI = 5 + 7 = (12 / 18) = 0,7

4.3 Actions in Analyse step

The results from the Measure step enables to create various charts and diagrams, and perform the analysis of the data from FMEA, FCC and TOC phases.

4.3.1 Analyse in FMEA and FCC

Based on the calculated data in FMEA and FCC from the Measure step, various charts are created that allow analyse these results. The Cost Weighted Chart for CWF_{RPN} and Pareto charts are built and compared.

Chart for CWF_{RPN}, C_{MO} and RPN_{Real} creation: Figure 4.4 presents the Cost Weighted Chart for RPN_{Real} per operation from FMEA, for CWF_{RPN} and C_M and C_O from FCC. This chart shows which operations have high RPN_{Real} value (quality), CWF_{RPN} and C_{MO} (direct cost) impact on the final product (e.g., these are operations *"OpJ"* and *"OpK"*). The chart shows that these operations are critical from any point of view (quality and cost) and they have priority for improvement as compared to other operations, for example, visually it can be noticed that the operation *"OpI"* has low RPN value, material/component direct cost and low CWF_{RPN}. In other words, it does not have high impact on the quality and cost of the final product.

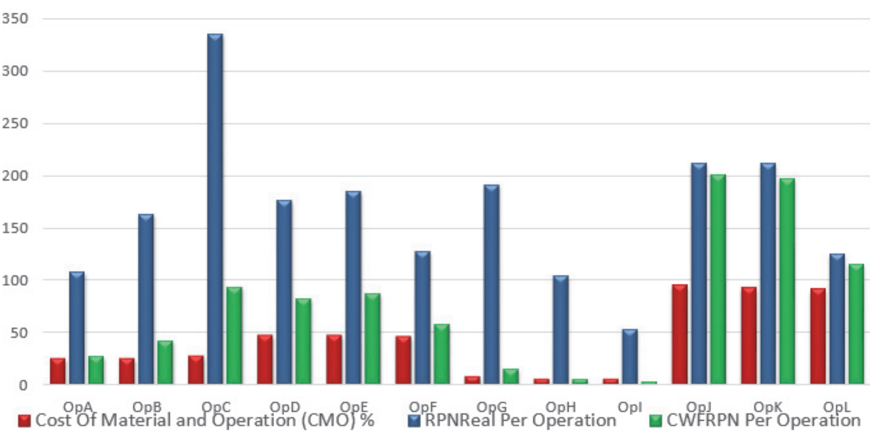

Figure 4.4. Chart for RPN_{Real}, C_{MO} and CWF_{RPN} per operation

Pareto chart creation for RPN_{Real}: Based on the calculated RPN_{Real} values from the FMEA, the Pareto chart per failure is created, which also shows in which operation it happened. The chart presented in Figure 4.5 indicates the most critical failures in the production process from the product quality point of view. Using this chart, an engineer can define which failures should be eliminated or at least where RPN_{Real} values should be decreased in order to improve the *PSPL* that influences the Quality KPI.

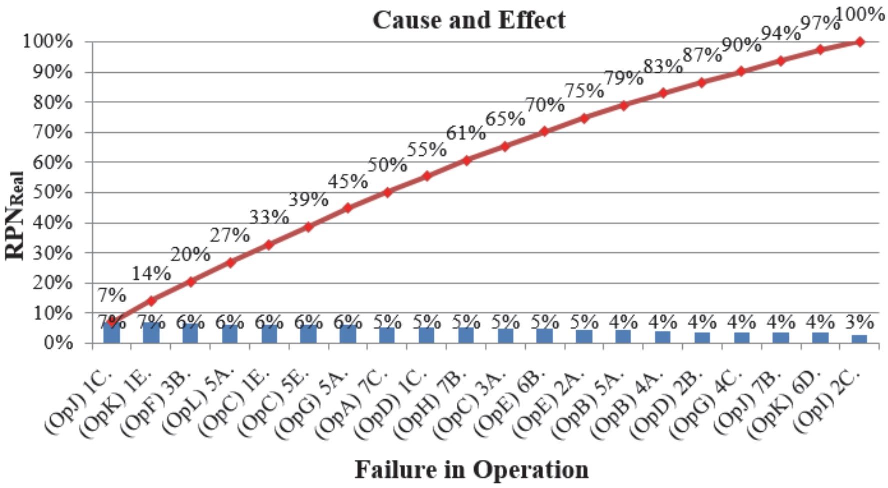

Figure 4.5. Pareto chart for RPN_{Real} of failure per operation

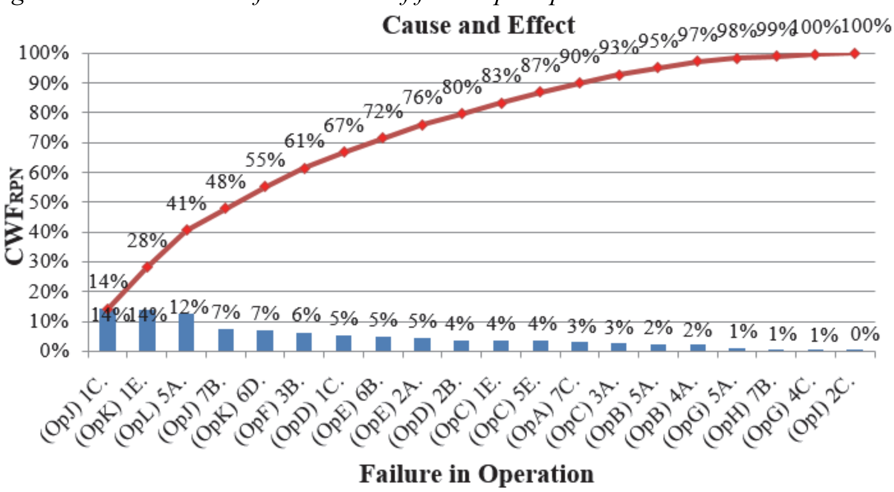

Figure 4.6. Pareto chart for CWF_{RPN} of failure per operation

Pareto chart creation for CWF_{RPN}: Based on the calculated CWF_{RPN} values from the FCC, the Pareto chart for per failure is created, which also shows in which operation it happened (a similar RPN_{Real} is presented in Figure 4.5). The chart presented in Figure 4.6 indicates the most critical failures in the process from the financial point of view. Using this chart, an engineer can define which failures should be decreased or eliminated to improve the product CWF_{RPN} that influences the Cost KPI.

Table 4.1. Summary of failure sequence from Pareto charts

Sequence	RPN_{Real} per Operation	CWF_{RPN} per Operation
1	(OpJ) 1C. Software failure	(OpJ) 1C. Software failure
2	(OpK) 1E. Bad equipment work	(OpK) 1E. Bad equipment work
3	(OpF) 3B. Inattention to detail	(OpL) 5A. No training provided
4	(OpL) 5A. No training provided	(OpJ) 7B. On time delivery problem
5	(OpC) 1E. Bad equipment work	(OpK) 6D. Improper resource allocation
6	(OpC) 5E. Inadequate content	(OpF) 3B. Inattention to detail
7	(OpG) 5A. No training provided	(OpD) 1C. Software failure
8	(OpA) 7C. Defective material	(OpE) 6B. Work organization
9	(OpD) 1C. Software failure	(OpE) 2A. Defective or inadequate procedure
10	(OpH) 7B. Time delivery error	(OpD) 2B. Lack of procedure
11	(OpC) 3A. Inadequate work environment	(OpC) 1E. Bad equipment work
12	(OpE) 6B. Work organization	(OpC) 5E. Inadequate content
13	(OpE) 2A. Defective or inadequate procedure	(OpA) 7C. Defective material
14	(OpB) 5A. No training provided	(OpC) 3A. Inadequate work environment
15	(OpB) 4A. Inadequate design	(OpB) 5A. No training provided
16	(OpD) 2B. Lack of procedure	(OpB) 4A. Inadequate design
17	(OpG) 4C. Dimensions related problems	(OpG) 5A. No training provided
18	(OpJ) 7B. On time delivery problem	(OpH) 7B. Time delivery error
19	(OpK) 6D. Improper resource allocation	(OpG) 4C. Dimensions related problems
20	(OpI) 2C. Error in equipment or mat. select.	(OpI) 2C. Error in equipment or mat. select.

Comparison of these two charts shows that the failures have different sequences. For example, the sequence of failures in the Pareto chart for RPN_{Real} in the FMEA is different from the sequence of failures in the Pareto chart for CWF_{RPN} in the FCC. Table 4.1 presents differences in failure sequence, which show that only the sequence of three failures remained unchanged (1, 2, 20), all other failures are in different sequence. These are operations *(“OpJ”, “OpK”* and *“OpI”*) that have been already mentioned in Figure 4.4. It shows that operations *“OpJ”* and *“OpK”* are very critical from all quality and cost points of view and the operation *“OpI”* has low importance. Based on these results, an engineer, for instance, can make a decision that in the current process it is essential to improve first two operations that influence *PSPL* and CWF_{RPN} indicators and subsequently the Quality and Cost KPIs.

4.3.2 Analyse in FMEA

By applying the RPN_{Real} values from the FMEA, it can be observed that the process variability of the component name, work centres, operations and failures are identified by minimum and maximum RPN_{Real} value per failure. In addition, an average RPN_{Real} value per general production process is calculated. In this computational experiment, an example for a general production system is presented that has five different *“Wind Power Generator”* products (A, B, C, D, E) in the production process. The analysis made for the component name, work centres, operations, failure group and failure cause as presented in the figures below.

Component Name: The production process by the component name Generator (Figure 4.7) is selected and sorted, which shows that it is used for the production of five products (A, B, C, D, E). Also, this component is produced in the work centre “W10” with operations *“OpJ”*, *“OpK”* and *“OpL”* with many failures. In addition, it shows that the minimum RPN_{Real} value is 45 points, maximum 160 points and average 99 points.

Product Data						Production Data				Failure Classifier		Failure Mode and Effect Analysis			
															RPN
Product Name	Designation Code	Component ID	Component Name	BOM Level	Quantity	Work Centre Name	Operation Name	Operation Sequence	Operation Time, H	Failure Group	Failure Cause	Severity (S)	Occurrence (O)	Detection (D)	Failure
A	XYZ	2001	Generator	0	1	W10	OpJ	1	0,3	1. Equipment problem	1C. Software failure	7	4	5	140
										7. Supplier/subcontractor problem	7B. On-time delivery problem	6	3	4	72
							OpK	2	0,4	1. Equipment problem	1E. Bad equipment work	7	5	4	140
										6. Management problem	6D. Improper resource allocation	8	3	3	72
							OpL	3	0,1	5. Training deficiency	5A. No training provided	7	6	3	126
B	VWX	2002	Generator	0	1	W10	OpJ	1	0,3	6. Management problem	6D. Improper resource allocation	6	3	4	72
										1. Equipment problem	1D. Equipment failure	5	3	3	45
							OpK	2	0,4	5. Training deficiency	5E. Inadequate presentation or materials	6	5	4	120
										7. Supplier/subcontractor problem	7B. On-time delivery problem	7	3	3	63
							OpL	3	0,1	3. Personnel error	3C. Violation of requirement or procedure	6	5	3	90
C	HIJ	2003	Generator	0	1	W10	OpJ	1	0,3	5. Training deficiency	5D. Insufficient refresher training	8	5	4	160
										7. Supplier/subcontractor problem	7C. Defective product or material	5	4	3	60
							OpK	2	0,4	1. Equipment problem	1D. Equipment failure	6	5	4	120
										4. Design problem	4C. Dimensions related problems	7	4	3	84
							OpL	3	0,1	2. Procedure problem (Technology)	2A. Defective or inadequate procedure	6	5	4	120
D	TUV	2004	Generator	0	1	W10	OpJ	1	0,3	2. Procedure problem (Technology)	2B. Lack of procedure	6	3	4	72
										1. Equipment problem	1D. Equipment failure	5	3	3	45
							OpK	2	0,4	5. Training deficiency	5E. Inadequate presentation or materials	4	5	4	80
										7. Supplier/subcontractor problem	7C. Defective product or material	6	3	3	54
							OpL	3	0,1	3. Personnel error	3C. Violation of requirement or procedure	6	5	3	90
E	FGH	2005	Generator	0	1	W10	OpJ	1	0,3	1. Equipment problem	1C. Software failure	8	5	4	160
										7. Supplier/subcontractor problem	7B. On-time delivery problem	5	5	4	100
							OpK	2	0,4	3. Personnel error	3C. Violation of requirement or procedure	6	5	4	120
										4. Design problem	4C. Dimensions related problems	7	4	5	140
							OpL	3	0,1	2. Procedure problem (Technology)	2B. Lack of procedure	6	5	4	120
												Minimum			**45**
												Maximum			**160**
												Average			**99**

Figure 4.7. Process analysis per component

Work Centre: The production process by the work centre *"W01"* (Figure 4.8) is selected and sorted, which shows that it is used for the production of five products (A, B, C, D, E). Also, this work centre produces Rotor with operations *"OpA"* and *"OpB"* with many failures. In addition, it shows that the minimum RPN_{Real} value is 60 points, maximum 175 points and average 110 points.

Product Data						Production Data				Failure Classifier		Failure Mode and Effect Analysis			
Product Name	Designation Code	Component ID	Component Name	BOM Level	Quantity	Work Centre Name	Operation Name	Operation Sequence	Operation Time, H	Failure Group	Failure Cause	Severity (S)	Occurrence (O)	Detection (D)	RPN Failure
A	ABC	1001	Rotor	1	1	W01	OpA	1	0,3	7. Supplier/subcontractor problem	7C. Defective product or material	6	6	3	108
							OpB	2	0,5	4. Design problem	4A. Inadequate design	5	4	4	80
										5. Training deficiency	5A. No training provided	7	4	3	84
B	MNO	1004	Rotor	1	1	W01	OpA	1	0,4	3. Personnel error	3C. Violation of requirement or procedure	5	5	4	100
							OpB	2	0,5	5. Training deficiency	5A. No training provided	3	6	5	90
										1. Equipment problem	1C. Software failure	6	4	3	72
C	YZA	1007	Rotor	1	1	W01	OpA	1	0,4	1. Equipment problem	1B. Defective or failed material	7	5	4	140
							OpB	2	0,5	4. Design problem	4A. Inadequate design	5	7	5	175
										2. Procedure problem	2D. Error in tool or cutting data selection	8	5	4	160
D	KLM	1010	Rotor	1	1	W01	OpA	1	0,4	4. Design problem	4B. Drawing, specification, or data errors	5	4	3	60
							OpB	2	0,5	5. Training deficiency	5A. No training provided	3	6	5	90
										1. Equipment problem	1E. Bad equipment work	5	4	3	60
E	WXY	1013	Rotor	1	1	W01	OpA	1	0,4	3. Personnel error	3A. Inadequate work environment	7	5	4	140
							OpB	2	0,5	4. Design problem	4B. Drawing, specification, or data errors	5	6	5	150
										2. Procedure problem	2D. Error in tool or cutting data selection	7	5	4	140
												Minimum			60
												Maximum			175
												Average			110

Figure 4.8. Process analysis per work centre

Operation: It is a selected and sorted production process by the operation *"OpD"* (Figure 4.9) and it shows that it is used for production of five products (A, B, C, D, E). Also, this operation is used for the production of Stator in the work centre *"W03"* with many failures. In addition, it shows that the minimum RPN_{Real} value is 63 points, maximum 140 points and average 97 points.

Product Data						Production Data				Failure Classifier		Failure Mode and Effect Analysis			
Product Name	Designation Code	Component ID	Component Name	BOM Level	Quantity	Work Centre Name	Operation Name	Operation Sequence	Operation Time, H	Failure Group	Failure Cause	Severity (S)	Occurrence (O)	Detection (D)	RPN Failure
A	DEF	1002	Stator	1	1	W03	OpD	1	0,6	1. Equipment problem	1C. Software failure	7	5	3	105
										2. Procedure problem (Technology)	2B. Lack of procedure	8	3	3	72
B	PQR	1005	Stator	1	1	W03	OpD	1	0,6	2. Procedure problem (Technology)	2A. Defective or inadequate procedure	6	4	3	72
										3. Personnel error	3A. Inadequate work environment	7	3	3	63
C	BCD	1008	Stator	1	1	W03	OpD	1	0,6	7. Supplier/subcontractor problem	7A. Communication problems	6	5	4	120
										4. Design problem	4B. Drawing, specification, or data errors	7	4	5	140
D	NOP	1011	Stator	1	1	W03	OpD	1	0,6	7. Supplier/subcontractor problem	7A. Communication problems	6	4	3	72
										3. Personnel error	3B. Inattention to detail	7	3	3	63
E	ZAB	1014	Stator	1	1	W03	OpD	1	0,6	7. Supplier/subcontractor problem	7A. Communication problems	6	5	4	120
										4. Design problem	4C. Dimensions related problems	7	4	5	140
												Minimum			63
												Maximum			140
												Average			97

Figure 4.9. Process analysis per operation

Failure Group: It is a selected and sorted production process by the failure group *"Management problem"*, and Figure 4.10 shows that it is happening for production of five products (A, B, C, D, E). Also, this failure group occurs during the production of Stator, Rotor, Frame and Generator and in various operations. In addition, it shows that the minimum *RPNReal* value is 54 points, maximum 120 points and average 92 points.

Product Data						Production Data				Failure Classifier		Failure Mode and Effect Analysis			
Product Name	Designation Code	Component ID	Component Name	BOM Level	Quantity	Work Centre Name	Operation Name	Operation Sequence	Operation Time, H	Failure Group	Failure Cause	Severity (S)	Occurrence (O)	Detection (D)	RPN Failure
A	DEF	1002	Stator	1	1	W04	OpE	2	0,4	6. Management problem	6B. Work organization/planning deficiency	8	3	4	96
	JKL	2001	Generator	0	1	W10	OpK	2	0,4	6. Management problem	6D. Improper resource allocation	8	3	3	72
B	MNO	1004	Rotor	1	1	W02	OpC	3	0,6	6. Management problem	6A. Inadequate administrative control	5	4	4	80
	PQR	1005	Stator	1	1	W04	OpE	2	0,4	6. Management problem	6C. Inadequate supervision	5	3	5	75
	VWX	2002	Generator	0	1	W10	OpJ	1	0,3	6. Management problem	6D. Improper resource allocation	6	3	4	72
C	YZA	1007	Rotor	1	1	W02	OpC	3	0,6	6. Management problem	6E. Policy not adequately defined, disseminated, or enforced	7	3	5	105
	BCD	1008	Stator	1	1	W04	OpE	2	0,4	6. Management problem	6A. Inadequate administrative control	7	4	4	112
	EFG	1009	Frame	1	1	W05	OpG	1	0,4	6. Management problem	6D. Improper resource allocation	6	5	4	120
D	KLM	1010	Rotor	1	1	W02	OpC	3	0,6	6. Management problem	6B. Work organization/planning deficiency	5	4	4	80
	QRS	1012	Frame	1	1	W05	OpI	3	0,5	6. Management problem	6D. Improper resource allocation	6	3	3	54
E	WXY	1013	Rotor	1	1	W02	OpC	3	0,7	6. Management problem	6A. Inadequate administrative control	5	5	4	100
	ZAB	1014	Stator	1	1	W04	OpE	2	0,5	6. Management problem	6C. Inadequate supervision	7	4	4	112
	CDE	1015	Frame	1	1	W05	OpG	1	0,4	6. Management problem	6D. Improper resource allocation	6	5	4	120
												Minimum			**54**
												Maximum			**120**
												Average			**92**

Figure 4.10. Process analysis per failure group

Failure Cause: It is a selected and sorted production process at the failure cause *"Violation of requirement or procedure"* (Figure 4.11), which shows that it is happening in the production of four products (B, C, D, E). Also, this failure cause occurs during the production of Rotor and Generator in various operations. In addition, it shows that the minimum *RPNReal* value is 90 points, maximum 150 points and average 110 points.

Product Data						Production Data				Failure Classifier		Failure Mode and Effect Analysis			
Product Name	Designation Code	Component ID	Component Name	BOM Level	Quantity	Work Centre Name	Operation Name	Operation Sequence	Operation Time, H	Failure Group	Failure Cause	Severity (S)	Occurrence (O)	Detection (D)	RPN Failure
B	MNO	1004	Rotor	1	1	W01	OpA	1	0,4	3. Personnel error	3C. Violation of requirement or procedure	6	5	3	90
	VWX	2002	Generator	0	1	W10	OpL	3	0,2	3. Personnel error	3C. Violation of requirement or procedure	6	5	5	150
C	YZA	1007	Rotor	1	1	W02	OpC	3	0,6	3. Personnel error	3C. Violation of requirement or procedure	6	5	3	90
D	TUV	2004	Generator	0	1	W10	OpL	3	0,3	3. Personnel error	3C. Violation of requirement or procedure	6	5	4	120
E	FGH	2005	Generator	0	1	W10	OpK	2	0,5	3. Personnel error	3C. Violation of requirement or procedure	6	5	3	90
												Minimum			**90**
												Maximum			**150**
												Average			**110**

Figure 4.11. Process analysis per failure cause

Every production process may consist of many different operations, which operate in a specified order; moreover, these operations can be reused in the same production process. In addition, some specified operation may have different or even the same failure cause and the same or different *RPNReal* value in the same production process and/or in a general production system. In other words, there are many options. This kind of process analysis allows better understanding of which work centres, operations and failures are critical for the general production system. An engineer can identify the worst failures with high RPN_{Real} value and improve or eliminate them. Similar analysis can be done not only for a general production system, but also for some specified product type.

4.3.3 Analyse in FCC

After calculating CWF_{RPN} for both BOM levels (Connected Stator and Balanced Rotor) in the Measure step, the following summary can be made using the data from Figure 4.12. The CWF_{RPN} value for Connected Stator is higher than the CWF_{RPN} value for Balanced Rotor, despite the fact that the Balanced Rotor has more failures and higher RPN_{Real} value per BOM level in FMEA than the Connected Stator. It means that the improvements should be made on the Connected Stator that has high financial impact on the final product.

Exception: In real life, the CWF_{RPN} may have special exception. For example, the direct cost of Rotor Plates (Figure 4.1) is 10% from the Assembled Generator and this component does not influence the entire product quality, e.g., the defected Rotor Plates could be demounted from the design point of view; in this case, it does not have high financial impact on the final product. Another example, if a component can influence the entire product quality, e.g., the scrap component could not be demounted from the final product, from the design point of view, as this may result in entire product scrap. Here are Stator Coils that have high financial impact on the overall product. The total direct cost of this component is 10% from the Assembled Generator cost, but in case it has some undetected failures during the production process, it can cause the burning of the entire product (for instance, on the customer site) – loss of 100% of Assembled Generator. In this case, engineers should pay their attention to the process improvement for this important component.

4.3.4 Analyse in TOC

Using data from Figure 4.12, a Swimline diagram with the data from the PR card (work centre, operation name and time), FC (failures), FMEA (RPN_{Real} values) and FCC (CWF_{RPN} values) was created.

In this computational experiment, the PC is an assembly department (W10) that causes product *TH* restriction. Figure 4.12 allows to understand visually which failures are necessary to improve (decrease RPN_{Real} values of failures) or eliminate to decrease the operations *CT* and increase the product *TH* to improve the product Delivery KPI. Table 4.2 shows the list of failures and their RPN_{Real} values that cause the *TH*. For example, the worst failure groups are *"1. Equipment problem"* and *"5. Training deficiency"*. In order to decrease the operations *CT* and increase the product *TH* of the work centre (W10), it is necessary to improve or eliminate three first failures because their RPN_{Real} values are high (140 points). These failures influence the production process delay (very frequent corrections and idle time) that consequently increases the operations *CT* and decreases the product *TH*.

After the failures are improved or eliminated and the PC elevated in the work centre (W10), the PC can move to another work centre, for example, to the work centre (W05). The same improvement (*CT* reduction by eliminating failures) should be repeated until the next constraint is elevated.

Table 4.2. List of failures in the assembly department for improvement

Failure Group	**Failure Cause**	***S***	***O***	***D***	***RPN_{Real}***
1. Equipment problem	1C. Software failure	7	4	5	140
1. Equipment problem	1E. Bad equipment work	7	5	4	140
5. Training deficiency	5A. No training provided	7	6	3	126
7. Supplier / subcontracting problem	7B. On time delivery problem	6	3	4	72
6. Management problem	6D. Improper resource allocation	8	3	3	72

4.4 Actions in Improve step

After performing comparative analysis of the KPIs using the AHP approach, it is revealed that the most important KPI is the Quality, but in this section examples of the corrective actions for Cost and Delivery KPIs will be presented as well.

Based on the results from the first three steps, an engineer can develop an improvement program that enables to decrease production process variability and number of failures. Below examples of corrective actions for every KPI are given.

To improve the Quality KPI, it is first necessary to determine on what *PSPL* process it operates and which failures are most harmful to the production process (using RPN_{Real} values), i.e., to determine which failures have a negative impact on the quality of the semi-products as well as on the final product. To do this, it is necessary to build the Pareto chart presented in Figure 4.5. This chart shows the most harmful failures (according to the Pareto law 80/20): *"(OpJ) 1C. Software failure"*, *"(OpK) 1E. Bad equipment work"* and *"(OpF) 3B. Inattention to detail"*. These failures are related to the *"Equipment problem"* and *"Personnel error"* failure group. From here it can be summarized that in order to reduce the RPN_{Real} values of these failures or eliminate them completely and increase *PSPL* that influences the Quality KPI, it is necessary to take corrective actions. For example, provide employee required training how to operate a machine, create a simple and clear instruction guide and during the training period provide an experienced operator as the mentor who can help acquire needed experience.

The same approach should be carried out for the Cost KPI. It is necessary to determine which failures are most harmful in the production process from the financial point of view (using CWF_{RPN} values). The Pareto chart presented in Figure 4.6 shows the most harmful failures: *"(OpJ) 1C. Software failure"*, *"(OpK) 1E. Bad equipment work"* and *"(OpL) 5A. No training provided"*. These failures are related to the *"Equipment problem"* and *"Training deficiency"* failure group. As in the previous case, in order to improve the Cost KPI, it is first necessary to reduce the RPN_{Real} values of the failures that influence the high CWF_{RPN} values or eliminate them completely. In that case, as in the previous example, employee training should be provided how to operate a machine, create a simple and clear instruction guide and provide a mentor who can help acquire needed experience during the training period.

From the two examples above, it can be summarized that the cause of poor product quality and financial losses is the lack of operator knowledge and experience. In that case, in order to increase these KPIs, company management should provide required training to the operators to increase their competence.

To improve the product Delivery KPI, a very similar approach should be used. A Swimline diagram created with the required data in Figure 4.12 shows the most harmful failures presented in Table 4.2. This table reveals that there are three failures with a high RPN_{Real} value that are related to *"1C. Software failure"* and *"1E. Bad equipment work"* that both are related to *"1. Equipment problem"* failure group and *"5A. No training provided"* that is related to *"5. Training deficiency"* failure group. These two failures delay the production process (frequent problem corrections, scrap rework, idle time etc.) that increases the process *CT* and decreases the product *TH*. In addition, the repeat problem with equipment causes the company fine (penalty) for the product delayed delivery every month in amount of 10 000€ (120 000€ per year). In order to improve product delivery on-time, it is necessary to increase product *TH* that can be done by replacing old equipment by new one. This solution requires investment into new equipment but at the same time facilitates company to decrease the process *CT*, increase the product *TH* and satisfy the customer by releasing needed quantities of products on-time.

The price of new equipment is equal to 360 000€. As this is the investment (overhead cost), the cost of new equipment pay off or break-even point can be calculated in the following way (360 000 / (12 x 10 000) = 3 years). Thus, the company investment into the new equipment begins to make a profit in just three years. But from the author's point of view, it is more important to have a satisfied customer, as the satisfied customer is willing to make repeat orders, which is very important for the company stability, wellbeing and financial revenue.

When the needed corrective actions are implemented, the *"mini DMAIC process"* should be carried out until the process in the work centre – W10 becomes stable. After improvement of the process, the constraint can move to another work centre, for example, to the work centre – W05. Then, the same procedure (*CT* reduction by eliminating failures and applying corrective actions) should be repeated until the constraint is elevated.

The overall result of the previous paragraph shows that in all cases mainly the same failures related to the *"1. Equipment problem"* failure group. If in the first two cases, the failures affect the quality and direct cost of the product and it can be solved by increasing the competence of the operators, then in the last case, the same failures which affect the product TH can be solved with the acquisition of new equipment. In this computational experiment, it is decided that by combining the two types of solutions into one common, i.e. acquire new equipment and provide training to the operators, this will improve the quality, direct cost and the delivery of the product.

Production Route										Measure		Measure and Analyse														
Product Data						Production Data				Failure Classifier		Failure Mode and Effect Analysis							Failure Cost Calculation							
												Theoretical RPN (RPNTheoretical) and Percent Per Process: 20 000 / 100%											Cost Weighted Factor for Risk Priority Number (CWFRPN)			
															Real Risk Priority Number (RPNReal)											
Product Name	Designation Code	Component ID	Component Name	BOM Level	Quantity	Work Centre Name	Operation Name	Operation Sequence	Operation Time, H	Failure Group	Failure Cause	Severity (S)	Occurrence (O)	Detection (D)	Failure	Operation	Work Centre	BOM Level	Cost of Material (CM) from Product %	Cost of Operation (CO) from Product %	Cost of Material and Operation (CMO) %	Cost of BOM Level (CBOML) %	Failure	Operation	Work Centre	BOM Level
Wind Power Generator A	ABC	1001	Balanced Rotor	1	1	W1	OpA	1	0,4	7. Supplier problem	7C. Defective material	6	6	3	108	108	272	608	25	1	26	30	28,1	28,1	73,4	182,4
							OpB	2	0,5	4. Design problem	4A. Inadequate design	5	4	4	80	164				1	26		20,8	42,6		
										5. Training deficiency	5A. No training provided	7	4	3	84								21,8			
						W2	OpC	3	0,6	1. Equipment problem	1E. Bad equipment work	8	5	3	120	336	336			3	28		33,6	94,1	94,1	
										5. Training deficiency	5E. Inadequate content	6	5	4	120								33,6			
										3. Personnel error	3A. Inadequate work environment	8	2	6	96								26,9			
	DEF	1002	Connected Stator	1	1	W3	OpD	1	0,6	1. Equipment problem	1C. Software failure	7	5	3	105	177	177	491	45	2	47	50	49,4	83,2	83,2	245,5
										2. Procedure problem	2B. Lack of procedure	8	3	3	72								33,8			
						W4	OpE	2	0,5	6. Management problem	6B. Work organization	8	3	4	96	186	314			2	47		45,1	87,4	150,7	
										2. Procedure problem	2A. Defective or inadequate procedure	5	3	6	90								42,3			
							OpF	3	0,4	3. Personnel error	3B. Inattention to detail	8	4	4	128	128				1	46		58,9	58,9		
	GHI	1003	Frame	1	1	W5	OpG	1	0,4	4. Design problem	4C. Dimensions related problems	6	4	3	72	192	351	351	5	3	8	10	5,8	15,4	35,1	35,1
										5. Training deficiency	5A. No training provided	6	5	4	120								9,6			
							OpH	2	0,3	7. Supplier problem	7B. On-time delivery problem	7	3	5	105	105				1	6		6,3	6,3		
							OpI	3	0,3	2. Procedure problem	2C. Error in equipment or mat. select.	6	3	3	54	54				1	6		3,2	3,2		
	XYZ	2001	Assembled Generator	0	1	W10	OpJ	1	0,7	1. Equipment problem	1C. Software failure	7	4	5	140	212	550	550	90	5	95	**100**	133	201,4	550	550
										7. Supplier problem	7B. On-time delivery problem	6	3	4	72								68,4			
							OpK	2	0,8	1. Equipment problem	1E. Bad equipment work	7	5	4	140	212				3	93		130,2	197,2		
										6. Management problem	6D. Improper resource allocation	8	3	3	72								67			
							OpL	3	0,5	5. Training deficiency	5A. No training provided	7	6	3	126	126				2	92		115,9	115,9		
									6																	

RPNReal Per Process	2 000
RPNReal Percent Per Process	10%
Process Yield (PY)	**90%**
PSPL	**2,78σ**

Figure 4.12. Data Mart report

4.5 Actions in Control step

The goal of the Control step is to document and sustain the corrective actions made and monitor the implemented solution in the daily production process. The improvements should be checked by applying the *"mini DMAIC"* process and continuous improvements for the process must be made. If the implemented corrective actions satisfy, then continuous improvement for other problem processes should be proceeded.

4.5.1 Validation of the improvements

When the corrective actions were applied (new equipment purchased and necessary training provided), based on the charts below, the following conclusions can be drawn. The failures that had high RPN_{Real} values earlier have low values now. These values influence the *PSPL* KPI that shows the level of product quality (2,9σ), CWF_{RPN} KPI that shows financial impact of a failure on the final product, and the *TH* KPI that affects product delivery. The Data Mart report presented in Figure 4.17 shows the improvements (highlighted by yellow).

Comparing the chart from Figure 4.4 and the new chart from Figure 4.13, it is revealed that after improvement of selected failures, the operations *"OpF"*, *"OpJ"*, *"OpK"* and *"OpL"* have less impact on the Quality and the Cost KPI. This chart also shows that, for example, the next improvement can be made for the operation *"OpC"* that has high impact on the product Quality and the Cost KPIs.

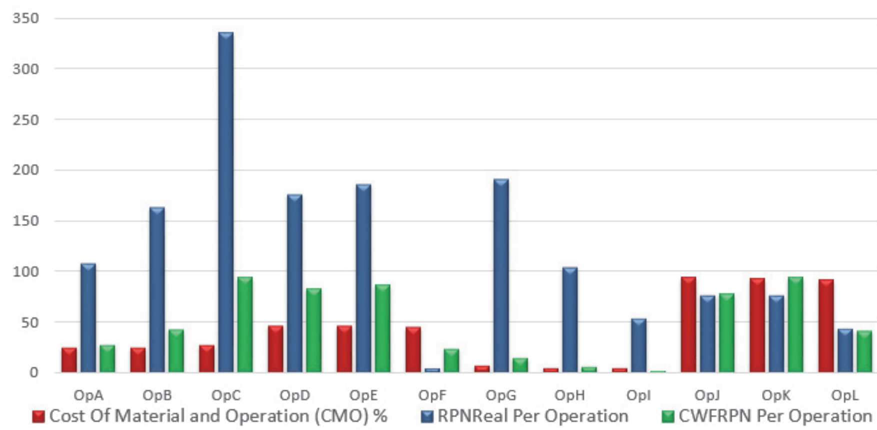

Figure 4.13. Chart for RPN_{Real}, C_{MO} and CWF_{RPN} per operation

Comparing the Pareto chart in Figure 4.5 and the new Pareto chart in Figure 4.14, it can be summarized that the sequence of the failures after improvement is changed. The new chart in Figure 4.14 indicates the most critical failures in the production process from the product quality point of view. Using this chart, an engineer can define which failures are necessary to eliminate to increase the *PSPL* KPI.

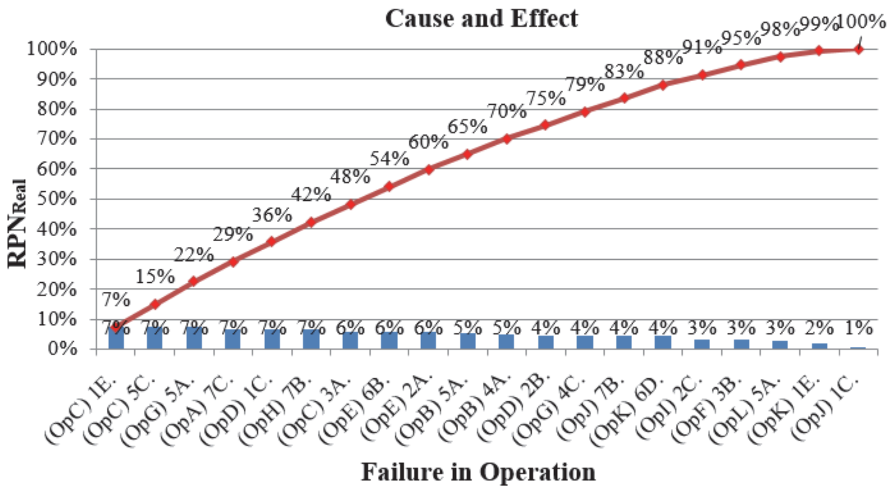

Figure 4.14. Pareto chart for the RPNReal of failure per operation

Comparing the Pareto chart in Figure 4.6 and the new Pareto chart in Figure 4.15, it can be summarized that the sequence of the failures after improvement is changed. The new chart presented in Figure 4.15 indicates the most critical failures in the process from the finance point of view. Using this chart, an engineer can define which failures are necessary to eliminate to improve the *CWFRPN* KPI.

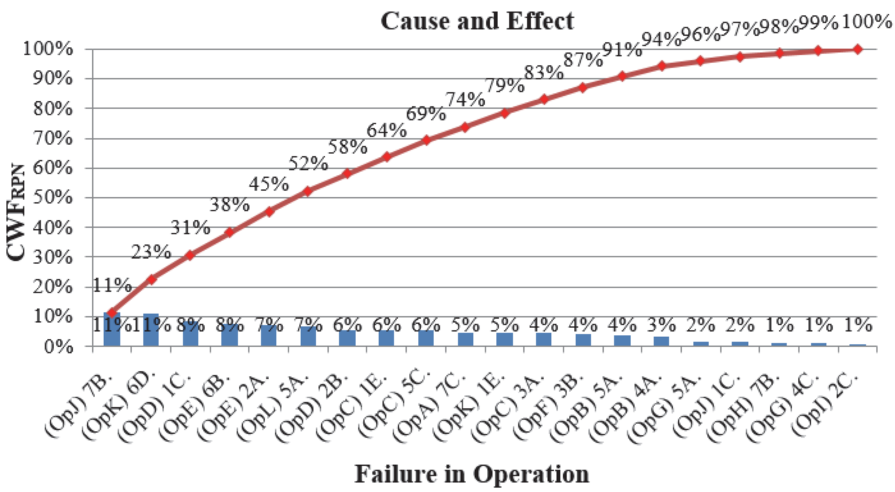

Figure 4.15. Pareto chart for the CWFRPN *of failure per operation*

The Swimline diagram in Figure 4.16 shows the failures, operations and work centres (highlighted by red) where improvements were made. The purpose of the improvements was to decrease operations *CT* in the work centre (W10) by eliminating the RPN_{Real} values of failures (new equipment and training to the operator). After the process constraint was eliminated, the process became stable and reliable, the operation *CT* was decreased and the product *TH* of the assembly department (W10) was increased. The *TH* can be re-calculated using Equation (1.1); the result is: Throughput of 6,7 units as compared to the previous 5 units.

$$TH = \frac{10}{1.5} \approx 6{,}7$$

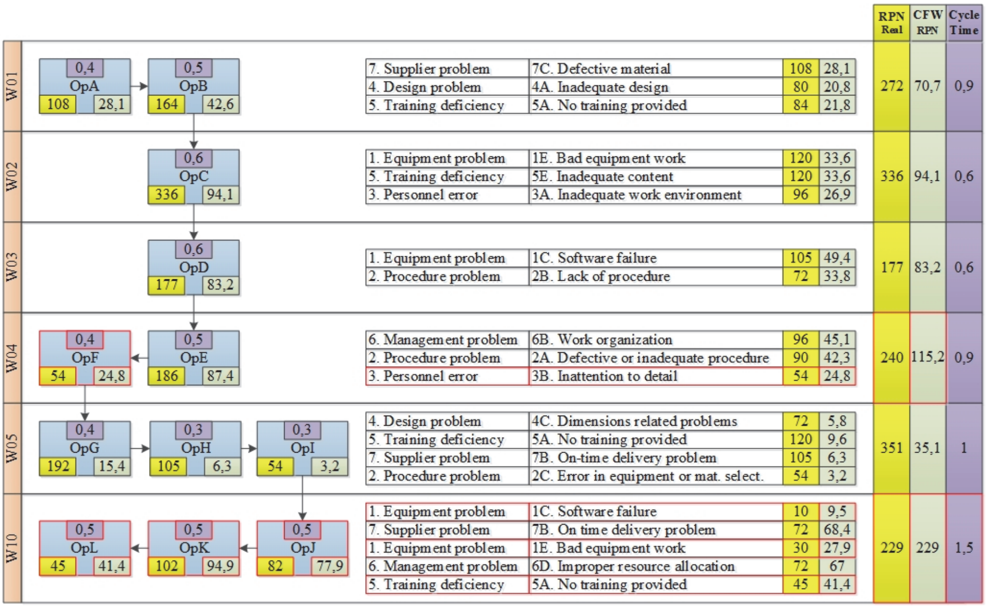

Figure 4.16. Improved Process Constraint in TOC

4.5.2 KPIs re-calculation

When the improvements for the production process KPIs (*PSPL*, CWF_{RPN} and *TH*), which influence the Quality, Cost and Delivery KPIs are made, they should be re-calculated in the following way.

Company received 10 units, the order has 1 defect unit. The **Quality KPI** for this order is 90%. Calculation: (9/10 = 90%).

Customer ordered 10 units, the order has a requested release date of November 1. The company delivered 9 units on time, the remaining 1 unit on November 5. The **Delivery KPI** for this order is 90%. Calculation: (9/10 = 90%).

The **Cost KPI** is improved indirectly by improving the reliability of the production processes. The more reliable the production process, the less scrap rework is needed because of additional cost expenditures and the less idle time that influences the product delivery on time in case company delivers product not on time, it has to pay penalties. As a result, the less extra expenditures (scrap rework, idle time, etc.), the more the company saves financially.

Production Route – Product Data: Product Name	Designation Code	Component ID	Component Name	BOM Level	Quantity	Production Data: Work Centre Name	Operation Name	Operation Sequence	Operation Time, H	Measure – Failure Classifier: Failure Group	Failure Cause	Measure and Analyse – Failure Mode and Effect Analysis: Severity (S)	Occurrence (O)	Detection (D)	Real Risk Priority Number (RPN_{Real}): Failure	Operation	Work Centre	BOM Level	Failure Cost Calculation: Cost of Material (C_M) from Product %	Cost of Operation (C_O) from Product %	Cost of Material and Operation (C_{MO}) %	Cost of BOM Level (C_{BOML}) %	Cost Weighted Factor for Risk Priority Number (CWF_{RPN}): Failure	Operation	Work Centre	BOM Level
Wind Power Generator A	ABC	1001	Balanced Rotor	1	1	W1	OpA	1	0,4	7. Supplier problem	7C. Defective material	6	6	3	108	108	272	608	25	1	26	30	28,1	28,1	73,4	182,4
							OpB	2	0,5	4. Design problem	4A. Inadequate design	5	4	4	80	164				1	26		20,8	42,6		
										5. Training deficiency	5A. No training provided	7	4	3	84								21,8			
						W2	OpC	3	0,6	1. Equipment problem	1E. Bad equipment work	8	5	3	120	336	336			3	28		33,6	94,1	94,1	
										5. Training deficiency	5E. Inadequate content	6	5	4	120								33,6			
										3. Personnel error	3A. Inadequate work environment	8	2	6	96								26,9			
	DEF	1002	Connected Stator	1	1	W3	OpD	1	0,6	1. Equipment problem	1C. Software failure	7	5	3	105	177	177	417	45	2	47	50	49,4	83,2	83,2	208,5
										2. Procedure problem	2B. Lack of procedure	8	3	3	72								33,8			
						W4	OpE	2	0,5	6. Management problem	6B. Work organization	8	3	4	96	186	240			2	47		45,1	87,4	115,2	
										2. Procedure problem	2A. Defective or inadequate procedure	5	3	6	90								42,3			
							OpF	3	0,4	3. Personnel error	3B. Inattention to detail	6	3	3	54	54				1	46		24,8	24,8		
	GHI	1003	Frame	1	1	W5	OpG	1	0,4	4. Design problem	4C. Dimensions related problems	6	4	3	72	192	351	351	5	3	8	10	5,8	15,4	35,1	35,1
										5. Training deficiency	5A. No training provided	6	5	4	120								9,6			
							OpH	2	0,3	7. Supplier problem	7B. On-time delivery problem	7	3	5	105	105				1	6		6,3	6,3		
							OpI	3	0,3	2. Procedure problem	2C. Error in equipment or mat. select.	6	3	3	54	54				1	6		3,2	3,2		
	XYZ	2001	Assembled Generator	0	1	W10	OpJ	1	0,5	1. Equipment problem	1C. Software failure	5	2	1	10	82	229	229	90	5	95	100	9,5	77,9	229	229
										7. Supplier problem	7B. On-time delivery problem	6	3	4	72								68,4			
							OpK	2	0,5	1. Equipment problem	1E. Bad equipment work	5	2	3	30	102				3	93		27,9	94,9		
										6. Management problem	6D. Improper resource allocation	8	3	3	72								67			
							OpL	3	0,5	5. Training deficiency	5A. No training provided	5	3	3	45	45				2	92		41,4	41,4		
									5,5																	

Theoretical RPN ($RPN_{Theoretical}$)	20 000
and Percent Per Process	100%
RPN_{Real} Per Process	1 605
RPN_{Real} Percent Per Process	8%
Process Yield (PY)	92%
PSPL	2,9σ

Figure 4.17. Data Mart report after improvement (highlighted by yellow)

CONCLUSIONS

In order to fulfil the research objective, **four main tasks** were implemented.

1. The new dynamic management framework for continuous improvement of the production process was developed. This framework enables to improve **process** Key Performance Indicators (KPIs), such as Process/Product Sigma Performance Level *(PSPL)*, Cost Weighted Factor for RPN (CWF_{RPN}) and Throughput (*TH*) that influence the **product** Quality, Cost and Delivery KPIs.

2. The framework was integrated into five steps of Six Sigma DMAIC (Define, Measure, Analyse, Improve, Control) methodology. The basic focus of this research is on the *Measure* and *Analyse* step. The main target of this framework is to improve the production process by decreasing the number of defects/failures in the process, thus decreasing their real Risk Priority Number (RPN_{Real}) value that increases production process KPIs.

In the Define step, the problem and main KPIs were identified and evaluated.

In the *Measure* step, different phases were considered: the modified Failure Classifier (FC), Failure Mode and Effect Analysis (FMEA), Failure Cost Calculation (FCC), Theory Of Constraints (TOC), and Analytic Hierarchy Process (AHP).

- In the FC phase, the types of failures for each operation were assigned. Further, this became the basis for the next steps and phases of the research.
- In the FMEA phase, the weight of each failure was assessed, measured in FC, by Severity, Occurrence and Detection rating and then the RPN_{Real} value was calculated. In addition, based on the FMEA results, the *PSPL* was calculated that indicates the general level of the process/product quality.
- In the FCC phase, the direct costs of the components and BOM levels were calculated using the RPN_{Real} values from the FMEA and the financial impact of failure (CWF_{RPN}) on the final product that allows monitoring the product direct cost.
- In the TOC phase, the operation Cycle Time (*CT*) was calculated that enables identification of the Process Constraint (PC) of the process. Further, this PC was elevated by reducing the RPN_{Real} values or the number of failures in the process that in turn allowed to decrease the operation *CT* and increase the product throughput *TH*.
- Using the AHP approach, product KPIs were compared and those most important for improvement were identified.

In the *Analyse* step, based on the results from the Measure step, various charts and diagrams were built. Introduction of a new analysis method in which various charts/diagrams are compared and analysed facilitated identification of which failures should be improved or eliminated to increase the level of specified KPI for the specified process and product. The results revealed the most critical failures in the process from the product quality, cost and delivery point of view. Based on these results and AHP comparison, an engineer can make decisions about the failures to be improved for a particular KPI and for some specified product type or for the general production system.

- In the FMEA phase, using the RPN_{Real} values, the variability of the process by failures, operations, work centres and BOM level was observed and the Pareto chart was created and analysed.
- In the FCC phase, using the CWF_{RPN} values, the Pareto chart was created that allowed analysis of failures from the financial point of view.
- In addition, using RPN_{Real} value from FMEA, CWF_{RPN} and Cost of Material and Operation (C_{MO}) from FCC, the chart was created that visually indicated which operations have worst impact on the final product from the quality and direct cost point of view.
- In the TOC phase, a Swimline diagram with the presented data from FC (failures), FMEA (RPN_{Real} value) and FCC (CWF_{RPN} value) was created. This diagram allowed visual understanding of which failures with RPN_{Real} values should be improved or eliminated to decrease the operation *CT* and increase product *TH*.

The first three steps of the DMAIC process (Define, Measure, Analyse) characterize the nature of the problem to be solved. When these steps were completed, the problems and their root causes were known. Further, based on these steps, the Improve and Control steps were applied where appropriate changes in the manufacturing process were implemented and sustained.

3. The new Data Mart was developed for the presented framework and applied into the Information System (IS) environment. This Data Mart plays the role of a *"dashboard"* that allows a decision maker's quick access to the required data, creating various reports and charts for analysis, monitoring production processes (e.g., based on the data for the previous day) that indicate which failures should be improved to increase the specific KPI.

4. The presented new framework was checked in a computational experiment with the real data from production floor. In order to improve the process KPIs, it is necessary to strive to eliminate failures or decrease RPN_{Real} values. The smaller the number of failures and/or their RPN_{Real} value, the higher are the process and product KPIs, customer satisfaction and company revenue.

Scientific novelty of the research

The novelty of this research is the dynamic management framework for continuous improvement of the production process that enables improvement of product Quality, Cost and Delivery based on the priorities of the decision maker. This framework was applied into the Data Mart and IS environment that enables the following actions to be performed:

- Assessment and monitoring of the production process KPIs (PSPL, CWFRPN and TH) (based on data for the last day) using the data from FMEA, FCC and Swimline process that influence product KPIs (Quality, Cost and Delivery);
- Process KPIs show the following: *PSPL* – level of process/product quality; CWF_{RPN} – failure weight from the financial point of view; *TH* – allows to

identify PC and elevate it by eliminating failures and decreasing *CT* of operations;
- Identification of failures that are worst in the process from the product KPIs point of view;
- Determination of priorities for improvement of product KPIs (Quality, Cost or Delivery) from the company and/or customer point of view using the AHP approach.

Future work

Marina Kostina's work (Kostina, 2012) has presented an approach that enables to improve the reliability of production processes using Bayesian Believe Networks (BBN) (O'Hagan, 1994; Heckerman, 1998; Neapolitan, 2003; Shevtshenko and Wang, 2009), e.g. to identify what the probability of scrap of the final product is after applying corrective actions for the specific failure. Figure B (section 1) shows the basic steps of this approach. In this thesis, for probability calculation, BBN software GeNIe was used with the RPN_{Real} values from FMEA and failures from FC that allowed calculation of the Probability of Scrap.

The current work (section 2) and Kostina's PhD work (section 1) and possibly other studies can be the basis for the future work using BBN. For instance, the approach of Kostina can be applied to calculate the Cost Weighted Probability of Final Product Failure using the CWF_{RPN} from FCC and failures from FC. Such approach enables to identify what the probability of improvement or deterioration of product Quality or Cost is after the corrective actions are applied. Also, by identifying PC in TOC, an engineer can see which failures influence the *TH*. Then, by applying corrective actions to the specified failure, an engineer can compare how the corrective action can influence the probability of the product Quality and Cost (dashed arrow). Therefore, a decision can be made which is more important Quality or Cost at improved Delivery or maybe there is no reason to improve Delivery as the product Quality and Cost are more important for a customer. Figure B shows future work in section 3.

In addition, one of the most important goals of the future work is to create software for the above described framework. This kind of software will allow the production engineers select quickly, efficiently and with high precision the worst failures which influence the process and product KPIs and then improve them.

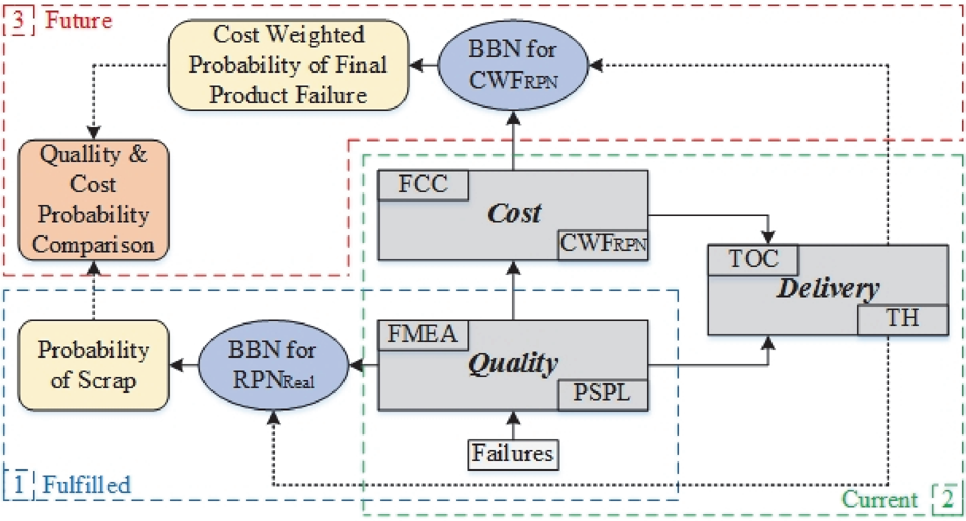

Figure B. Basic steps of the fulfilled, current and future work

ABSTRACT

Dynamic Management Framework for Continuous Improvement of Production Processes

To be competitive and successful on the market place today and satisfy customers, companies have to make strenuous efforts, for example, to improve various Key Performance Indicators (KPIs). However, the most widely spread problem faced by many manufacturing companies is that companies know the problems they have, for instance, unreliable production processes, poor product quality, financial losses, delay in product delivery, but frequently, they are unaware of the root causes of these problems. To solve these problems, companies are trying to implement various quality improvement programs, tools and methodologies. In many cases, these measures are used quite successfully to attain the goals appointed, but at the same time, they are working separately from each other and as a result, are not effective and consolidated enough.

Therefore, in this research a framework that integrates various quality improvement tools and methodologies has been created. This framework enables continuous enhancement of the reliability of a production process that influences the improvement of product quality, cost and delivery, with lower expenditures by collecting production data (problems, failures) about production processes. Further, these data help to define the most critical operations in the process and improve them. As a result, the process variability is reduced and process reliability is increased, which in turn decreases product scrap and rework. A reliable production process can save resources (labour, time, money), consequently can provide better product quality, save money and reduce delivery time, which improves company revenue and customer satisfaction.

Finally, the presented new framework will be adapted into the database – Data Mart, which will play the role of a *"dashboard"* which allows monitoring production processes (collect data about production problems, failures), measuring and analysis (based on various charts) based on data for the previous day. In addition, the new Data Mart will be applied into the Information Systems (IS) environment with various tools (Product Data Management (PDM), Extract Transfer Load (ETL), Enterprise Resource Planning (ERP) system) that enable us to process different data from one system to another and derive new knowledge useful for business processes management, decision making and customer satisfaction.

By integrating various quality improvement tools and methodologies with Information Technologies (IT) and IS tools, it will hold a vital and successful role in company's business. This kind of integration helps businesses improve the efficiency and effectiveness of their production and business processes, production team support and collaboration and managerial decision-making, for example, which KPI is more important for a product, a company and a customer. This new framework strengthens company competitive positions, enables the company to be more adaptable to the rapidly changing marketplace and increase financial revenue.

KOKKUVÕTE

Tootmisprotsesside pideva parenduse dünaamiline juhtimisraamistik

Konkurentsivõime ja edu ning klientide rahulolu tagamiseks tänapäevasel turul peavad firmad tugevasti pingutama. Näiteks peavad nad parandama oma põhitegevuse tulemusnäitajaid. Samal ajal paljud tootmisfirmad tunnistavad, et nad on teadlikud oma probleemidest, näiteks et tootmisprotsess on madala töökindlusega, toode on madala kvaliteediga, esineb finantskadusid, venitusi kauba tarnimisel jne. Sageli aga nad ei mõista nende probleemide tekke põhiallikaid. Nende probleemide lahendamiseks püüavad firmad rakendada mitmesuguseid kvaliteedi kindlustamise programme, instrumente ja metodoloogiaid. Paljudel juhtudel saab neid edukalt kasutada seatud eesmärkide saavutamiseks. Samal ajal aga rakendatakse neid eraldi, mis ei võimalda saavutada efektiivseid ja kontsentreeritud tulemusi.

Selletõttu on antud uurimuses loodud raamistik, mis integreerib mitmesugused kvaliteedi kindlustamise vahendid ja metodoloogiad. Nimetatud raamistik võimaldab järjepidevalt parandada tootmisprotsessi usaldusväärsust, mis mõjutab toote kvaliteedi, hinna ja tarne parandamist madalamate kulutustega, kasutades selleks tootmisandmete kogumist tootmisprotsessist (probleemid, tõrked). Need andmed aitavad defineerida ja parandada protsessi kõige kriitilisemaid operatsioone. Tootmisprotsesside täiustamine vähendab protsesside varieerumist ja suurendab protsesside töökindlust, mis omakorda vähendab jäätmeid ja uustöötluse vajadust. Töökindel tootmisprotsess võib säästa ressursse (tööd, aega, raha), seega võimaldab paremat tootekvaliteeti, raha säästmist ja tarneaja lühendamist, mis parandab firma sissetulekuid ja kliendi rahulolu.

Kokkuvõttes, esitatud uus raamistik on kohandatud vastavaks Data Mat andmebaasile, mis mängib nn armatuurlaua osa, võimaldades tootmisprotsesside jälgimist (andmete kogumist tootmisprotsessi probleemide ja tõrgete kohta), neid mõõta ja analüüsida (erinevate skeemide alusel) eelmise päeva andmete põhjal. Lisaks rakendatakse uut Data Mart'i informatsioonisüsteemide (IS) keskkonnas koos mitmesuguste instrumentidega (Product Data Management (PDM), Extract Transfer Load (ETL), Enterprise Resource Planning (ERP) süsteemidega), mis võimaldab erinevaid andmeid ühes süsteemis töödelda ja saada uusi teadmisi, mida saab kasutada äriprotsesside juhtimisel, otsuste tegemisel ja kliendi rahulolu kindlustamisel.

Erinevate kvaliteedi kindlustamise vahendite ja metodoloogiate integreerimine infotehnoloogias (IT) ja infosüsteemides (IS) täidab olulist rolli firma edukas äritegevuses. Selline integratsioon aitab parandada äritegevuse efektiivsust ning tootmis- ja äriprotsesside tõhusust, meeskondade toetust ja koostööd, samuti otsuste tegemist juhtkonna tasandil; näiteks missugused võtmetulemusnäitajad on tähtsamad toote, firma ja kliendi puhul. See uus raamistik tugevdab firma konkurentsipositsiooni ja võimaldab paremini adapteeruda kiiresti muutuva turu tingimustes ja suurendada sissetulekuid.

ACKNOWLEDGEMENTS

First of all, I would like thank sincerely my supervisor, Dr. Eduard Shevtshenko for his supervision and support during my work, for his wisdom and inspiration throughout the thesis process and for all the opportunities he has given to me. I would like also express my gratitude to Dr. Tatjana Karaulova who also was very helpful and offered me invaluable assistance, guidance and shared her knowledge. My thanks are due to Tallinn University of Technology and to the Faculty and staff of the Department of Mechanical Engineering for providing the necessary resources to complete my thesis. I am very thankful to all my PhD colleagues Marina Kostina, Viktoria Baškite, Igor Poljantšikov, Roman Zahharov, Innar Liiv and to my colleagues on my job for informal discussions and assistance during this thesis. Most importantly, I am very grateful to my family. Without their support and constant love to me, this work would never have been possible.

REFERENCES

Anbari, F. T., Six Sigma method and its applications in project management, In Proceedings of the Project Management Institute Annual Seminars and Symposium, (2002), San Antonio, Texas, Vol.3, 10.

Antony, J., & Banuelas, R., Key ingredients for the effective implementation of Six Sigma program, Measuring Business Excellence, (2002), Vol.6, 4, 20–27.

Antony, J., Some pros and cons of Six Sigma: an academic perspective, The TQM Magazine, (2004), Vol.16, 4, 303–306.

Antony, J., Krishan, N., Cullen, D., & Kumar, M., Lean Six Sigma for higher education institutions (HEIs): Challenges, barriers, success factors, tools/techniques, International Journal of Productivity and Performance Management, (2012), Vol.61, 8, 940–948.

Aon Management Consulting, Lean Six Sigma, The Leadership Report, (2003).

Badiru, A. B., Handbook of industrial and systems engineering, (2005), CRC Press.

Baek, J.Y., Kim, B.H., Lee, G.B., Park, S.E., Lee, H.C., Design of the support system for the production control of injection forming process using DFSS methodology, Annals of DAAAM and Proceedings of the International DAAAM Symposium, (2006), 25–26.

Barchetti, U., Bucciero, A., Guido, A. L., Mainetti, L., & Patrono, L., Supply Chain Management and Automatic Identification Management convergence: Experiences in the Pharmaceutical Scenario, Supply Chain Coordination and Management, (2011), 978–953.

Barquin, R. C., & Edelstein, H. A., Building, using, and managing the data warehouse, Prentice-Hall, Inc., (1997).

Bhanumurthy, M.V., Profitability through lean Six Sigma: Save energy – Save environment, AIChE Annual Meeting, Conference Proceedings, (2012).

Bill Of Materials, Available from: http://www.arenasolutions.com/resources/articles/creating-bill-of-materials/, http://www.investopedia.com/terms/b/bill-of-materials.asp, http://www.accountingtools.com/definition-bill-of-materials, Accessed: 26.03.2015.

Brandl, D., Business to manufacturing (B2M) collaboration between business and manufacturing using ISA-95, Revue De L Electricite Et De L Electronique, (2002), Vol.8, 46–52.

Brook, Q., Lean Six Sigma and Minitab, The Complete Toolbox Guide For all Lean Six Sigma Practitioners, (2010), Quentin.

Bubshait, A.A & Al-Dosary, A.A., Application of lean six sigma methodology to reduce the failure rate of valves at oil field, Lecture Notes in Engineering and Computer Science, (2014), Vol.2, 1010–1015.

Cost definition, Available from: https://www.e-conomic.co.uk/accountingsystem/glossary/cost, Accessed: 26.03.2015.

Chenoweth, T., Schuff, D., & St Louis, R., A method for developing dimensional data marts, Communications of the ACM, (2003), Vol.46, 12, 93–98.

Chiarini, A., Risk management and cost reduction of cancer drugs using Lean Six Sigma tools, Leadership in Health Services, (2012), Vol.25, 4, 318–330.

Chung, S. H., Lee, A. H., & Pearn, W. L., Analytic network process (ANP) approach for product mix planning in semiconductor fabricator, International Journal of Production Economics, (2005), Vol.96, 1, 15–36.

Das, N., Gauri, S. K., & Das, P., Six Sigma principles in marketing: an application, International Journal of Six Sigma and Competitive Advantage, (2006), Vol.2, 3, 243–262.

Dassault Systems & DELMIA, Plant to Enterprise Integration: ISA-95 is a Nice Start, (2012).

Davenport, T. H., Mission critical: realizing the promise of enterprise systems, Harvard Business Press, (2000).

De Ambroggi, M., & Trucco, P., Modelling and assessment of dependent performance shaping factors through analytic network process, Reliability Engineering & System Safety, (2011), Vol.96, 7, 849–860.

De Geus, A. P., Planning as learning, Harvard Business Review, (1988), 70–74.

De Koning, H., Does, R. J., & Bisgaard, S., Lean Six Sigma in financial services, International Journal of Six Sigma and Competitive Advantage, (2008), Vol.4, 1, 1–17.

Deng, Z., Lu, Y., Wei, K. K., & Zhang, J., Understanding customer satisfaction and loyalty: An empirical study of mobile instant messages in China, International Journal of Information Management, (2010), Vol.30, 4, 289–300.

Dettmer, H. W., Goldratt's theory of constraints: a systems approach to continuous improvement, (1997), ASQ Quality Press.

DoE, U. S., Root cause analysis guidance document, Technical Report DOE-NE-STD-1004-92, (1992), US Department of Energy, Office of Nuclear Energy, Washington, DC.

Ehie, I., & Sheu, C., Integrating Six Sigma and Theory of Constraints for continuous improvement: a case study, Journal of Manufacturing Technology Management, (2005), Vol.16, 5, 542–553.

ELT system, Available from: http://trianzblog.com/wordpress/?p=203, Accessed: 09.04.2015.

George, M. L., & George, M., Lean six sigma for service, New York: McGraw-Hill, (2003), 117–130.

Gilchrist, W., Modelling failure modes and effects analysis, International Journal of Quality & Reliability Management, (1993), Vol.10, 5.

Goldratt, E. M., Theory of constraints, (1990), Croton-on-Hudson, NY: North River.

Goldratt, E. M., Cox, J., & Whitford, D., The goal: a process of ongoing improvement, (1992), Great Barrington, MA: North River Press, Vol.2.

Goldratt, E. M., It's Not Luck, (1994), Great Barrington, MA: North River Press.

Goldratt, E. M., Critical chain: A business novel, (1997), Great Barrington, MA: North River Press.

Goldratt, E. M., Schragenheim, E., & Ptak, C. A., Necessary but not sufficient, (2011).

Graham, S., Coburn, D., & Oleson, C., The Foundations of Wisdom: A Study of the Financial Impact of Data Warehousing, International Data Corporation, (1996).

Heckerman, D., A Tutorial on Learning with Bayesian Networks, (1998), Springer Netherlands, 301–354.

Hennig-Thurau, T., & Klee, A., The impact of customer satisfaction and relationship quality on customer retention: A critical reassessment and model development, Psychology & Marketing, (1997), Vol.14, 8, 737–764.

Houari, N., & Far, B. H., An intelligent project lifecycle data mart-based decision support system, In Electrical and Computer Engineering, Canadian Conference on IEEE, (2004), Vol.2, 727–730.

Houben M., Using Bayesian Belief Networks for Reliability Management, Construction and Evaluation: a Step by Step Approach, (2010), PhD Theses, Technische Universiteit Eindhoven.

ICH Q9 Quality Risk Management, European Medicines Agency Inspections, (2006).

Inmon, W. H., The data warehouse and data mining, Communications of the ACM, (1996), Vol.39, 11, 49–50.

Inmon, W. H., Building the data warehouse, (2005), John Wiley & Sons, Vol.3.

International standard ISO/IEC/IEEE 42010:2011, Systems and software engineering – Architecture description, (2011).

ISO 9000 Standards, Available from: http://www.iso.org/iso/home/standards/management-standards/iso_9000.htm, Accessed: 07.04.2015.

Jacob, D., Bergland, S., & Cox, J., Velocity: Combining Lean, Six Sigma and the Theory of Constraints to achieve breakthrough performance, A business novel, (2009), Simon and Schuster.

Jacoby, D., Measuring sourcing performance: What's the mystery?, Purchasing, (2005), Vol.134.

Jin, K., Abdul-Razzak, H., Elkassabgi, Y., Zhou, H., & Herrera, A., Integrating the Theory of Constraints and Six Sigma in Manufacturing Process Improvement, In Proceedings of World Academy of Science, Engineering and Technology, (2009), Vol.37.

Johnson, S. K., Combining QFD and FMEA to optimize performance, In Annual Quality Congress Proceedings-American Society for Quality Control, (1998), 564–575.

Johnson, D. J., A framework for reducing manufacturing throughput time, Journal of manufacturing systems, (2003), Vol.22, 4, 283–298.

Karaulova, T., Kostina, M., & Shevtshenko, E., Reliability Assessment of Manufacturing Processes, International Journal of Industrial Engineering and Management, (2012), Vol.3, Iss3, 143–151.

Karaulova, T., Kostina, M and Sahno, J., Framework of reliability estimation for manufacturing processes, Mechanics, (2012), Vol.18, 6, 713–720.

Kendall, M. G., & Babington Smith, B., The problem of m rankings, Annals of Mathematical Statistics, (1939), Vol.10, 275–287.

Kimball, R., The Data Warehouse toolkit: practical techniques for building dimensional data warehouse, (1996), NY: John Willey & Sons, Vol.248, 4.

Kimball, R., A dimensional modelling manifesto, (1997), Vol.10, 9, 58–70.

Kimball, R., The Data Warehouse lifecycle toolkit: expert methods for designing, developing, and deploying data warehouses, (1998), John Wiley & Sons.

Kimball, R., & Ross, M., The data warehouse toolkit: the complete guide to dimensional modelling, (2002), US: John Wiley & Sons.

Koning, H., Verver, J. P., Heuvel, J., Bisgaard, S., & Does, R. J., Lean Six Sigma in healthcare, Journal for Healthcare Quality, (2006), Vol.28, 2, 4–11.

Kostina, M., Reliability Management of Manufacturing Processes in Machinery Enterprises, (2012), PhD Theses, Tallinn University of Technology, Faculty of Mechanical Engineering, Department of Machinery, Tallinn, Estonia.

Koudsi, S., Actually, it is like brain surgery, Fortune, Time Inc., (2000), Vol.141, 6, 233–235.

Krishna, R. & Dangayach, G. S., Six Sigma implementation at an auto component manufacturing plant: a case study, International Journal of Six Sigma and Competitive Advantage, (2007), Vol.3, 3, 282–302.

Krishna, R., Sharan Dangayach, G., Motwani, J., & Akbulut, A. Y., Implementation of Six Sigma approach to quality improvement in a multinational automotive parts manufacturer in India: a case study, International Journal of Services and Operations Management, (2008), Vol.4, 2, 264–276.

Kumar, S., Tiffany, M., & Vaidya, S., Supply chain analysis of e-tailing versus retailing operation: a case study, Enterprise Information Systems, (2014), 1–27.

Kumaravadivel, A., & Natarajan, U., Application of six sigma DMAIC methodology to sand-casting process with response surface methodology, The International Journal of Advanced Manufacturing Technology, (2013), Vol.69, 5–8, 1403–1420.

Kwak, Y. H., & Anbari, F. T., Benefits, obstacles, and future of six sigma approach, Technovation, (2006), Vol.26, 5, 708–715.

Lead Time Terminology in Manufacturing, Available from: http://www.leadtimes.org/, Accessed: 01.08.2014.

Lean Six Sigma, Available from: http://www.tocico.org/?page=tls_portal, Accessed: 30.01.2015.

Lebovitz, P.P., Design data management for the small engineering shop, (1997), Machine Design.

Legendre, P., Species associations: the Kendall coefficient of concordance revisited, Journal of Agricultural, Biological, and Environmental Statistics, (2005), Vol.10, 226–245.

Legendre, P., Coefficient of concordance, Encyclopedia of Research Design, (2010), SAGE Publications.

Lendvay, M., Dependability Assurance of Industrial Production Processes, Proceedings: Science in Engineering, Economics and Education, (2004), Budapest.

Little, J. D., & Graves, S. C., Little's law, In Building Intuition, (2008), Springer US 81–100.

Lõun, K., Riives, J., & Otto, T., Evaluation of the operation expedience of technological resources in a manufacturing network, Estonian Journal of Engineering, (2011), Vol.17, 1, 51–65.

MacDermott, R. E., Raymond J. M., & Michael R. B., The basics of FMEA, (1996), Productivity Press.

Mansir, B. E., & Schacht, N. R., Total quality management: a guide to implementation, (1989), Logistics Management Inst Bethesda MD.

Markus, M. L., Tanis, C., & Van Fenema, P. C., Enterprise Resource Planning: multisite ERP implementations, Communications of the ACM, (2000), Vol.43, 4, 42–46.

Matzler, K., & Hinterhuber, H. H., How to make product development projects more successful by integrating Kano's model of customer satisfaction into quality function deployment, Technovation, (1998), Vol.18, 1, 25–38.

Mazumder, Q.H., Applying six sigma in higher education quality improvement, ASEE Annual Conference and Exposition, (2014), Conference Proceedings.

McClusky, R., The rise, fall and revival of Six Sigma quality, Measuring Business Excellence, (2000), Vol.4, 2.

Mekki, K. S., Robust design failure mode and effects analysis in designing for Six Sigma, International Journal of Product Development, (2006), Vol.3, 3, 292–304.

Moody, D. L., & Kortink, M. A., From enterprise models to dimensional models: a methodology for data warehouse and data mart design, DMDW, (2000), 5–12.

Morphy, E., Measuring up, Export Today, (1999), Vol.15, 6, 52–7.

Myszewski, J. M., Mathematical model of the occurrence of human error in manufacturing processes, Quality and Reliability Engineering International, (2010), Vol.26, 8, 845–851.

Nave, D., How to compare six sigma, lean and the theory of constraints, Quality Progress, (2002), Vol.35, 3, 73–80.

Neapolitan, R. E., Learning Bayesian Networks, (2003), Upper Saddle River: Prentice Hall, Vol.38.

Nonthaleerak, P., & Hendry, L., Exploring the Six Sigma phenomenon using multiple case study evidence, International Journal of Operations & Production Management, (2008), Vol.28, 3, 279–303.

O'Brien, J., & Marakas, G. M., Management Information Systems, (2008), The McGraw-Hill Companies, New York, USA.

O'Hagan, A. & Forster, J., Kendall's advanced theory of statistics, (1994), Bayesian inference, London: Edward Arnold, Vol.2b.

Pacheco, D., Theory of Constraints and Six Sigma: Convergences, Divergences and Research Agenda for Continuous Improvement, Independent Journal of Management & Production, (2014), Vol.5, 2, 331–343.

Pande, P. S., Holpp, L., & Pande, P., What is six sigma?, (2002), New York: McGraw-Hill, Vol.1.

Peltonen, H., Pitkänen, O., & Sulonen, R., Process-based view of product data management, Computers in Industry, (1996), Vol.31, 3, 195–203.

Phillips, S., Dunkin, A., Treece, J. B., & Hammonds, K. H., King Customer, Business Week, (1990), Vol.12, 88–92.

Pritsker, A. A. B., Waiters, L. J., & Wolfe, P. M., Multiproject scheduling with limited resources: A zero-one programming approach, Management science, (1969), Vol.16, 1, 93–108.

Process Sigma, Available from: http://www.isixsigma.com/new-to-six-sigma/sigma-level/how-calculate-process-sigma, Accessed: 15.01.2015.

Production Route Card, Available from: http://www.enotes.com/american-scholar/q-and-a/what-meant-by-job-card-route-card-used-production-99397, Accessed: 30.04.2015.

Rancour, T., & McCracken, M., Applying Six Sigma methods for breakthrough safety performance, Professional Safety, (2000), Vol.45, 10, 29–32.

Reh, F. J., Key Performance Indicators (KPl), (2005).

Reid, R. Dan. and Sanders, Nada. R., Operations Management: An Integrated Approach, (2004), Management Science, Vol.2.

Riives, J., Karjust, K., Küttner, R., Lemmik, R., Koov, K., & Lavin, J., Software development platform for integrated manufacturing engineering system, In Proceedings of the 8th International Conference of DAAAM Baltic Industrial Engineering, (2012), 555–560.

Saaksvuori, A., & Immonen, A., Product Lifecycle Management, (2008), Springer-Verlag, Berlin, Heidelberg, Vol.3.

Saaty, T. L., Risk - Its priority and probability: The analytic hierarchy process, Risk Analysis, (1987), Vol.7, 2, 159–172.

Saaty, T. L., What is the analytic hierarchy process?, (1988), Springer, Berlin Heidelberg.

Saaty, T. L., How to make a decision: the analytic hierarchy process, European journal of operational research, (1990), Vol.48, 1, 9–26.

Sahno, J., Savimaa, R., Kangilaski, T., Opik, R., Maleki, M., & Machado, V., Data mart framework for production route selection, In Annals of DAAAM for 2011 & Proceedings of the 22nd International DAAAM Symposium, (2011), 1543–1544.

Sahno, J., Opik, R., Kostina, M., Paavel, M., Shevtshenko, E., & Wang, Y., Knowledge Management Framework for Production Route Selection in Manufacturing Enterprises, In 8th International DAAAM Baltic Conference Industrial Engineering, (2012), 567–572.

Sahno, J., Sevtsenko, E., & Karaulova, T., Knowledge Management Framework for Six Sigma Performance Level Assessment, In Advances in Information Systems and Technologies, Springer Berlin Heidelberg, (2013), 255–267.

Sahno, J., & Shevtshenko, E. Quality Improvement Methodologies for Continuous Improvement of Production Processes and Product Quality and Their

Evolution, In 8th International DAAAM Baltic Conference Industrial Engineering, (2014), 181–186.

Sahno, J., Shevtshenko, E & Zahharov, R., Framework for Continuous Improvement of Production Processes and Product Throughput, 25th DAAAM International Symposium on Intelligent Manufacturing and Automation, DAAAM 2014, (2015), Procedia Engineering, 511–519.

Sahno, J., Shevtshenko, E., Karaulova, T. and Tahera, K., Framework for continuous improvement of production processes, Journal of Engineering Economics, (2015), Vol.26, 2, 169–180.

Sarkar, B. N., Designing sustainable strategies for continuous improvement deployment programme: lessons from a steel plant in India, International Journal of Six Sigma and Competitive Advantage, (2007), Vol.3, 4, 352–376.

Seemer, R.H., Defects Per Million Opportunities, (2010).

Shevtshenko, E.; Wang, Y., Decision support under uncertainties based on robust Bayesian networks, International Journal of Computer Applications in Technology, (2009), Vol.36, 247–258.

Six Sigma Tools & Templates, Available from: http://www.isixsigma.com/tools-templates/, Accessed: 01.02.2015.

Snee, R. D., Why should statisticians pay attention to Six Sigma?, Quality Progress, (1999), Vol.32, 9, 100–103.

Sproull, B., The Ultimate Improvement Cycle: Maximizing Profits Through the Integration of Lean, Six Sigma, and the Theory of Constraints, (2012), CRC Press.

Stamatis, D. H., Failure mode and effect analysis: FMEA from theory to execution, ASQ Press, (2003).

Stéen, J., Improving Supply Chain Management with Advanced Planning and Scheduling: Effects and possibilities with an international perspective, (2006).

Stephens, J. S., & McDonald Jr, C. L., Lean Six Sigma, The Journal of Organizational Leadership and business, (2007).

Stewart, G., Supply chain performance benchmarking study reveals keys to supply chain excellence, Logistics Information Management, (1995), Vol.8, 2, 38–44.

Teamcenter Gateway for SAP Business Suite (T4S), Available from: http://plmware.tesis.de/index.php?page=1043, Accessed: 20.06.2014.

Torbica, Z. M., & Stroh, R. C., Customer satisfaction in home building, Journal of Construction Engineering and Management, (2001), Vol.127, 1, 82–86.

Tseng, M. L., Chiang, J. H., & Lan, L. W., Selection of optimal supplier in supply chain management strategy with analytic network process and choquet integral, Computers & Industrial Engineering, (2009), Vol.57, 1, 330–340.

Umble, E. J., Haft, R. R., & Umble, M. M., Enterprise Resource Planning: Implementation procedures and critical success factors, European journal of operational research, (2003), Vol.146, 2, 241–257.

United Nations Industrial Development Organization (UNIDO), Product Quality: A guide for small and medium-sized enterprises, (2006), Vienna.

United States Patent, Patent Number: 5731572, (Date of Patent: 24.03.1998).

Van den Heuvel, J., Does, R. J., & De Koning, H., Lean Six Sigma in a hospital, International Journal of Six Sigma and Competitive Advantage, (2006), Vol.2, 4, 377–388.

Vassiliadis, P., Simitsis, A., & Skiadopoulos, S., Conceptual modeling for ETL processes, In Proceedings of the 5th ACM international workshop on Data Warehousing and OLAP, (2002), ACM, 14–21.

Watson, H. J., & Gray, P., Decision support in the data warehouse, (1997), Prentice Hall Professional Technical Reference.

Watson, H. J., Annino, D. A., Wixom, B. H., Avery, K. L., & Rutherford, M., Current practices in data warehousing, Information Systems Management, (2001), Vol.18, 1, 47–55.

Watson, H. J., Wixom, B. H., Buonamici, J. D., & Revak, J. R., Sherwin-Williams' data mart strategy: creating intelligence across the supply chain, Communications of the Association for Information Systems, (2001), Vol.5, 9, 1–27.

Watson, G. H., Six Sigma for business leaders: a guide for implementation, (2004), GOAL/QPC.

Weber, A., & Thomas, R., Key performance indicators, Measuring and Managing the Maintenance Function, (2005), Ivara Corporation, Burlington.

Wild, R., Production and operations management: text and cases, (1995), Burns & Oates.

Wind, Y., & Saaty, T. L., Marketing applications of the analytic hierarchy process, Management Science, (1980), Vol.26, 7, 641–658.

Wu, W. W., & Lee, Y. T., Selecting knowledge management strategies by using the analytic network process, Expert systems with Applications, (2007), Vol.32, 3, 841–847.

Yang, K., Design for Six Sigma for Service: Theory of Constraints, McGraw-Hill, (2005).

Yang, M. S., Li, Y., Liu, Y., & Gao, X. Q., A Method for Problem Selection in the 6σ Definition Stage, Advanced Materials Research, Vol.139, 1485–1489, (2010).

LIST OF PUBLICATIONS

1.Sahno, J., Shevtshenko, E., Karaulova, T. and Tahera, K., Framework for continuous improvement of production processes, *Journal of Engineering Economics,* (2015), Vol.26, 2, 169–180, ISSN: 2029-5839.

2.Sahno, J., Shevtshenko, E., Zahharov, R., Framework for Continuous Improvement of Production Processes and Product Throughput, *25th DAAAM International Symposium on Intelligent Manufacturing and Automation, DAAAM 2014,* (2015), Procedia Engineering, 511–519, ISSN: 1877-0509.

3.Sahno, J. & Shevtshenko, E., Quality Improvement Methodologies for Continuous Improvement of Production Processes and Product Quality and Their Evolution, *Proceedings of the 9th International DAAAM Baltic Conference,* (2014), 181–185, ISSN: 2346-612X.

4.Sahno, J., Sevtsenko, E., Karaulova, T., Knowledge Management Framework for Six Sigma Performance Level Assessment, *Advances in Information Systems and Technologies,* (2013), Portugal: Springer-Verlag Heidelberg, 255–267, ISSN: 2194-5357.

5.Karaulova, T., Kostina, M., Sahno, J., Framework of reliability estimation for manufacturing processes, *Mechanika,* (2012), Vol.18, 6, 713–720, ISSN: 1392-1207.

6.Kostina, M., Karaulova, T., Sahno, J., Maleki, M., Reliability estimation for manufacturing processes, *Journal of Achievements in Materials and Manufacturing Engineering,* (2012), Vol.51, 1, 7–13, ISSN: 1734-8412.

7.Sahno, J., Opik, R., Kostina, M., Paavel, M., Shevtshenko, E., Wang, Y., Knowledge Management Framework for Production Route Selection in Manufacturing Enterprises, *Proceedings of the 8th International Conference of DAAAM Baltic Industrial Engineering, Tallinn, Estonia,* (2012), 567–572.

8.Sahno, J., Polyantchikov, I., Pribytkova, M., Shevtshenko, E., Model based enterprise manufacturing capacity definition and product cost estimation for SME, *Journal Of Machine Engineering,* (2011), Vol.11, 1–2, 23–34, ISSN: 1895–7595.

9.Sahno, J., Savimaa, R., Kangilaski, T., Opik, R., Maleki, M., Machado, V-C., Data Mart framework for production route selection, *Proceedings of the 22nd International DAAAM Symposium, Vienna, Austria, DAAAM International Vienna,* (2011), 1543–1544, ISSN: 1726-9679.

10.Karaulova, T., Pribytkova, M., Sahno, J., Shevtshenko, E., Design of reliable production route system, *Proceedings of the 22nd International DAAAM Symposium, Vienna, Austria, DAAAM International Vienna,* (2011), 539–540, ISSN: 1726-9679.

APPENDIX

No.	Activity	Description and Equation	Section
1	Problematic process definition Failure assignment and measurement		2.1 Define 2.2.1 Measure in FC
2	Occurrence Index calculation and Occurrence rating assessment	$I_O = \frac{\sum S_Q}{\sum P_Q} \times 100\%$	2.2.2 Measure in FMEA
3	Severity and Detection rating assessment in an external source, e.g. in the ERP system	Measurement in team using FMEA rank table.	
4	RPN real *(*RPN_{Real}*)* value per failure, calculation	$RPN_{Real} = S \times O \times D$	
5	RPN real *(*RPN_{Real}*)* value per operation, work centre, BOM level and process calculation		
6	Theoretical RPN *(*$RPN_{Theoretical}$*)* value calculation	$\sum RPN_{Theoretical} = \sum F \times 1000$	
7	Theoretical RPN *(*$RPN_{Theoretical}$*)* per process calculation		
8	RPN_{Real} percent calculation	$RPN_{Real}\% = \frac{\sum RPN_{Real}}{\sum RPN_{Theoretical}} \times 100\%$	
9	Process Yield (*PY*) calculation	$PY = 100\% - RPN_{Real}\%$	
10	Process/Product Sigma Performance Level *(PSPL)* calculation Average *PSPL* calculation	Define *PSPL* from Six Sigma scale table using *PY.* $PSPL_{Average} = \frac{\sum_{i=1}^{n} PSPL_i}{n}$	
11	Cost of Material and Operation *(*C_{MO}*)* calculation and conversion into percent value	$C_{MO} = C_M + C_O$ $C_{MO}\% = \frac{C_{MO} \times 100\%}{C_{FP}}$	2.2.3 Measure in FCC
12	Cost of BOM Level *(*C_{BOML}*)* calculation	$C_{BOMLN} = \sum_{y=1}^{m} \sum_{i=1}^{n} C_M yi + \sum C_O yi$	
13	Cost Weighted Factor of RPN *(*CWF_{RPN}*)* per failure, operation and work centre calculation	$CWF_{RPNFOW} = \frac{C_{MO}}{C_{BOML0}} \times \sum RPN_{Real}$	
14	Cost Weighted Factor of RPN *(*CWF_{RPN}*)* per BOM level calculation	$CWF_{RPNBOMLN} = \frac{C_{BOMLN}}{C_{BOML0}} \times \sum RPN_{Real}$	
15	Create Swimline process based on the data from PR (work centre, operation name, operation time, failure group and cause); from FMEA (RPN_{Real} per failure, operation, work centre); from FCC (CWF_{RPN} per failure, operation, work centre)		2.2.4 Measure in TOC
16	Identify process constraint by operation Cycle Time (*CT*) in the work centre and calculate process Throughput (*TH*)	$TH = \frac{WIP}{CT}$	
17	Compare KPI using AHP and identify which KPI has priority for improvement from the customer point of view		2.2.5 Comparison of KPIs in AHP

CURRICULUM VITAE

1.Personal data

Name	Jevgeni Sahno
Date and place of birth	15.11.1984, Kohtla-Järve
Citizenship	Estonian

2. Contact information

Address	Kaare tee 1A-1, Rae vald, 75304 Järveküla, Estonia
Phone	+372 55900731
E-mail	jevgeni.sahno@gmail.com

3.Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinn University of Technology	2009	MSc in Engineering
Tallinn University of Technology	2007	BSc in Engineering
Kohtla-Järve Tammiku Gymnasium	2004	Secondary education

4.Language competence/skills (fluent; average, basic skills)

Language	Level
Estonian	Average
Russian	Native
English	Fluent

5.Professional Employment

Period	Organisation	Position
2011 –	AS ABB	Process Development Engineer
2009 – 2011	AS E–Profiil	Design and Technology Engineer
2008 – 2008	AS JOT Automation	Design Engineer
2008 – 2008	AS Tammer	Design Engineer
2007 – 2008	AS Ferreks	Design and Technology Engineer
2006 – 2006	AS BLRT Group	CNC Machine Operator

ELULOOKIRJELDUS

1.Isikuandmed
Ees- ja perekonnanimi Jevgeni Sahno
Sünniaeg ja -koht 15.11.1984, Kohtla-Järve
Kodakondsus Eesti

2.Kontaktandmed
Aadress Kaare tee 1A-1, Rae vald, 75304 Järveküla, Eesti
Telefon +372 55900731
E-posti aadress jevgeni.sahno@gmail.com

3.Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	2008	Tehnikateaduste magistrikraad
Tallinna Tehnikaülikool	2005	Tehnikateaduste bakalaureusekraad
Kohtla-Järve Tammiku Gümnaasium	2002	Keskharidus

4.Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Eesti keel	Kesktase
Vene keel	Emakeel
Inglise keel	Kõrgtase

5.Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2011 –	AS ABB	Protsesside arendusinsener
2009 – 2011	AS E-Profiil	Projekteerija ja tehnoloog
2008 – 2008	AS JOT Automation	Projekteerija
2008 – 2008	AS Tammer	Projekteerija
2007 – 2008	AS Ferreks	Projekteerija ja tehnoloog
2006 – 2006	AS BLRT Group	CNC-pingi operaator

DISSERTATIONS DEFENDED AT TALLINN UNIVERSITY OF TECHNOLOGY ON *MECHANICAL ENGINEERING*

1. **Jakob Kübarsepp**. Steel-Bonded Hardmetals. 1992.

2. **Jakub Kõo**. Determination of Residual Stresses in Coatings &Coated Parts. 1994.

3. **Mart Tamre**. Tribocharacteristics of Journal Bearings Unlocated Axis. 1995.

4. **Paul Kallas**. Abrasive Erosion of Powder Materials. 1996.

5. **Jüri Pirso**. Titanium and Chromium Carbide Based Cermets. 1996.

6. **Heinrich Reshetnyak**. Hard Metals Serviceability in Sheet Metal Forming Operations. 1996.

7. **Arvi Kruusing**. Magnetic Microdevices and Their Fabrication methods. 1997.

8. **Roberto Carmona Davila**. Some Contributions to the Quality Control in Motor Car Industry. 1999.

9. **Harri Annuka**. Characterization and Application of TiC-Based Iron Alloys Bonded Cermets. 1999.

10. **Irina Hussainova**. Investigation of Particle-Wall Collision and Erosion Prediction. 1999.

11. **Edi Kulderknup**. Reliability and Uncertainty of Quality Measurement. 2000.

12. **Vitali Podgurski**. Laser Ablation and Thermal Evaporation of Thin Films and Structures. 2001.

13. **Igor Penkov**. Strength Investigation of Threaded Joints Under Static and Dynamic Loading. 2001.

14. **Martin Eerme**. Structural Modelling of Engineering Products and Realisation of Computer-Based Environment for Product Development. 2001.

15. **Toivo Tähemaa**. Assurance of Synergy and Competitive Dependability at Non-Safety-Critical Mechatronics Systems design. 2002.

16. **Jüri Resev**. Virtual Differential as Torque Distribution Control Unit in Automotive Propulsion Systems. 2002.

17. **Toomas Pihl**. Powder Coatings for Abrasive Wear. 2002.

18. **Sergei Letunovitš**. Tribology of Fine-Grained Cermets. 2003.

19. **Tatyana Karaulova**. Development of the Modelling Tool for the Analysis of the Production Process and its Entities for the SME. 2004.

20. **Grigori Nekrassov**. Development of an Intelligent Integrated Environment for Computer. 2004.

21. **Sergei Zimakov**. Novel Wear Resistant WC-Based Thermal Sprayed Coatings. 2004.

22. **Irina Preis**. Fatigue Performance and Mechanical Reliability of Cemented Carbides. 2004.

23. **Medhat Hussainov**. Effect of Solid Particles on Turbulence of Gas in Two-Phase Flows. 2005.

24. **Frid Kaljas**. Synergy-Based Approach to Design of the Interdisciplinary Systems. 2005.

25. **Dmitri Neshumayev**. Experimental and Numerical Investigation of Combined Heat Transfer Enhancement Technique in Gas-Heated Channels. 2005.

26. **Renno Veinthal**. Characterization and Modelling of Erosion Wear of Powder Composite Materials and Coatings. 2005.

27. **Sergei Tisler**. Deposition of Solid Particles from Aerosol Flow in Laminar Flat-Plate Boundary Layer. 2006.

28. **Tauno Otto**. Models for Monitoring of Technological Processes and Production Systems. 2006.

29. **Maksim Antonov**. Assessment of Cermets Performance in Aggressive Media. 2006.

30. **Tatjana Barashkova**. Research of the Effect of Correlation at the Measurement of Alternating Voltage. 2006.

31. **Jaan Kers**. Recycling of Composite Plastics. 2006.

32. **Raivo Sell**. Model Based Mechatronic Systems Modeling Methodology in Conceptual Design Stage. 2007.

33. **Hans Rämmal**. Experimental Methods for Sound Propagation Studies in Automotive Duct Systems. 2007.

34. **Meelis Pohlak**. Rapid Prototyping of Sheet Metal Components with Incremental Sheet Forming Technology. 2007.

35. **Priidu Peetsalu**. Microstructural Aspects of Thermal Sprayed WC-Co Coatings and Ni-Cr Coated Steels. 2007.

36. **Lauri Kollo**. Sinter/HIP Technology of TiC-Based Cermets. 2007.

37. **Andrei Dedov**. Assessment of Metal Condition and Remaining Life of In-service Power Plant Components Operating at High Temperature. 2007.

38. **Fjodor Sergejev**. Investigation of the Fatigue Mechanics Aspects of PM Hardmetals and Cermets. 2007.

39. **Eduard Ševtšenko**. Intelligent Decision Support System for the Network of Collaborative SME-s. 2007.

40. **Rünno Lumiste**. Networks and Innovation in Machinery and Electronics Industry and Enterprises (Estonian Case Studies). 2008.

41. **Kristo Karjust**. Integrated Product Development and Production Technology of Large Composite Plastic Products. 2008.

42. **Mart Saarna**. Fatigue Characteristics of PM Steels. 2008.

43. **Eduard Kimmari**. Exothermically Synthesized B_4C-Al Composites for Dry Sliding. 2008.

44. **Indrek Abiline**. Calibration Methods of Coating Thickness Gauges. 2008.

45. **Tiit Hindreus**. Synergy-Based Approach to Quality Assurance. 2009.

46. **Karl Raba**. Uncertainty Focused Product Improvement Models. 2009.

47. **Riho Tarbe**. Abrasive Impact Wear: Tester, Wear and Grindability Studies. 2009.

48. **Kristjan Juhani**. Reactive Sintered Chromium and Titanium Carbide-Based Cermets. 2009.

49. **Nadežda Dementjeva**. Energy Planning Model Analysis and Their Adaptability for Estonian Energy Sector. 2009.

50. **Igor Krupenski**. Numerical Simulation of Two-Phase Turbulent Flows in Ash Circulating Fluidized Bed. 2010.

51. **Aleksandr Hlebnikov**. The Analysis of Efficiency and Optimization of District Heating Networks in Estonia. 2010.

52. **Andres Petritšenko**. Vibration of Ladder Frames. 2010.

53. **Renee Joost**. Novel Methods for Hardmetal Production and Recycling. 2010.

54. **Andre Gregor**. Hard PVD Coatings for Tooling. 2010.

55. **Tõnu Roosaar**. Wear Performance of WC- and TiC-Based Ceramic-Metallic Composites. 2010.

56. **Alina Sivitski**. Sliding Wear of PVD Hard Coatings: Fatigue and Measurement Aspects. 2010.

57. **Sergei Kramanenko**. Fractal Approach for Multiple Project Management in Manufacturing Enterprises. 2010.

58. **Eduard Latõsov**. Model for the Analysis of Combined Heat and Power Production. 2011.

59. **Jürgen Riim**. Calibration Methods of Coating Thickness Standards. 2011.

60. **Andrei Surzhenkov**. Duplex Treatment of Steel Surface. 2011.

61. **Steffen Dahms**. Diffusion Welding of Different Materials. 2011.

62. **Birthe Matsi**. Research of Innovation Capasity Monitoring Methodology for Engineering Industry. 2011.

63. **Peeter Ross**. Data Sharing and Shared Workflow in Medical Imaging. 2011.

64. **Siim Link**. Reactivity of Woody and Herbaceous Biomass Chars. 2011.

65. **Kristjan Plamus**. The Impact of Oil Shale Calorific Value on CFB Boiler Thermal Efficiency and Environment. 2012.

66. **Aleksei Tšinjan**. Performance of Tool Materials in Blanking. 2012.

67. **Martinš Sarkans**. Synergy Deployment at Early Evaluation of Modularity of the Multi-Agent Production Systems. 2012.

68. **Sven Seiler**. Laboratory as a Service – A Holistic Framework for Remote and Virtual Labs. 2012.

69. **Tarmo Velsker**. Design Optimization of Steel and Glass Structures. 2012.

70. **Madis Tiik**. Access Rights and Organizational Management in Implementation of Estonian Electronic Health Record System. 2012.

71. **Marina Kostina**. Reliability Management of Manufacturing Processes in Machinery Enterprises. 2012.

72. **Robert Hudjakov**. Long-Range Navigation for Unmanned Off-Road Ground Vehicle. 2012.

73. **Arkadi Zikin**. Advanced Multiphase Tribo-Functional PTA Hardfacings. 2013.

74. **Alar Konist**. Environmental Aspects of Oil Shale Power Production. 2013.

75. **Inge Roos**. Methodology for Calculating CO_2 Emissions from Estonian Shale Oil Industry. 2013.

76. **Dmitri Shvarts**. Global 3D Map Merging Methods for Robot Navigation. 2013.

77. **Kaia Lõun**. Company's Strategy Based Formation of e-Workplace Performance in the Engineering Industry. 2013.

78. **Maido Hiiemaa**. Motion Planner for Skid-Steer Unmanned Ground Vehicle. 2013.

79. **Dmitri Goljandin**. Disintegrator Milling System Development and Milling Technologies of Different Materials. 2013.

80. **Dmitri Aleksandrov**. Light-Weight Multicopter Structural Design for Energy Saving. 2013.

81. **Henrik Herranen**. Design Optimization of Smart Composite Structures with Embedded Devices. 2014.

82. **Heiki Tiikoja**. Experimental Acoustic Characterization of Automotive Inlet and Exhaust System. 2014.

83. **Jelena Priss**. High Temperature Corrosion and Abrasive Wear of Boiler Steels. 2014.

84. **Aare Aruniit**. Thermoreactive Polymer Composite with High Particulate Filler Content. 2014.

85. **Dmitri Gornostajev**. Development of the Calculation Method for Barge Hull. 2014.

86. **Liina Lind**. Wear of PVD Coatings on Fineblanking Punches. 2014.

87. **Nikolai Voltšihhin**. Design and Technology of Oxides-Containing Ceramic-Based Composites. 2014.

88. **Aleksander Šablinski**. RANS Numerical Modelling of Turbulent Polydispersed Flows in CFB Freeboard. 2015.

89. **Tanel Aruväli**. Wireless Real-time Monitoring of Machining Processes. 2015.

90. **Andrei Bogatov**. Morphological Changes on Diamond and DLC Films During Sliding Wear. 2015.