THESIS ON MECHANICAL ENGINEERING E71

Reliability Management of Manufacturing Processes in Machinery Enterprises

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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.

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MEHHANOTEHNIKA E71

Tootmisprotsesside usaldusväärsuse haldamine masinaehituse ettevõtetes

MARINA KOSTINA

TTÜ KIRJASTUS

ABSTRACT

Nowadays to be successful on market require from companies a lot of efforts. Success depends on many factors and one of them is reliability and reliable production process particularly. From one side it is caused by external factors - customers demand for high quality and reliable products is increased and from another side by internal factors - without measure of process losses companies cannot estimate how much money they lose monthly due to unreliable production processes. Process reliability is a method for identifying problems, which has significant cost reduction opportunities for improvements. Reliability of production processes is a key issue that ensures the stability of production system operation. It improves product quality and reduces production losses. In this thesis, the focus lays on reliability as a reliability of product manufacturing which is expressed by successful operations, absence of breakdowns and failures.

The aim of the current research is to develop a reliability assessment tool which must help engineers quickly and with great precision estimate the most unreliable places of a production process and to suggest the most efficient ways for the reliability improvement.

In the work, a framework for analysis of failures of production process is introduced, which provides recommendations of corrective actions for elimination of critical faults at machinery manufacturing. In the central part of the proposed framework is the standard FMEA (Failure Mode and Effect Analysis), which gives us not only quantitative assessment of operations failures in the process, but ways of them elimination, therefore it was taken as base for this research.

In this research the Bayesian Belief Network (BBN) is used as a reliability prediction model. The BBN model should be able to predict more effective ways for process reliability improvement in order to provide a basis for decision support. For this aim FMEA-BBN integration method is introduced in the research. Hence, BBN provides a method measuring the effectiveness of recommendations used for process reliability improvement.

The tool developed in this research to analyse a production process enables companies to analyse process as a whole as well as its parts separately and get efficient prognosis for production process improvement. This research provides a systematic approach for estimation of manufacturing process reliability in machinery industry. The reliability analysis model supports the corrective action selection process. The Bayesian Network approach enables to select the appropriate recommendations for work station reliability improvement without significant increase of production cost.

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ABBREVIATIONS

BBN – Belief Bayesian Network
CA – Corrective Action
ERP – Enterprise Resource Planning
FMEA – Failure Mode and Effects Analysis
FRACAS - Failure Reporting Analysis & Corrective Action System
FTA – Fault Tree Analysis
Fuzzy ART - Fuzzy Adaptive Resonance Theory
HACCP - Hazard Analysis Critical Control Point
IDEF0 - Integration Definition for Function Modeling
IEC - International Electrotechnic Committee
MA – Markov Analysis
MTBF – Mean Time Before Failure
MTTF – Mean Time To Failure
MTTR – Mean Time To Repair
QFD - Quality Function Deployment
RBD – Reliability Block Diagram
RCA - Root Cause Analysis
RP – Reliability Prediction
RPN – Reliability Prediction Number
RAM - Reliability, Availability, and Maintainability
SME – Small and Medium Enterprises
TOPSIS - Technique for Order Preference by Similarity to Ideal Solution

CONTENTS

INTRODUCTION

Background

In today's competitive environment companies are increasingly align their organizational structure and competitive strategies to diverse market demands. The companies improve their capability, long term flexibility and responsiveness of this process. Sustainable world class performance begins with a solid foundation that includes reliable assets, stable and repeatable business and work processes and a well-trained and empowered workforce. The production system and its internal structures have been in the central place of the entrepreneurial activities and plans, which foster adaptation to actual market needs. Moreover a reliable production system ensures the sustainability of an enterprise in a dynamic business environment. Thus the system reliability assessment and prediction has become increasingly important which concerns the different stages of the operating process. It is critical to develop efficient reliability assessment techniques for the complicated manufacturing systems, which usually have different failure mechanisms, in order to ensure adequate performance under extreme and uncertain demands (Leangsuksun et al., 2003).

From a classical engineering approach, reliability is defined as the ability of a system or component to perform its required functions under stated conditions for specified period of time. To truly achieve excellence, however, a more holistic view is required. The traditional asset reliability must be expanded to include business and work process reliability and an empowered workforce of engaged employees. Effective leadership and a robust change management methodology support these three foundational concepts.

Thereby today the goal for many plants is to increase overall production reliability, meaning the maximization of output with current resources by reducing waste in equipment reliability and process reliability. In order to do this nowadays there are plenty of standard methods of reliability improvement, equipment maintenance and growth of products quality. However SMEs often encounter with difficulties to implement reliability principles in production due to complexity of the existing methods. Sometimes it is difficult for an enterprise to choose the method mostly suitable for its production. In addition a lot of the standard methods require availability of expensive software and skilled employees.

Another week point of using the standard methods in the intended way is that the most effective use of them is during the development stage of the production process. Thus SMEs face with problems of inefficiency of standard reliability methods application because majority of production processes at SMEs are in running stage for a long time.

Even if a company finally decides that reliability is very important factor and starts analysing and implementing some reliability principles it often faces difficulties on a stage of decision making what to do in order to improve reliability and how to decide what action is the best in every concrete case.

Objective and tasks of the research

The objective of the current research is to develop a reliability assessment tool which must help engineers quickly and with great precision estimate the most unreliable places of a production process and to suggest the most efficient ways for the reliability improvement. In the frame of this objective it is required to extend the existing reliability assessment methods and integrate them into a common framework. The reliability assessment tool must ensure accurate analysis due to constantly renewal data.

During the research the following tasks should be solved:

- State of the art in the field
- Choosing of the most appropriate methods for reliability analysis at machinery enterprises
- Elaboration of the effective decision making methodology for production process reliability growth. Use of Bayesian belief networks in context of a process reliability prediction.
- Connection of the methodology with the standard methods for reliability estimation
- Elaboration of classifier of faults for machine processes
- Qualification of FMEA parameters for reliability estimation
- Practical implementation of the proposed methodology
- Transfer of data from reliability analyzing system to decision making system

Scope of the research

The scope of the thesis has to be formulated to set bounds to an area of the research. Scope and object of the research: SMEs in manufacturing (particularly, a machine building) industry with little, medium or high level of automation; with fully automated or semi-automated production lines. The range of products may vary widely. The methodology is especially suitable for SMEs where the production process is not constant but may vary depending on a production route. The results of the research are mainly oriented on shop-floor operations management.

Hypotheses

Implementation of this method ought to give:

- Significant cost-saving opportunities for industrial enterprises can be achieved through the practical realization of reliability improvement;

- Using of the proposed methodology enables to increase quality of products;
- The integration of technological processes with reliability analysis enables to increase the production process efficiency;
- The planning and scheduling of preventive maintenance activities is often crucial for the cost-effectiveness of many large industrial organizations;
- Implementation of this method can make businesses more profitable by increasing of productivity and decreasing of rejects and rework.

Structure of the thesis

The research is organized in the following sequence (see Fig. 1). The introductive chapter shows the importance of the selected research problem. The main objectives, tasks, scope and hypothesis of the research are formulated.

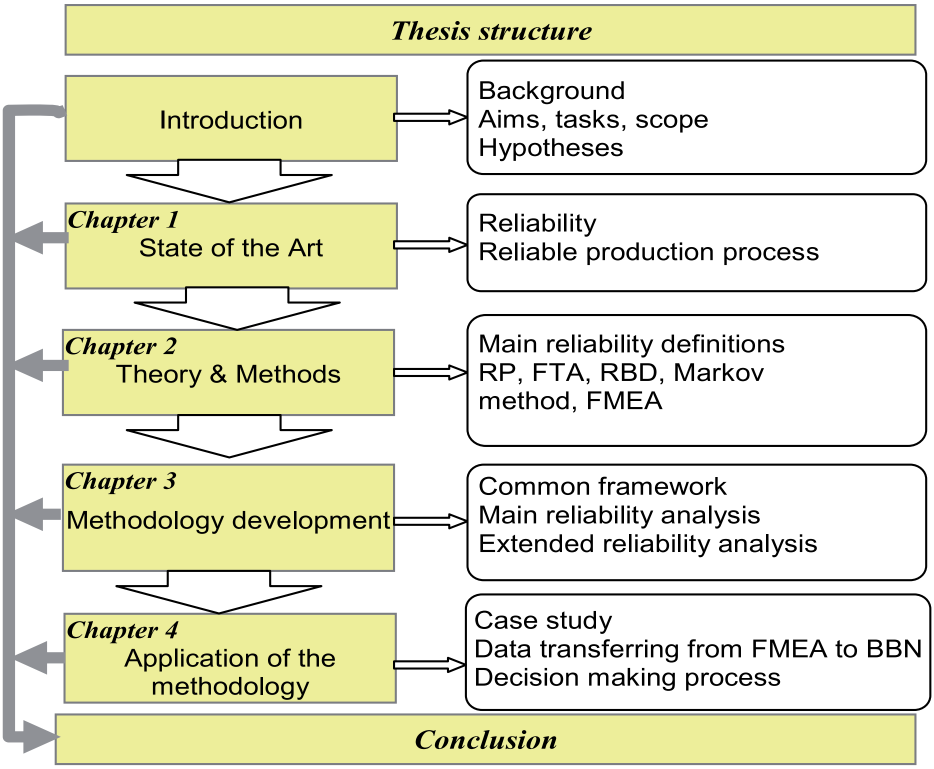


Figure 1. Structure of the thesis

The first chapter is reviewing relevant literature and shows state of the art in the reliability analysis of the manufacturing systems.

The second chapter is overview of the existing theories and methods for processes reliability estimation, consideration of the standard methods in production process reliability field. Particular attention is paid to the FMEA method because in the research it is the main element of an offered methodology of processes reliability improvement.

The third chapter is the main part of the research and contains the offered methodology framework and steps for analysis implementation. The framework consists from two parts: main FMEA-BBN and extended processes analysis by using standard types of reliability analysis and process model.

The fourth chapter is the research case study. It is the practical implementation of the elaborated methodology: Bayesian Belief Networks which is built based on imported data from FMEA table.

1. STATE OF THE ART

1.1 Reliability definition

Sustainable world class performance begins with a solid foundation that includes reliable assets, stable and repeatable business and work processes, and a well-trained, engaged work force.

Reliability is a broad term that focuses on the ability of an item (or system) to perform a required function under stated conditions for a stated period of time (BS 4778, 2012**)**. Mathematically speaking, assuming that an item is performing its intended function at time equals zero, reliability can be defined as the probability that an item will continue to perform its intended function without failure for a specified period of time under stated conditions. A "system" defined here could be an electronic or mechanical hardware product, a software product, a manufacturing process, or even a service.

The definition of reliability has been debated much in literature. In general, two different definitions of reliability can be given, focusing either on the producer's perspective, or on the user's perspective. From the producer's perspective, reliability is defined as a characteristic of an item (amongst others Lewis (1996), Birolini (2007)), i.e.: "the probability that a system will perform its intended function for a specified period of time under a given set of conditions" (Lewis, 1996). Implicit in this definition is the assumption that unreliability is caused by a product failure, and that product failure is an unambiguous concept, since the required function, the conditions and the time interval are explicitly mentioned and defined prior to use.

In this thesis, reliability is looked at from the manufacturer's point of view. In this thesis, the focus on reliability lays on reliability a characteristic of the technical product production. Rather than rigidly defining reliability, reliability is addressed through the aspects that define reliability, i.e.:

- Dependability
- Successful operation
- Absence of breakdowns and failures.

1.1.1 What does 'reliability' mean for engineers

The goal for any plant is to increase overall production reliability, meaning the maximization of output with current resources by reducing waste in equipment reliability and process reliability (the latter is often used in process industry; it may be called "manufacturing reliability" in discrete manufacturing). Equipment and process reliability jointly create reliable production (Idhammar, 2005).

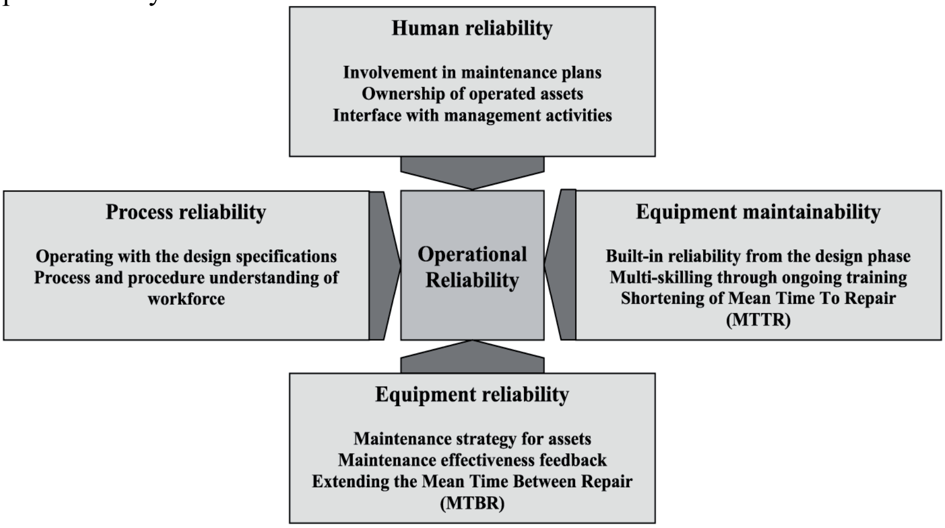
For engineers 'reliability' means (http://wildeanalysis.co.uk/reliability):

- Predicting product/process failures, understanding why the failures occurred.
- Improving the product/process in an objective way
- Creating optimised test plans
- Planning/scheduling maintenance activities and predicting spare part requirements.

The term "reliability" is often used as an overarching concept that includes availability and maintainability. Reliability in its purest form is more concerned with the probability of a failure occurring over a specified time interval, whereas availability is a measure of something being in a state (mission capable) ready to be tasked (i.e., available). Reliability is the wellspring for the other RAM system attributes of Availability and Maintainability (Asthana & Olivieri, 2009), (MIL-HDBK-338B, 1998). Maintenance's primary responsibility is equipment reliability. Lack of equipment reliability creates waste due to failing components, quality losses for the reason of equipment problems, or speed losses because of component wear or breakdowns

1.1.2 Operational reliability

Operations' primary responsibility is process reliability, where the process, or manufacturing, is operating with as little waste as possible. Examples of process waste are quality and production losses due to operating parameters such as setting of pressures, machine speeds, cutting tool selection. In Figure 1.1 are shown main directions for supporting operational reliability of production system.



Source: Duran (2000)

Figure 1.1 Operational reliability (Duran, 2000)

Process reliability and systems engineering are the means to achieve optimum value from physical assets over a facility's lifetime. Thereby, activities are identified that should be completed during each stage of the project life cycle. The application of performance measurements for the operation and support stages is proposed to influence decision making in the process industry.

1.2 Why is reliability important

There are a number of reasons why reliability is an important product attribute, including (http://www.weibull.com/basics/reliability.htm):

- **Reputation.** A company's reputation is very closely related to the reliability of its products. The more reliable a product is, the more likely the company is to have a favourable reputation.
- **Customer Satisfaction.** While a reliable product may not dramatically affect customer satisfaction in a positive manner, an unreliable product will negatively affect customer satisfaction severely. Thus high reliability is a mandatory requirement for customer satisfaction.
- **Warranty Costs.** If a product fails to perform its function within the warranty period, the replacement and repair costs will negatively affect profits, as well as gain unwanted negative attention. Introducing reliability analysis is an important step in taking corrective action, ultimately leading to a product that is more reliable.
- **Repeat Business.** A concentrated effort towards improved reliability shows existing customers that a manufacturer is serious about its product, and committed to customer satisfaction. This type of attitude has a positive impact on future business.
- **Cost Analysis.** Manufacturers may take reliability data and combine it with other cost information to illustrate the cost-effectiveness of their products. This life cycle cost analysis can prove that although the initial cost of a product might be higher, the overall lifetime cost is lower than that of a competitor's because their product requires fewer repairs or less maintenance.
- **Customer Requirements.** Many customers in today's market demand that their suppliers have an effective reliability program. These customers have learned the benefits of reliability analysis from experience.
- **Competitive Advantage.** Many companies will publish their predicted reliability numbers to help gain an advantage over their competitors who either do not publish their numbers or have lower numbers.

1.3 Reliability of production system

What is a production system? The production system reflects the whole enterprise including all required functions, activities, processes, and resources to produce marketable performances (Cochran et al., 2000).

The term "process" generally describes a deliberately-defined sequence of coherent actions in time and space. Objects are processed materials and information. Processes serve three managerial tasks of the production system (Womack & Jones, 1996):

1. Problem solving task: taking running from a concept through a detailed design, engineering of products and dedicated manufacturing systems up to production launch.
2. Information management task: a detailed scheduling running up from an incoming customer order to a delivery.
3. Physical transformation task: the processing started from raw materials up to a finished product delivery to the customer.

Process management contains a body of knowledge for the process improvement. By enhancing efficiency and effectiveness, the process management offers the potential to improve customer satisfaction, followed by increased profits, fast growth, and a sustainable business. Most organizations are motivated to manage their process through several dimensions. In order to increase the profitability, organisations reduce the process cost, increase throughput and improve the quality of products at the same time.

A process management involves five phases (see Fig. 1.2):

1. Process mapping;
2. Process diagnosis;
3. Process design;
4. Process implementation;
5. Process maintenance.

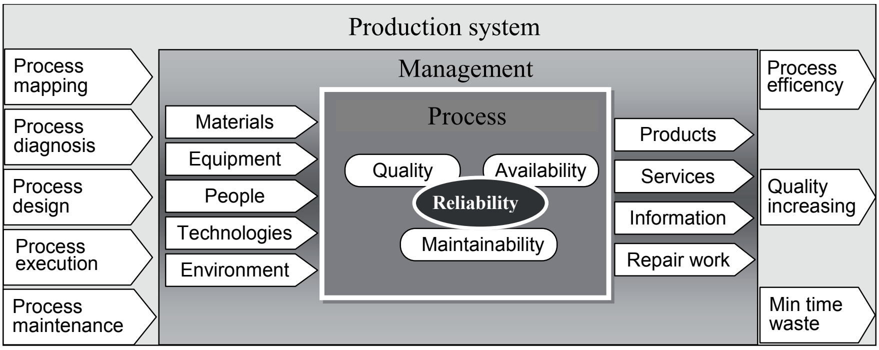


Figure 1.2 Main parameters of a production system

Process reliability is the capacity of equipment or processes to operate without failure. The business issues of reliability are prevention and control of failures to reduce costs for improving customer satisfaction. The process reliability is a method for identifying the problems, which have significant cost reduction opportunities for improvements.

When the complexity of systems increases, their reliability suffers from deterioration. At the same time, more severe requirements are set to the system reliability. A non-sufficient reliability of a system results in:

- Increased operating costs of machines,
- Increased breakdown time of machines;
- Unacceptable rate of malfunctions to occur.

Production starts with the decision to produce and continues until the finished product is complete. Reliability plays a significant role in the overall performance of a manufacturing system. Any undesired stop in this duration can be defined as a failure of a production system. Although many studies have examined reliability of individual components of a production system such as machines and humans, studies on reliability of a production system as a whole are limited in the literature. In terms of effective production planning and control, it is essential to compute the reliability of a production system especially if a company has high costs caused by unmet due dates (Görkemli & Ulusoy, 2010).

Machine reliability has been always recognized as an important factor in most of the performance-related studies. Koren et al. (1998) studied the connection between machine reliability and system productivity, and investigated the system productivity by estimating throughput based on different states of the same system. Zakarian and Kusiak (1997) developed an analytical approach to evaluate the system reliability as a measure of the system performance. They modelled and evaluated process reliability considering the reliability of activities of the process. The overall system availability was evaluated by calculating the probabilities of machine subsets in working condition. Traditionally, machine configuration and process plan are performed with the assumption that all the machines are totally reliable and can be available at any time, which is never the case in practice. Machine failures may have a great impact on the due date and other performance criteria. Disturbances caused by these breakdowns lead to scheduling problems, which decrease the productivity of the entire manufacturing process. However, the adverse effects of machine breakdowns are different. Highly automated mass production systems are more sensitive to the reliability changes. Comparably, job shop manufacturing systems are more flexible in dealing with the machine failures (Sun et al., 2008).

Reliability modelling and analysis of the multi-operational manufacturing systems have drawn extensive attention, both from single machine level and system level. Machine-level reliability is the statistical measurement of the reliability of the tool components within a machine, typically from their individual operational historical data. Meanwhile, system-level reliability is the joint reliability estimation of its constituent machines or subsystems. Wang et al. (2001) investigated the statistical distribution to characterize the reliability of machining centres, and found that the failure process best fit an exponential distribution. Chen et al. (2004) proposed the integration of dimensional quality and locator reliability for the body-in-white assembly in the automotive industry. However, the model used in the assembly process could not be directly applied to the machining process.

Complex systems may have both kinds of uncertainty. Researchers have stated that probability theory can be used in concept with fuzzy set theory for the modelling of complex systems (Zadeh, 1995), (Barrett and Woodall, 1997), (Ross et al., 2003) and (Singpurwalla and Booker, 2004). Bayesian statistics provide a natural framework combining random and non-random uncertainty so fuzzy Bayesian methods are developed for the solutions of the reliability problems. The proposed model of a production system is solved using the fuzzy Bayesian reliability method developed by (Wu, 2004) and (Wu, 2006). Using the definition of fuzzy random variables, an interval containing all the fuzzy Bayes point estimators of system reliability is defined. Membership function of the fuzzy Bayes point estimator is evaluated under resolution identity theorem.

Mathematical and statistical methods can be used for quantifying reliability (prediction, measurement) and for analysing reliability data. However, because of the high levels of uncertainty involved these can seldom be applied with the kind of precision and credibility that engineers are accustomed to when dealing with most other problems. In practice the uncertainty is often in orders of magnitude. Therefore the role of mathematical and statistical methods in reliability engineering is limited, and appreciation of the uncertainty is important in order to minimize the chances of performing inappropriate analysis and of generating misleading results. Mathematical and statistical methods can make valuable contributions in appropriate circumstances, but practical engineering must take precedence in determining the causes of problems and their solutions. Unfortunately not all reliability training, literature and practice reflect this reality (O’Connor et al., 2002).

1.4 Reliability engineering

Reliability theory is the foundation of reliability engineering. For engineering purposes, reliability is defined as the probability that a system will perform its intended function during a specified period of time under stated conditions. Reliability engineering is performed throughout the entire life cycle of a system, including development, testing, production, and operation.

Reliability engineering is a strategic task concerned with predicting and avoiding failures. For quantifying reliability issues it is important to know why, how, how often, and costs of failures. In the real world all potential failures are seldom well known or well understood which makes failure prediction a probabilistic issue for reliability analysis.

1.4.1 The objectives and functions of reliability engineering

The objectives of reliability engineering, in the order of priority, are (O’Connor et al., 2002):

1. To apply engineering knowledge and specialist techniques to prevent or to reduce the likelihood or frequency of failures.
2. To identify and correct the causes of failures that do occur, despite the efforts to prevent them.
3. To determine ways of coping with failures that do occur, if their causes have not been corrected.
4. To apply methods for estimating the likely reliability of new designs, and for analysing reliability data.

The main function of reliability engineering is to develop the reliability requirements for the system, design the system or product to meet the reliability requirements, establish an adequate reliability program, and perform appropriate analysis to monitor the actual reliability of the system or product during its life. Reliability improvement can be thought of as a process or main elements of the process, which are (http://www.exponent.com/reliability_engineering/):

- Reliability strategies
- System or product design
- Failure modes and effects analysis
- Reliability modelling and estimation
- Reliability testing (accelerated life-cycle tests)
- Quality assurance strategies
- Work management and execution
- Continuous improvement

Continuous improvement is the process by which an organization learns from the performance of each in the process and applies that knowledge to improve effectiveness and efficiency through each process cycle. It includes proper work closeout procedure, as well as a comprehensive corrective action program (and culture), bolstered by a robust root-cause analysis program. The proper application of metrics and/or key performance indicators also plays a key role in this element.

Reliability policies must integrate safety, quality, risk, and financial requirements for the company to achieve the business objectives. Reliability policies must be understandable to the common person and come from top levels of management for credibility, legitimacy, constancy of purpose for improvements, and setting the organization to work for a common objective (Barringer, 2004).

1.4.2 The benefits of reliability engineering

The main benefits of Reliability Engineering are summarized as follows (Benbow & Broom, 2009):

- Achieve the final customers expectations about the functionality and expected life of the specific component, product or system
- Decrease all foreseeable equipment safety and health hazards
- Improve Reliability and Availability of the systems (decrease failure rates)

- Accomplishment of the Production Objectives
- Improve marketing and warranty material

Reliability Engineering is achieved by conducting and managing different processes throughout the lifecycle of the system or facility. Different engineering tools and tasks are used during the following projects stages:

- Development and Design
- Manufacturing, Construction and Commissioning
- Service or Operation
- Decommissioning and Abandonment

The business objective is to minimize and mitigate all foreseeable risks (i.e. safety, environmental, business and reputation) by conducting diverse reliability processes.

1.4.3 The most important reliability activities

The reliability evaluation of a product or process can include a number of different reliability analyse. Depending on the phase of the product lifecycle, certain types of analysis are appropriate. As the reliability analysis is being performed, it is possible to anticipate the reliability effects of design changes and corrections. The different reliability analysis are all related, and examine the reliability of the product or system from different perspectives, in order to determine possible problems and assist in analyzing corrections and improvements (O'Connor et al., 2002).

Realistically, it is impossible to avoid all feasible failures of a system or a product on the design stage, so one of the goals of reliability engineering is to recognize the most expected failures and then to identify appropriate actions to mitigate the effects of those failures (Lendvay, 2004).

The most important reliability activities are (Benbow & Broom, 2009):

- Reliability Data Collection such as previous projects lessons learned, risk review, technology qualification status, benchmarking, etc
- Probability and Statistics
- Reliability Testing
- Reliability Modelling: FMECA, FTA, RBD, ETA, RCA, RAM
- Reliability in Design and Development
- Reliability, Maintainability and Availability
- Failure Analysis and Correction (FRACAS) (http://imrconsulting.net/?page_id=31)

These methods are not new! – FMEA in aerospace dates back to the late 1940s, Weibull analysis was first described in a 1951 paper by Waloddi Weibull and modern DoE dates back to 1935 with the work of Sir Ronald Fisher for instance. However, it is my experience that they are not deployed across industry to their maximum business effectiveness (http://wildeanalysis.co.uk/casestudies/reliability-engineering-in-product-design).

FRACAS (Failure Reporting Analysis & Corrective Action System). All high reliability companies have a formal FRACAS system. This could be implemented in a bespoke relational database or in a series of spreadsheets. A FRACAS system is simply a closed-loop recording and control system for capturing, collating and analysing failure data in order to prioritise and manage corrective actions. It is the starting point for many reliability engineering processes such as FMEA, DoE and accelerated testing.

RCA (Root Cause analysis) is the underlying reason for a failure, anything else is just a symptom. RCA is simply the systematic search for the underlying reasons for failure. The tools of RCA are equally simple – but can be effectively applied to complex problems. Typical RCA tools are brainstorming, check sheets, Pareto analysis, process maps, cause & effect diagrams.

- It is important to realise that every product failure has:
- set-up factors that established the vulnerability;
- triggering factor(s) that enabled the vulnerability;
- exacerbating factors that made the effect as bad as it was;
- mitigating factor(s) that kept the effect from being worse.

It should be noted that in real life there is never one single root cause – and that each root cause can have a ‘physical’ a ‘systemic’ and a ‘human’ component. RCA is an essential component of an effective FRACAS system.

Reliability engineering can be done by a variety of engineers, including reliability engineers, quality engineers, test engineers, systems engineers or design engineers. In highly evolved teams, all key engineers are aware of their responsibilities in regards to reliability and work together to help improve the product.

The reliability engineering activity should be an ongoing process starting at the conceptual phase of a product design and continuing throughout all phases of a product lifecycle. The goal always needs to be to identify potential reliability problems as early as possible in the product lifecycle. While it may never be too late to improve the reliability of a product, changes to a design are orders of magnitude less expensive in the early part of a design phase rather than once the product is manufactured and in service (http://www.weibull.com/basics/reliability.htm).

1.5 Reliable manufacturing process

A process is a sequence of activities which are performed across time and place. A process also has a well defined beginning and end with identifiable inputs and outputs (see Fig.1.3).

Process reliability is a method for identifying problems, which have significant cost reduction opportunities for improvements. It started with the question: “Do I have a reliability problem or a production problem?”

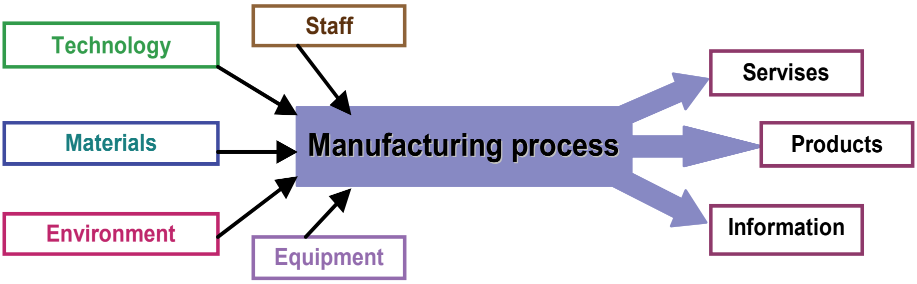


Figure 1.3 Input/Output of a manufacturing process

Sometimes the problems are identified with a root for maintenance improvements. Very often the problems have roots in the operations area (Barringer, 2000). Strict requirements of reliability on modern devices, long-term error-free operation, durability, reparability, storability, make is necessary to determine as a most important technical parameters of industrial production process (Lendvay, 2004)

Even though a product has a reliable design, when the product is used in the field, its reliability may be unsatisfactory. The reason for this low reliability may be an unreliable manufacturing process. If we look back at the definition of reliability it can be said that in terms of a production process the definition means that a reliable production process must fulfil its function or in other words produce qualified products in required time. In case one of these two characteristics does not fulfil the requirements the production process becomes unreliable. Unreliable production processes waste money. Few companies know or measure the reliability of their processes. All unmeasured processes are verbalized as reliable. This fantasy continues until the process is measured. Most processes are unreliable and thus need improvements (http://www.barringer1.com/pdf/Barringer-Reliability-Review-Article.pdf).

In order to monitor and control different system processes, researchers used numerous types of modelling techniques. In the literature on process industry, the majority of researches have been devoted to a consideration of process deterioration or process breakdown, without regarding management requirements. Among these researches, numerous analyses have examined the effects of process deterioration on the optimal lot sizing problems (Rahim & Ben-Daya, 2001), (Rahim & Ohta, 2005), (Kim & Hong, 2001), (Wang & Sheu, 2001), (Porteus, 1986), (Kim & Hong, 1999), (Lee & Park, 1991), (Rahim & Al-Hajailan, 2006).

Every excellent process first needs availability. Availability, in the most simple form, is uptime/(uptime + downtime). Detractors from availability are downtime (unavailability).

Transients occur during the rise to availability or fall from availability as production output varies because of start-up/shut-down conditions. Transients are detractors from excellent processes. Transients also represent the loss of function when it is needed, which is a failure just as obvious downtimes which occur from failures.

Plants designed for excellence use detailed availability calculations based on reliability and maintainability (RAM) models to make availability calculations rather than simply state a hopeful number than cannot be demonstrated. RAM models use equipment life and equipment repair times to find central tendency for operational availability. RAM models also estimate the expected number of annual plant failures. Calculated availability values avoid the usually optimistic "best guesses" which often do not include detailed plans for excellent performance.

Excellent processes consistently have optimally large output quantities, small output variability, and the products produce conform to the contract specifications. Performance from excellent processes is both predicable and reliable (Barringer, 2004).

1.5.1 Manufacturing process variability

The main cause of production–induced unreliability is the variability inherent in production process. Variability exists in all production systems and can have an enormous impact on performance. For this reason, the ability to measure, understand, and manage variability is critical to effective manufacturing management (Hoop & Spearman, 2000).

Variability plays a vital role in determining the reliability of most products and processes. Therefore understanding the causes and effects of variability is necessary for the creation of reliable products and for the solution of problems of unreliability (O'Connor et al., 2002).

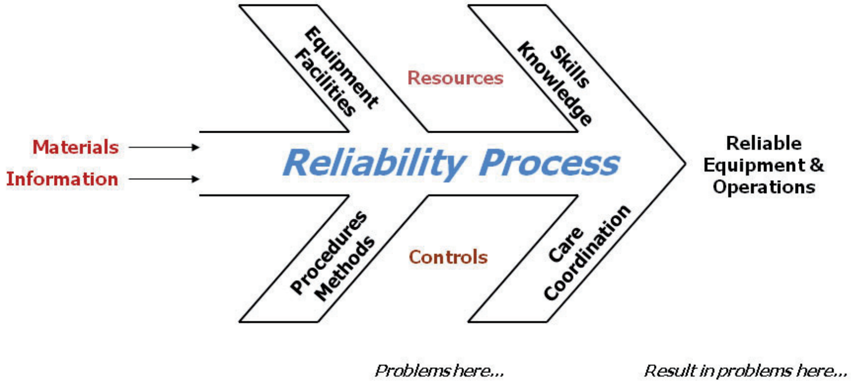


Figure 1.4 Factors influencing variation in the process (http://www.itrco.com/Reliability/ReliabilityProcess/Default.aspx)

By nature, all processes exhibit some variation. When reliability is viewed as a process, reliability and maintenance professionals understand there are two types of variation: controlled and uncontrolled. Controlled variation is usually associated with common causes and is consistent over time. Uncontrolled variation is usually associated with special causes and changes over time. As can be seen in the process diagram below (see Fig. 1.4), there are many factors influencing variation.

Reliability team strives to help customers reduce controlled variation and eliminate all uncontrolled variation through the use of predictive technologies. Controlled variation in the reliability process can be caused by routine equipment wear and the influence of planned preventive maintenance, among many other factors. Examples of causes of uncontrolled variation include unplanned outages due to catastrophic equipment failures and spare part stock outs.

1.6. Quality of manufacturing process

Quality concept now applied not only to the products but also to the manufacturing processes. Many versions of process improvement techniques, steps, and procedures have been defined and developed. These include Deming's 14 points for process quality improvement (Neave & Detoro, 1990), business process reengineering (Morris & Brandon, 1993), and continuous process improvement (Imai, 1986). However, as pointed by Janakiram and Keats (Janakiram &Keat, 1995), few researchers or engineers use the Failure Mode and Effects Analysis (FMEA) techniques as a process quality improvement tool. As a result, they suggested its use in quality improvement programs and indicated how it could be applied.

1.7 Failure Mode and Effects Analysis for process quality improvement

Firstly FMEA was introduced in 1960s by Americans for improving of reliability in aerospace industry. Since that time FMEA was repeatedly improved and in 1977 it was announced by Ford Motor Company as the operation standard. Several industrial FMEA standards have been developed later on and are widely used, for example MIL-HDBK-1629A (1984) (US Department of Defence), Automotive Industry Action Group (AIAG) (1993) and Society of Automotive Engineers (SAEARP5580) (2001). In spite of this FMEA still has some shortcomings and number of methodologies have been proposed to eliminate these shortcomings. For instance prioritizing of RPN is often considered as the weakest sides of FMEA so in 1990s some authors (Raheja 1991, De Risi 1996) suggested to prioritize failure modes by defining threshold for RPN parameter: if RPN is greater than, for example, 100 it is required to implement some improvements. However this tactics shows itself like inefficient because during preparation of FMEA an evaluating team may unconsciously diminish severity, occurrence or detection parameter in order to get RPN lower that the threshold.

In 2001 it was proposed by Franceschini and Galetto to define failure mode priorities using Multi Expert - Multiple Criteria Decision Making (ME – MCDM) technique. The novelty of the method consists of new management of data provided by the design team, normally given on qualitative scales, without necessitating an arbitrary and artificial numerical conversion (Franceschini & Galetto, 2001).

In 2002 it was proposed by Puente to structure expert knowledge in the form of qualitative decision rules whereby a risk priority category can be assigned to each cause of failure. This effectively mitigates one of the main criticisms aimed at the traditional model, since the structure of the rule system being proposed allows considerable weighting of the severity index "S" associated to a cause of failure. Additionally to this proposal, a fuzzy decision system is proposed, which increases the continuity of the FMEA decision model, and which optimizes risk discrimination of different causes of failure (Puente et al., 2002).

In 2010 it was suggested by Sharma to use principles of fuzzy logic and decision making system to model the discrepancies associated with the traditional procedure of risk ranking in FMEA. Using of this method allows the maintenance managers to understand the behavioural dynamics of the respective units and the analysts to predict the reliability measure for the system(s) and take necessary steps to improve system performance (Sharma & Sharma, 2010).

In 2008 Aidini and Ozkan have introduced the method named Fuzzy Adaptive Resonance Theory (Fuzzy ART), one of the ART networks, to evaluate RPN in FMEA. They propose to evaluate severity, occurrence and detection values constituting RPN value independently for each input. Thus, in case when two RPN values are equal to each other, FMEA values are evaluated separately with severity, detection and occurrence values rather than with a multiple of these parameters (Keskin & Ozkan, 2008).

In 2008, it was proposed to improve FMEA from economical point of view by Ahsen. The idea was to evaluate severity of failures from economical perspective. This gives more realistic estimation of failures which is sometimes totally contrasted to traditional RPN estimation (Ahsen, 2008).

In 2009 Sachdeva proposed to combine FMEA with technique for order preference by similarity to ideal solution (TOPSIS). This unification allows finding RPN more punctually and therefore estimating failure modes more precisely (Sachdeva et al., 2009).

In 2004 Arcidiacono suggested the FMETA method for evaluating of reliability. This method is a combination of FMEA and FTA. As he proposed FMEA is used here for making cause and effect relationship and FTA gives an opportunity to analyze and optimise the most critical events (Arcidiacono & Campatelli, 2004).

Of course there are other methods of combining FMEA with for example quality control techniques and some of them are introduced in Table 1.1. However we are not interested in those methods in the frame of this thesis because they do not propose estimation of RPN.

Table 1.1 Combining of FMEA with other techniques proposed by different authors

Authors	Subject	Methods
Ginn et al. (1998), Al-Mashari et al. (2005), Yanik (2010), Bosch & nríquez (2005)	Combining of QFD and FMEA in order to support upstream design and planning, and downstream problem solving and prevention	FMEA and QFD
Bertolini et al. (2006)	Combining of FMEA and Petri nets in order to simulate the reliability behaviour of a complex system	FMEA and Petri nets
Shahin (2004)	Estimating of severity parameter and RPN in FMEA from customer point of view	FMEA and Kano model
Varzakas & Arvanitoyannis (2007)	Combining of FMEA and HACCP in order to prevent reoccurring of failures and using of Pareto diagram to optimise detection of failures	FMEA and HACCP

1.8 Conclusions of Chapter 1

Customers are placing increased demands on companies for high quality, reliable products. Reliability, from an engineering perspective, is commonly defined as the likelihood of a system performing its intended function under planned and unplanned circumstances. Reliability of production processes is a key issue to ensuring a stable system operation, increasing a product quality, and reducing production losses. Traditionally, reliability has been achieved through extensive testing and use of techniques such as probabilistic reliability modelling. These are techniques done in the late stages of development. The challenge is to design in quality and reliability early in the development cycle.

FMEA is methodology for analyzing potential reliability problems early in the development cycle where it is easier to take actions to overcome these issues, thereby enhancing reliability through design. FMEA is used to identify potential failure modes, determine their effect on the operation of the product, and identify actions to mitigate the failures. A crucial step is anticipating what might go wrong with a product. While anticipating every failure mode is not possible, the development team should formulate as extensive a list of potential failure modes as possible.

The early and consistent use of FMEAs in the design process allows the engineer to design out failures and produce reliable, safe, and customer pleasing products. FMEAs also capture historical information for use in future product improvement.

2. BASICS AND MAIN METHODS OF RELIABILITY PREDICTION

Literature discusses many qualitative as well as quantitative methods for reliability prediction. However, in this thesis, the focus lies neither in providing an extensive description of the different methods, nor in the exhaustive identification of the available methods. This section discusses only a limited number of reliability prediction methods.

The descriptions of the methods include a short description of the goal of the method, of the way in which it is applied as well as a discussion on the way in which the methods deal with the issues regarding reliability prediction. The techniques that are included in the discussion are a number of widely-used techniques.

2.1 Basics of reliability

Reliability is the probability that a system will operate successfully for a specified period of time, under specified conditions, when used for the manner and purpose for which it was intended (MIL-HDBK-338B, 1998).

The Table 2.1 describes some of the fundamental terms connected to reliability:

Table 2.1 The fundamental reliability terms (Speaks, Scott, 2001)

Reliability Measure	Description
Failure	An event, or inoperable state, in which any item or part of an item does not, or would not, perform as previously specified
Failure Rate	The expected rate of occurrence of failure or the number of failures in a specified time period. Failure rate is typically expressed in failures per million or billion hours
Mean Time Between Failures (MTBF)	The number of hours to pass between failures. MTBF is typically expressed in hours.
Mean Time To Failure (MTTF)	The average time to failure for a system that is not repairable. Once a failure occurs, the system cannot be used or repaired.
Mean Time To Repair (MTTR)	It is the expected span of time from a failure (or shut down) to the repair or maintenance completion. This term is typically only used with repairable systems.

As is mentioned above the reliability, *R(t),* of the component is the probability of a component surviving to a time *t* and is expressed as

$$R(t) = \int_t^{\infty} f(t)dt \tag{2.1}$$

where *f(t)* is the probability density function of the random variable, time to failure.

The rate at which failures occur in the interval t_1 to t_2 , the failure rate, $\lambda(t)$, is defined as the ratio of probability that failure occurs in the interval, given that it has not occurred prior to t_1, the start of the interval, divided by the interval length.

$$\lambda(t) = \frac{R(t)-R(t+\Delta t)}{\Delta t R(t)} \tag{2.2}$$

The failure rate can therefore be defined as the probability of failure in unit time of a component that is still working satisfactorily. For constant failure rate λ, which is true for many cases, $R(t)$ is given by

$$R(t) = e^{-\lambda t} \tag{2.3}$$

(MIL-HDBK-338B, 1998).

A common graphical interpretation of the failure rate is shown in Figure 2.1. This model is known as the “bathtub” curve and was initially developed to model the failure rates of mechanical equipment.

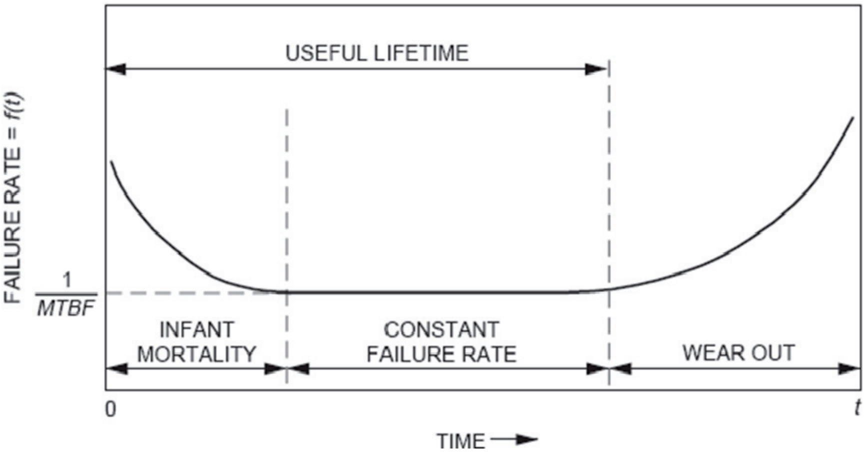


Figure 2.1 Failure rate bathtub curve

(Kayali, Ponchak, Shaw, 1996)

The failure rate is theorized to be high at the start, dropping off as the weaker devices fail early. The failure rate then approaches a constant as the components enter their useful lifetime. Failures in this period can be attributed to random overload of the components. Finally, wear-out occurs and the curve increases sharply.

2.2 Commonly used methods for reliability estimation

Because reliability is such a crucial element to business success, analysis techniques and methods have been developed over time to help analyze and measure reliability to enable companies to improve areas of weakness.

According to the international standard 300-3-1 of International Electrotechnic Committee (IEC) the mostly used reliability procedures are:

- Reliability Prediction,
- Reliability Block Diagram,
- Fault Tree Analysis,
- Markov Analysis,
- Fault Mode and Effects Analysis (Lendvay, 2004).

2.2.1 Reliability Prediction

Reliability Prediction (RP) is one of the most common forms of reliability analysis. RP predicts the failure rate of components and overall system reliability. A reliability prediction can also assist in evaluating the significance of reported failures. Ultimately, the results obtained by performing a reliability prediction analysis can be useful when conducting further analyses such as RBD (Reliability Block Diagram) or FTA (Fault Tree analysis).

At a given point in time, a component or system is either functioning or it has failed, and that the component or system operating state changes as time evolves. A working component or system will eventually fail. The failed state will continue forever, if the component or system is non-repairable. A repairable component or system will remain in the failed state for a period of time while it is being repaired and then transcends back to the functioning state when the repair is completed. This transition is assumed to be instantaneous. The change from a functioning to a failed state is failure while the change from a failure to a functioning state is referred to as repair. It is also assumed that repairs bring the component or system back to an “as good as new” condition. This cycle continues with the repair-to-failure and the failure-to-repair process; and then, repeats over and over for a repairable system (ITEM Software, 2007).

These states are characterized by following categories: the mean time to failure (MTTF), the mean time to repair (MTTR) and the mean time between failures (MTBF) (see Fig. 2.2).

MTTF is a basic measure of reliability for non-repairable systems. MTTF is the number of total working hours (uptime) of all devices divided by the number of breakdowns.

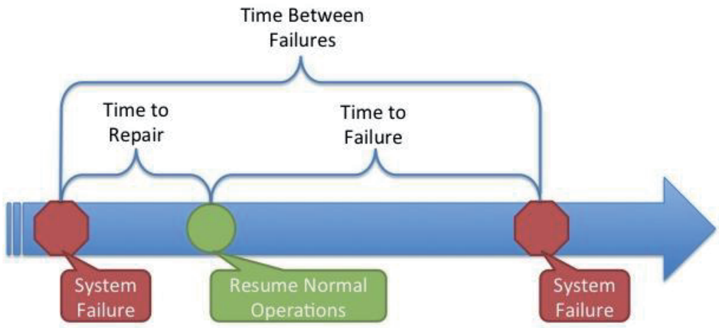


Figure 2.2 One cycle of MTTF, MTTR and MTBF (http://blog.fosketts.net)

$$MTTF = T_{up}/N, \tag{2.4}$$

where

T_{up} = total uptime

N = Number of breakdowns.

MTTR is defined as the total amount of time spent performing all corrective or preventative maintenance repairs divided by the total number of those repairs. It is the expected span of time from a failure (or shut down) to the repair or maintenance completion. This term is typically only used with repairable systems.

$$MTTR = T_{down}/N, \tag{2.5}$$

where

T_{down}= total downtime

N = number of breakdowns

MTBF is a basic measure of reliability for repairable items. MTBF considers total time from one failure to the next failure and is often calculated as a sum of MTTR and MTTF

$$MTBF = MTTR+MTTF \tag{2.6}$$

Taking into consideration equations 2.4 and 2.5, the equation 2.6 becomes

$$MTBF = \frac{T_{up}+T_{down}}{N} \tag{2.7}$$

Advantages of RP:

- time and cost claim of analysis is small,
- allows preparing maintenance strategy.

Disadvantages of RP:

- don’t analyse fault cause and effects,
- date are in running stage.

2.2.2 Reliability Block Diagram

Reliability Block Diagram (RBD) is a deductive method to evaluate reliability of a system. RBD gives a graphical analysis of logical structure of the system, on which individual partial systems and/or parts some reliability connections exist. This method allows representing the possible ways of successful operation of the system by those arrays (partial systems/components) the common operation of which is necessary for the operation of the system. There are several methods for evaluation of the reliability diagram. Depending on the type of the system structure, simple Boolean-like methods, analysis of the successful way of operation as well as truth tables can be used to predict the reliability and usability of the system.

The rational course of a RBD stems from an input node located at the left side of the diagram. The input node flows to arrangements of series or parallel blocks that conclude to the output node at the right side of the diagram. A diagram should only contain one input and one output node.

The RBD system is connected by a parallel or series configuration. A parallel connection is used to show redundancy and is joined by multiple links or paths from the Start Node to the End Node. A series connection is joined by one continuous link from the Start Node to the End Node.

A system can contain a series, parallel, or combination of series and parallel connections to make up the network (see Fig. 2.3) (ITEM Software, 2007).

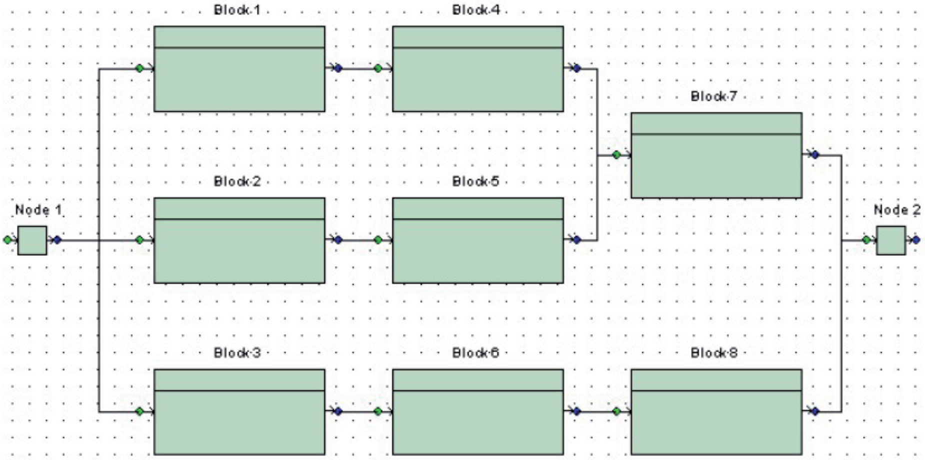


Figure 2.3 An example of RBD

Advantages of RBD:

- most types of system configuration are demonstrated,
- analyses the combined events,
- values simply functional and non-functional units with Boole-algebra.

Disadvantages of RBD:

- don’t give cause and effects ways,
- must know reliability functions for every events,
- don’t examine complicated repair and maintenance strategies.

2.2.3 Fault Tree Analysis

The Fault Tree Analysis (FTA) tool deals with determination and analysis of conditions and factors that cause an occurrence of a preliminary defined not desired event, or that significantly effect on the operation, safety, economy or other prescribed parameter of the system. As was mentioned above, FMEA is considered a "bottoms up" analysis, whereas an FTA is considered a "top down" analysis. This tool evaluates system (or sub-system) failures one at a time but can combine multiple causes of failure by identifying causal chains. The results are represented pictorially in the form of a tree of fault modes (see Fig. 2.4).

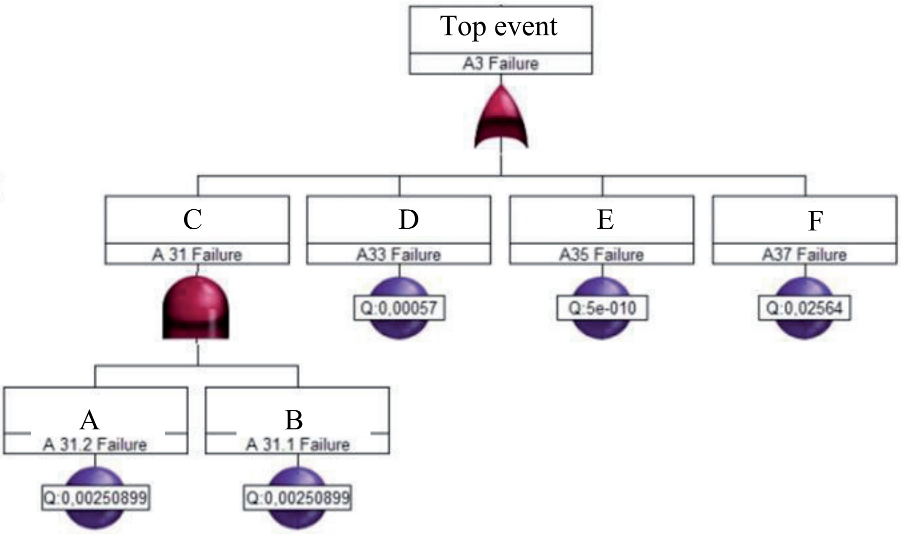


Figure 2.4 An example of FTA

Numerical analysis is performed on the basis of the fault tree. Faultless condition of a system, its usability parameters are estimated using methods of Boolean algebra. At each level in the tree, combinations of fault modes are described with logical operators: AND (see Fig. 2.5 a), OR (see Fig. 2.5 b), EVENT (see Fig. 2.5 c), etc. AND gate denotes that an output fault event occurs only if all the input fault events occur. Probability of failure for AND gate is calculated according Equation 2.8:

$$P_F = P_A * P_B \tag{2.8}$$

OR gate denotes that an output fault event occurs if one or more of the input fault events occur. Probability of failure for OR gate is calculated according Equation 2.9:

$$P_F = P_A + P_B - P_A * P_B \tag{2.9}$$

EVENT represents a resultant event that results from the combination of fault events through the input of a logic gate. FTA relies on the experts' process understanding to identify causal factors.

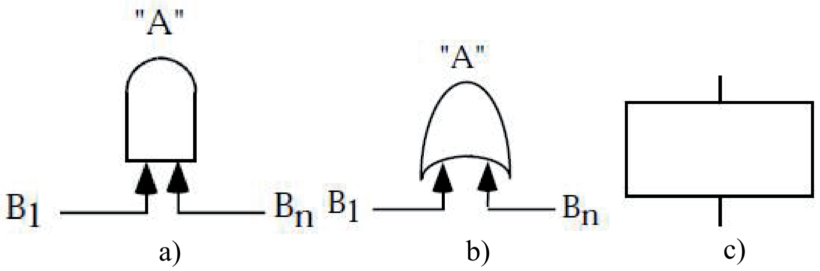


Figure 2.5 a) AND gate, b) OR gate, c) EVENT

FTA can be used to establish the pathway to the root cause of the failure. FTA can be used to investigate complaints or deviations in order to fully understand their root cause and to ensure that intended improvements will fully resolve the issue and not lead to other issues (i.e. solve one problem yet cause a different problem). FTA is an effective tool for evaluating how multiple factors affect a given issue. The output of an FTA includes a visual representation of failure modes. It is useful both for risk assessment and in developing monitoring programs.

Advantages of FTA:

- identifies the logical way of failures,
- demonstrates redundancy systems, logical way of defects,
- prepares ways to failures simply.

Disadvantages of FTA:

- very big trees can be because of detailed analysis,
- don't present state transition ways,
- don't examine complicated repair and maintenance strategies.

2.2.4 Markov Analysis

The Markov Analysis (MA) is another old and well-proven reliability technique. It is time dependent approach, i.e. given state probabilities depending on time. For a safety system it should then be derived the time dependent solution for the interval T, and then calculated the average over the interval (Hokstad et al, 2009).

Markov Analysis is mainly an inductive analysing method; it is suitable for analysing of functionally complex structures and repair/maintenance strategies.

The method uses the theory of Markov processes. Theoretically it evaluates probability of being in a given functional status of system elements (parts, partial systems) or probability of occurrence of given events at given times or periods (Lendvay, 2004).

Markov model is a state diagram model with circles and arrows (see Fig. 2.6). The circles represent the component states (working or failed), the arrows stand for the direction of transitions between the states (failure or repair), so the arrows are directed arcs. The failure or repair rates are presented by the arrows with numeric values.

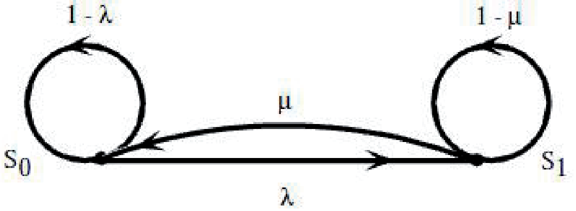


Figure 2.6 An example of simple Markov model

The unit is in state S_0, if it is successful, or in state S_1, if it failed. The model can move from state S_0 to state S_1 at a rate of λ (the failure rate), or from state S_1 to state S_0 at μ (the repair rate) (Matijevics & Jeges, 2005).

Advantages of MA:

- identifies operating and non-operating state of systems with random variable,
- demonstrates multi-state events,
- values complicated repair events.

Disadvantages of MA:

- because of big number of system-state can be too complicated,
- don’t help logical solution of problems,
- supposes constancy of state transition rates.

2.2.5 Failure Mode and Effects Analysis

Failure Mode and Effects Analysis (FMEA) is a reliability procedure which provides an evaluation of potential failure modes for processes and their likely effect on outcomes and/or product performance. It determines, by 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 suitably especially when it is examined what effects have faults of basic materials, parts and equipment on the next functional level of higher order, and what fault mechanism can be established at this level. FMEA can be applied to equipment and facilities and might be used to analyze a manufacturing operation and its effect on 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, 2006).

In performing the analysis, each failure studied is considered to be the only failure in the system, i.e., a single failure analysis. FMEA utilizes inductive logic in a "bottoms up" approach. Beginning at the lowest level of the system hierarchy and from a knowledge of the failure modes of each part, the analyst traces up through the system hierarchy to determine the effect that each failure mode will have on system performance (MIL-HDBK-338B, 1998).

There is a person responsible for making of FMEA however collection of FMEA data must be performed within the frames of a team-work. The group should be possibly compiled of experienced specialists, for example of engineers from the area of designing, manufacturing, mounting, repairing, quality and testing.

Row no.	Process name	Process Description	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause of Failure	Occurrence	Current Controls Prevention	Current Controls Detection	Detection	RPN	Recommended Action(s)	Action Results			
			Failure description			Description							Sev	Occ	Detec	RPN

Figure 2.7 A FMEA form

FMEA is presented in form of a table (see Fig. 2.7). Every row is a single failure mode which is described by number of characteristics: how must be, what can fail, effect and cause of this fail and current control. Once failure modes are established, risk reduction can be used to eliminate, contain, reduce or control the potential failures.

Also every failure mode is evaluated by three main characteristics: Severity (S), Occurrence (O) and Detection (D). Severity means criticality of a failure, occurrence is how often the failure happens and detection means what kind of control we have in a process to detect the failure. All three parameters are estimated on a scale of “1” to “10”. Ranks for estimation of each characteristic are given in Tables 2.2-2.4.

Table 2.2 Ranks for severity estimation

Severity of Effect on Product	Rank	Severity of 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 2.3 Ranks for occurrence estimation

Likelihood of Failure	Occurrence of Causes	Occurrence Rank
Very High	>1 per 10	10
High	1 in 20	9
	1 in 50	8
	1 in 100	7
Moderate	1 in 500	6
	1 in 2000	5
	1 in 10000	4
Low	1 in 100000	3
	1 in 1000000	2
Very Low	Failure eliminated by preventive control	1

Table 2.4 Ranks for detection estimation

Detection by Process Control	Detection Rank
No current process control; cannot detect; is not analysed	10
Failure and errors are not easily detected (e.g. random process 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

As a result RPN number is calculated as a multiplication of S, O and D.

$$RPN = S \times O \times D \tag{2.10}$$

Risks prioritization and further work with the most critical failure modes is realized according RPN. Several strategies exist for the mitigation of risk, for example:

- High Risk Priority Numbers
- High Severity Risks (regardless of RPN)
- High Design Risks (Severity x Occurrence)
- Other Alternatives (S,O,D) and (S,D) (Morris, 2011)

Advantages of FMEA:

- identifies connections between reasons and effects,
- demonstrates previous unknown event outcomes,
- it is a systematized analysis.

Disadvantages of FMEA:

- number of data can be too much,
- analysis can be converted into complicated,

- environment conditions, maintenance respects can be not examine (Lendvay, 2004).

An important critique of the FMEA is on the meaning of the RPN. 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 comparison. 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 FMEA is very successful and useful, it has to be said that FMEA as a tool has most value 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 get 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 has to be taken in order to reduce the RPN of high-ranking faults.

2.3 Conclusions of Chapter 2

The main aim of this chapter is to give an overview of basics of reliability principles and introduce main reliability definitions. The information how to calculate overall reliability of a production process is given. It is shown by means of the bathtub curve what are three levels of a production process life cycle. Also such definitions like failure rate, MTBF, MTTF and MTTR are presented which allow establishing basic reliability analysis of a production process only using data about failures from production.

An overview of 5 commonly used reliability methods is introduced: RP, RBD, FTA, MA and FMEA. What these methods are and what are their advantages and disadvantages is also shown.

The focus is done to the FMEA as a fundamental reliability method in the research: the whole methodology is build upon this method.

FMEA was chosen for several reasons:

- First of all FMEA is relatively low-tech method which can be understood and used by many practitioners.
- Secondly FMEA is very widespread used method; a lot of enterprises use it.
- Thirdly FMEA shows relationship between failure mode and cause of this failure. This is very important for the current research

because we got an opportunity for further analysis of the problem and failure cause removal.

3. DEVELOPMENT OF METHODOLOGY FOR PROCESS RELIABILITY IMPROVEMENT

3.1 Common framework of research

Reliability of production processes is a key issue that ensures the stable system operation, increase the product quality, and reduce production losses. In current research the framework for the analysis of production process failures is introduced, which also allows to define the most effective ways of their elimination.

The whole idea of the proposed methodology is represented in Figure 3.1. The pivot of the methodology is “main part of reliability analysis” which is supported by additional “extended part of reliability analysis”. This additional part can be used if required however it also can be missed from the analysis of the production process. The extended part of reliability analysis is described in details in Section 3.3.

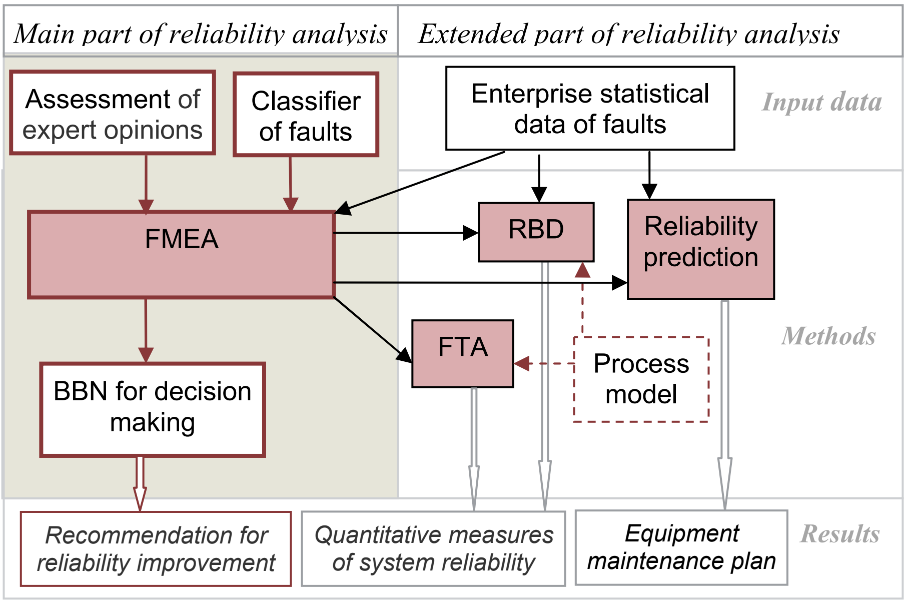


Figure 3.1 Main framework of methodology for process reliability improvement

As it was already mentioned above the main part of reliability analysis is the central part of the methodology. According to the Figure 3.1 the methodology is based on the FMEA. FMEA is the core part of the analysis. However it is proposed to use not a traditional FMEA but optimised for the current research.

3.2 Main part of reliability analysis

The main part of manufacturing processes reliability estimation consists from the following levels (see Fig. 3.2):

- Additional activities for FMEA parameters revision;
- Standard method of reliability analysis;
- Decision support for process improvement.

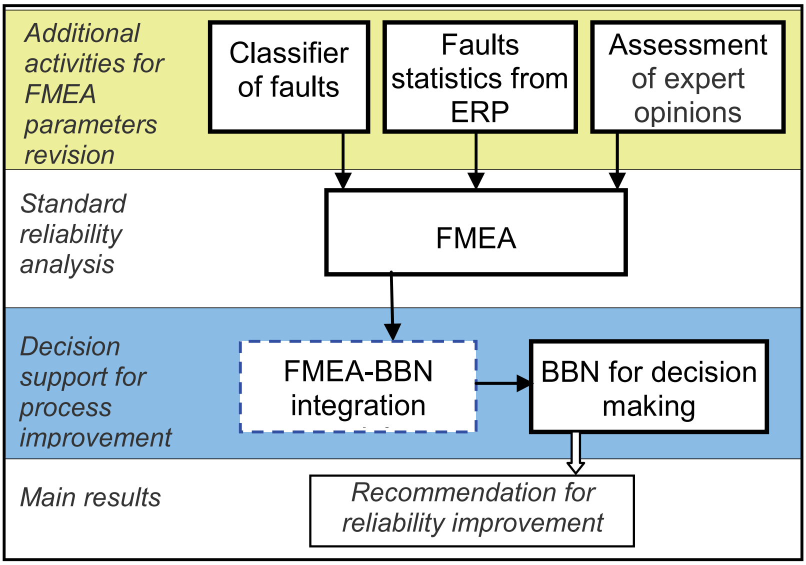


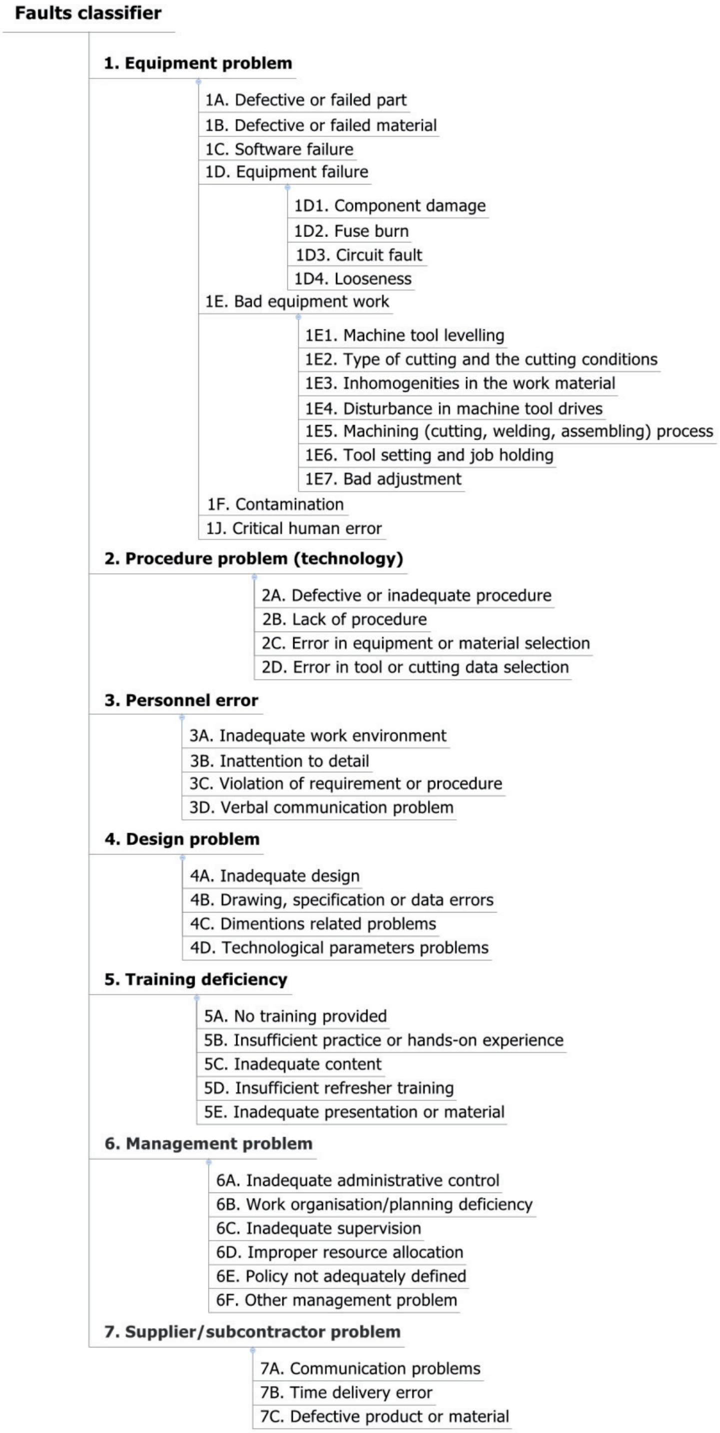
Fig. 3.2 Main part of reliability analysis

First of all the classifier of faults was developed and faults from this classifier are added as a column to the FMEA.

Secondly it is proposed to use an assessment of expert opinions in case when experts during FMEA preparation cannot unambiguously estimate severity and detection parameters.

Reliability management can be obtained through BBNs in the form of decision support. When FMEA is ready the information about failures and failures probabilities goes to BBN where the process of failure probability of the top level of the production process is calculated. The data transferring from FMEA to BBN occurs through FMEA-BBN module. This process is described in sub-chapter 4.1. On the basis of this probability a decision maker can decide that reliability level of the whole process is satisfied and consequently the process can be kept without changes or he can make a decision about necessity for introduction into process some actions for reliability improvement. In that case the BBN is used again for evaluation of different actions influence on reliability on the top level of the production process.

3.2.1 Classifier of faults



Faults classifier

- **1. Equipment problem**
  - 1A. Defective or failed part
  - 1B. Defective or failed material
  - 1C. Software failure
  - 1D. Equipment failure
    - 1D1. Component damage
    - 1D2. Fuse burn
    - 1D3. Circuit fault
    - 1D4. Looseness
  - 1E. Bad equipment work
    - 1E1. Machine tool levelling
    - 1E2. Type of cutting and the cutting conditions
    - 1E3. Inhomogenities in the work material
    - 1E4. Disturbance in machine tool drives
    - 1E5. Machining (cutting, welding, assembling) process
    - 1E6. Tool setting and job holding
    - 1E7. Bad adjustment
  - 1F. Contamination
  - 1J. Critical human error
- **2. Procedure problem (technology)**
  - 2A. Defective or inadequate procedure
  - 2B. Lack of procedure
  - 2C. Error in equipment or material selection
  - 2D. Error in tool or cutting data selection
- **3. Personnel error**
  - 3A. Inadequate work environment
  - 3B. Inattention to detail
  - 3C. Violation of requirement or procedure
  - 3D. Verbal communication problem
- **4. Design problem**
  - 4A. Inadequate design
  - 4B. Drawing, specification or data errors
  - 4C. Dimentions related problems
  - 4D. Technological parameters problems
- **5. Training deficiency**
  - 5A. No training provided
  - 5B. Insufficient practice or hands-on experience
  - 5C. Inadequate content
  - 5D. Insufficient refresher training
  - 5E. Inadequate presentation or material
- **6. Management problem**
  - 6A. Inadequate administrative control
  - 6B. Work organisation/planning deficiency
  - 6C. Inadequate supervision
  - 6D. Improper resource allocation
  - 6E. Policy not adequately defined
  - 6F. Other management problem
- **7. Supplier/subcontractor problem**
  - 7A. Communication problems
  - 7B. Time delivery error
  - 7C. Defective product or material

Figure 3.3 Faults classification for machinery enterprises

Classifier of faults is a systemised list of possible faults in production process which was elaborated specially for machinery enterprises. As a base for elaborated classifier the standard DOE-NE-STD-1004-92 was used. The classifier was adapted from this document for machinery enterprises (see Fig. 3.3). The assessment phase includes the analysis of the data for identifying the causal factors, summarizing the findings, and categorizing the findings by the cause categories.

The aim of the classifier is to arrange faults in production process and to be helpful to define quickly the causes of faults by the cause codes.

There are seven main failure classes are marked out in the classifier:

1. Equipment/Material Problem
2. Procedure Problem
3. Personnel Error
4. Design Problem
5. Training Deficiency
6. Management Problem
7. Supplier/ subcontractor problem

Those seven classes are sufficient to describe any failure. Every failure class by-turn consists of several failure causes.

When a team of experts prepares FMEA for the process, it includes the codes from the classifier to special column in FMEA for every failure mode. For this aim two new fields are added to standard FMEA structure, such as “Failure class” and “Cause code”, in Figure 3.4, they are marked by “*”.

Row No	Process Name	Work Station Name	Process Description	Potential Failure Mode		Potential Effect(s) of Failure	Severity	Potential Cause of Failure		Occurrence	Current Controls Prevention	Current Controls Detection	Detection	RPN	Corrective Action(s)	Severity	Expected Action Results		
				* Failure class	Failure description			* Cause Code	Description								Occurrence	Detection	RPN

Figure 3.4 The header of FMEA table with additional columns for data from classifier

After a FMEA is ready further analysis is released by grouping of data in FMEA according to failure classes and subsequent work performed separately with every class.

Priorities on the failure modes can be set according to the FMEA’s risk priority number (RPN). A concentrated effort can be placed on the higher RPN items. For this aim in our research we use Bayesian Belief Network (BBN). A structure of a BBN for the process is built on the base of the classifier, because structure of BBN is the same as structure of classifier with the faults from FMEA of the process.

3.2.2 Assessment of expert opinions

Assessment of expert opinions is used for more precise estimation of severity and detection parameters in FMEA. However it is not required to use this approach every time during FMEA preparation, only in case when the expert opinions do not match.

The FMEA method implementation may be characterised as activities of an organised group. The initiation of the FMEA requires formation of a team, which usually consists of a facilitator, a team leader, and functional experts from development, manufacturing, quality, and others specialists as appropriate. The team should first describe the process of unit operations in general, then divide each unit operation into its component parts and estimate every part by its main parameters. During the estimation of the parameters, especially the faults severity and detection, experts' opinions often diverge. In the current work we suggest to use the consistency assessment of the expert opinions that increase the quality of the estimation of the FMEA parameters.

Proposed by Maurice G. Kendall and Bernard Babington Smith (Kendall & Babington, 1939), Kendall's coefficient of concordance (*W*) is a measure of the agreement among several (*m*) quantitative or semi-quantitative variables that are assessing a set of n objects of interest (Legendre, 2005). The Kendall coefficient of concordance can be used to assess the degree to which a group of variables provide a common ranking for a set of objects. It should only be used to obtain a statement about variables that are all meant to measure the same general property of the objects (Legendre, 2010).

The consistency of the opinions of experts can assess the magnitude of the coefficient of concordance. 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 not consistent.

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

.

$$W = \frac{12S}{n^2(m^3-m)} \qquad (3.1)$$

Where

n – a number of experts for FMEA elaboration;

m - a number of objects of expertise (in FMEA more critical parameters such as severity and detection);

S - a sum of squared deviations of all the examination objects' rank.

S may be defined as:

$$S = \sum_{i=1}^{n} \left(\sum_{j=1}^{m} x_{ij} - \frac{1}{2} m(n+1) \right)^2 \tag{3.2}$$

where x_{ij} – the rank assigned to the i-th object j-th expert.

Parameters of FMEA: severity, detection and occurrence are critical and must be defined with the maximum precision. As it was mentioned above assessments of the expert opinions are needed for severity and detection parameters. Occurrence is taken from statistical data thus can be estimated very precisely. In our future work this parameter must be obtained from ERP system and have the possibility of regular updates.

3.2.3 Bayesian Belief Networks

Bayesian Belief Network (BBN) is a graphic probabilistic model through which one can acquire, capitalize on and exploit knowledge. It consists of a set of interconnected nodes, where each node represents a variable in the dependency model and the connecting arcs represent the causal relationships between these variables. Variable may be either discrete or continuous. In the case of discrete variables, they represent finite sets of mutually exclusive states which themselves can be categorical. Bayesian networks have a built-in computational architecture for computing the effect of evidence on the states of the variables (Neapolitan, 2003), (Shevtshenko &Wang, 2009).

The Bayesian networks are natural successors of statistical approaches, Artificial Intelligence and Data Mining. Particularly suited to considering of uncertainty, they can be easily described manually by experts in the field.

A key feature of Bayesian statistics (O'Hagan, 1994) is the synthesis of two separate sources of information - see Figure 3.5 for a schematic representation of this process. The result of combining the prior information and data in this way is the posterior probability.

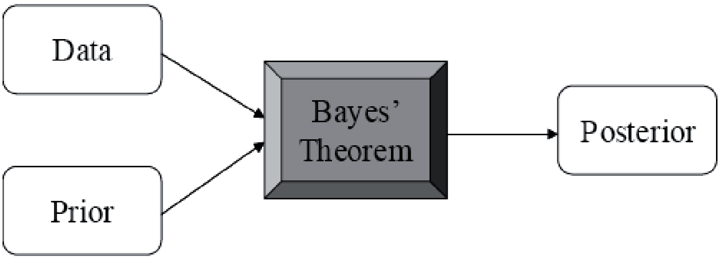


Figure 3.5 Synthesis of information by Bayes' theorem (O'Hagan, 1994)

A Bayesian network is a graphical model that encodes probabilistic relationships among variables of interest. When used in conjunction with statistical techniques, the graphical model has several advantages for data analysis, because (Heckerman, 1996):

- The model encodes dependencies among all variables, which aggravate the solution where some data entries are missing;
- The Bayesian network can be used to learn causal relationships, and hence to gain understanding about a problem domain and to predict the consequences of intervention;
- The model has both, causal and probabilistic semantics, it is an ideal representation for combining prior knowledge (which often comes in a causal form) and data;
- The Bayesian statistical methods, in conjunction with the Bayesian networks, offer an efficient and principled approach that avoids the over-fitting of data.

Due to the advantages listed above it was decided to use BBN in the current research. In this research the BBN is used to analyze the effect that the improvement of different fault groups will have.

In BBN, the decision-maker is concerned with determining the probability that a hypothesis (H) is true, from evidence (E) linking the hypothesis to other observed states of the world. The approach makes use of the Bayes' rule to combine various sources of evidence. The Bayes' rule states that the posterior probability of the hypothesis H, given that evidence E is present or P(H|E):

$$P(H \mid E) = \frac{P(E \mid H)P(H)}{P(E)} \tag{3.3}$$

Where *P*(*H*) is the probability of the hypothesis of being true prior to obtaining the evidence *E* and *P*(*E*|*H*) is the likelihood of obtaining the evidence *E,* given that the hypothesis *H* is true (Shevtshenko &Wang, 2009).

When the evidence consists of multiple sources denoted as 1 2 *n E*, *E* ,…,*E* , each of which is conditionally independent, the Bayes' rule can be expanded into the expression:

$$P(H \mid \bigcap_j E_{\mathrm{j}}) = \frac{\prod_{j=1}^{n} P(E_j \mid H)P(H)}{\prod_{j=1}^{n} P(E_j)} \tag{3.4}$$

This research presents the use of BBN as a decision support tool to achieve sustainability of production process.

3.3 Extended reliability analysis

Process modelling and simulation are used for a process visualisation and execution of a dynamic analysis of a system. The purpose of any model is to increase understanding and reasoned decision making from a model. It helps to support and improve the process.

Enterprises are competing in the environment, which requires the ability to reconfigure enterprise processes rapidly. This ability requires modelling methods to support an analysis and design in multiple aspects of a process performance and structure. The first and most important step in the modelling process is to create a logic network.

The purpose of modelling and simulations:

- analysing and understanding of the observed phenomena;
- testing of hypotheses and theories;
- prediction of the systems' behaviour under various conditions and scenarios.

For the analysis of manufacturing processes more suitable are structural modelling methods (Law & Kelton, 2000).

The IDEF0 modelling technique could test and evaluate each product and process alternative. There are several common measures of performance, obtained from a simulation study of a manufacturing system, including utilization of equipment and personnel (i.e., proportion of time busy).

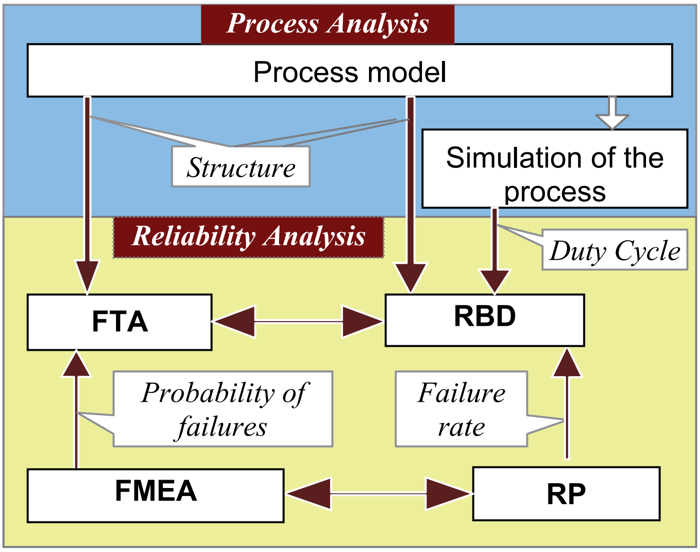


Figure 3.6 Connections between process and reliability analysis

Realistically, it is impossible to avoid all feasible failures of a system or a product on the design stage, so one of the goals of reliability engineering is to recognize the most expected failures and then to identify appropriate actions to mitigate the effects of those failures (Lendvay, 2004). As shown in Figure 3.6, for the system safety analysis the qualitative and quantitative methods were used. All they are interrelated and help to understand the logical structure of failure modes of a system.

For a more complete analysis of a process a structural and dynamic analysis are used for revealing the bottlenecks of the process, as well as FTA and RBD, which give the reliability of the system on the whole. The FTA, as well RBD, may be built on the base of a structural model of the process.

When establishing a reliability model of technical system, FTA and RBD are two well proven and frequently used techniques. Both are Boolean models, represent exactly the same things, and may be converted from one to another. Actually RBD is often mainly seen as method of representation than as an analysis method.

Roughly speaking RBD approach is often chosen when the system structure is fairly simple and the number of components is limited. However FTA constitutes a top down method, helping the analyst to develop the reliability model step by step from the unwanted “top” event. So if the system structure is very complex one might find it advantageous to use FTA to model it.

On the base of the FMEA and statistical data about failures in production, and using RP method it is possible to calculate an optimal plan of the equipment maintenance for a current process. Presence of a maintenance plan is quite important because probability of system failure, or system unreliability, corresponds to the probability of successful system maintenance, or system maintainability (Salvendy, 2001). When failure rate is known it also can be used in RBD.

If an enterprise is interested in building of FTA so information about probabilities of failures can be taken from FMEA. The main advantage of FTA above FMEA is combination of failures. By taking into account this plus, FTA avoids the obvious shortcomings of FMEA and additional information about failures can be obtained therefore the decision about improvements can be more reliable.

More detailed description of this approach can be found in our paper "Reliability Prediction for Man-Machine Production Lines" 2009, DAAAM International Scientific Book and T. Karaulova thesis (Karaulova,2004).

3.4 Conclusions of Chapter 3

In this chapter the main parts of the research are represented.

1) The main scheme of the methodology is shown at the beginning of the chapter. It is divided by two parts: main part of reliability analysis and extended reliability analysis. In the connection these two parts give an opportunity for full analysis of the production process however they can be used separately as well.

2) The main part of reliability analysis which consists of FMEA supported by classifier of faults and assessment of expert opinions is described in details. Reliability method FMEA gives not only qualitative assessment of operations

failures in the process, but also ways of them elimination therefore it was taken as base for this research. In details FMEA was described in previous chapter in section 2.5.5. In this chapter an overview of the classifier of fault and assessment of expert opinions is introduced.

3) The classifier of fault which is elaborated specially for machinery enterprises contains possibly all potential causes of failures. All causes are grouped into 7 main groups which cover all spheres of enterprise activities at production level: starting from equipment problems and up to problems in managing.

4) Assessment of expert opinion is proposed for specification of severity and detection parameters during FMEA making. This option can be used if there is disagreement between FMEA team members. If this method is used the Kendall's coefficient of concordance is calculated and a decision about severity and detection ranking is made on a base of this coefficient.

5) Theory of Bayes and Bayesian Networks introduced in this chapter is used as a tool for failure probability calculations in the following chapter. BBN, as a decision making tool, allows finding out the most effective way of reliability increasing.

6) Finally the extended reliability analysis represents how reliability analysis may be broadened by using FTA, RBD and RP methods. How these methods are suggested to combine and what outputs can be obtained from this. Many production processes have extra capacity. It is difficult to find it without any analysis. The combination of the methods described in this chapter may help to find the hidden losses in a process and make it more reliable. Also it is shown that combining of the process modelling with reliability techniques can facilitate building of FTA and RBD structures and also provide RBD with data about duty cycles of equipment. From FMEA is proposed to get data about failures and probabilities of these failures. This data can be used in FTA and RP.

As a reliability predicting and managing model, the BBN model should be able to predict more effective ways for process reliability improvement in order to provide a basis for decision support.

4. OFFERED METHODOLOGY IMPLEMENTATION ON PRACTISE

Problem of reliability of production process is not new for practitioners and there are a lot of methods exist to estimate production process reliability. Usage of these methods allows inquiring about reliability of a concrete production process however it is often not enough. The next step after estimating of reliability is making a decision about implementation of required corrective actions to improve reliability and this is often the decision what is difficult to make. No one can say with confidence what action is the best to improve reliability as much as possible or what is even more difficult to improve it enough. Therefore in this section the research is focused of integration of reliability tool FMEA with BBN. This integration allows estimating probability of fault for the whole process and probability of a process reliability improving after implementation of different corrective actions.

The proposed methodology is applied by data collected from machinery enterprise which is specialized in building of heavy machinery equipment. Reliability analysis, proposed in the methodology, is carried out for every production route of this enterprise.

4.1 Process reliability estimation

The standard FMEA is supplemented with such additional activities like classifier of faults, which gives failure codes for further analysis, and assessment of expert opinion, if required.

When FMEA is ready, extended reliability analysis begins. The information from FMEA goes to BBN where first of all probability of a fault of the production process is calculated and on the base of this calculation a decision maker decides if the production process requires improvements or not. If the process requires improvements BBN is used again to decide what concrete actions to implement. The main result of the analysis in BBN is a list of recommendations for reliability improvement.

4.1.1 Data transfer from FMEA to BBN

FMEA is ready and it is needed to transfer information from FMEA to BBN for further analysis. This process consists of 7 steps and shown in Figure 4.1 in details.

Step 1 (GENERAL part) – Faults classifier development. The classifier is already elaborated. It has to be done only once and now it can be implemented at any machinery enterprise.

Step 2 (GENERAL part) – FMEA elaboration (see Appendix A). FMEA is not a classical but according to classifier of faults contains such columns like “Failure class” and “Cause code”.

Step 3 (EXCEL part) – Grouping of failures in FMEA by codes. In order to carry out further analysis of failures it is required to sort failures by failure classes.

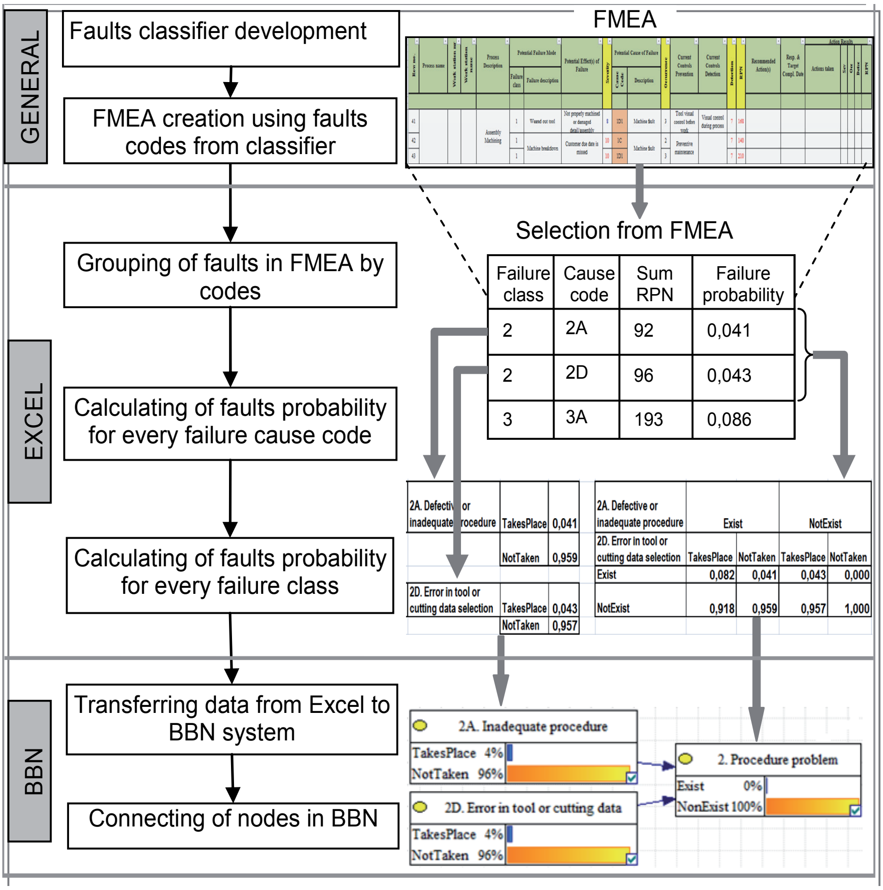


Figure 4.1 Process of data transfer from FMEA to BBN

Step 4 (EXCEL part) – Calculating of failure probability for every failure cause. The probability of error for every failure cause is calculated based on data received from FMEA by Equation 4.1:

$$P_{PR} = \frac{\sum RPN_{PC}}{\sum RPN_{Total}} \times 100\% \qquad (4.1)$$

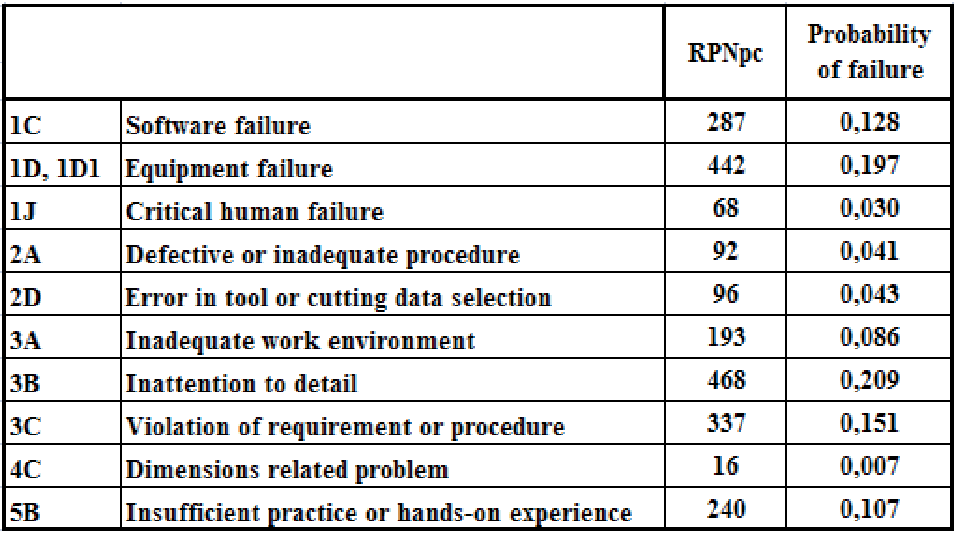
where:

P_{RP} – probability of every failure cause of the production route,

$\sum RPN_{PC}$ – RPN value for particular cause errors,

$\sum RPN_{Total}$ – Total RPN value of production route.

In the concrete example $\sum RPN_{Total} = 2239$. RPN_{PC} and probability of failure for every cause code see in Figure 4.2.



		RPNpc	Probability of failure
1C	Software failure	287	0,128
1D, 1D1	Equipment failure	442	0,197
1J	Critical human failure	68	0,030
2A	Defective or inadequate procedure	92	0,041
2D	Error in tool or cutting data selection	96	0,043
3A	Inadequate work environment	193	0,086
3B	Inattention to detail	468	0,209
3C	Violation of requirement or procedure	337	0,151
4C	Dimensions related problem	16	0,007
5B	Insufficient practice or hands-on experience	240	0,107

Figure 4.2 Failure probability for every failure cause

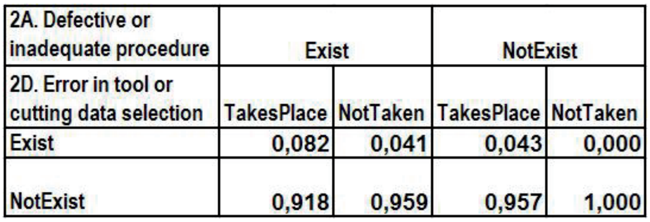
Step 5 (EXCEL part) – Calculating of faults probability for every failure class. On the base of the information that is got during step 4 probability of fault for every failure class can be calculated. For this aim different equations are used. In case of 2 events calculation is carried out according Equation 4.2:

$$P(A \cup B)=P(A)+P(B)-P(A \cap B) \qquad (4.2)$$

where:

$P(A)$ and $P(B)$ – probability of event A and B.

In the concrete case study there are 2 events, for example, in second failure class: 2A and 2D (see Fig.4.3).



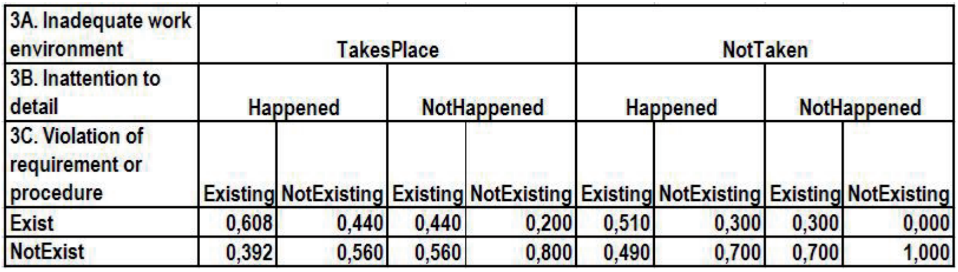
2A. Defective or inadequate procedure	Exist		NotExist	
2D. Error in tool or cutting data selection	TakesPlace	NotTaken	TakesPlace	NotTaken
Exist	0,082	0,041	0,043	0,000
NotExist	0,918	0,959	0,957	1,000

Figure 4.3 Failure probability for second failure class

If we calculate probability for 3 events, we use the same but broadened Equation 4.3:

$$P(A \cup B \cup C)=P(A)+P(B)+P(C)-P(A\cap B)-P(A\cap C)-P(B\cap C)+P(A\cap B\cap C)$$
(4.3)

In the concrete case study there are 3 events, for example, in third failure class: 3A, 3B and 3C (see Fig. 4.4).



3A. Inadequate work environment	TakesPlace				NotTaken			
3B. Inattention to detail	Happened		NotHappened		Happened		NotHappened	
3C. Violation of requirement or procedure	Existing	NotExisting	Existing	NotExisting	Existing	NotExisting	Existing	NotExisting
Exist	0,608	0,440	0,440	0,200	0,510	0,300	0,300	0,000
NotExist	0,392	0,560	0,560	0,800	0,490	0,700	0,700	1,000

Figure 4.4 Failure probability for third failure class

If it is required probability for more quantity of events can be calculated.

Step 6 (BBN part) – Transfer of required information through FMEA-BBN integration module. Universal format of data is used for storing and transferring from Excel to Bayesian environment (there is more detailed description of this process in section 4.1.4).

Step 7 (BBN part) – Connecting of nodes in BBN. After this step Bayesian network is ready to be analysed.

4.1.4 FMEA-BBN integration module

Data of FMEA in Excel and data in BBN system is stored in different units thus some integration module is required to transfer data automatically from one source to another. Figure 4.5 represents the common scheme how data from the FMEA comes to BBN system.

The following approach is used in the current research:

1. The template based on common classifier must be created in BBN system. This operation must be done once. The developed template based on the faults classifier is given in Figure 4.7.
2. Code generation for the structure of the classifier. This will be done using the opportunities of the BBN system. The generated code of the model is stored in *xdsl* format of the structure which may be obtained from *GeNIe* (BBN tool).
3. The integration module gets information about probabilities of failures from FMEA and starts scanning the generated code of the template in order to find and leave active failures which have come from FMEA and delete failures

with zero probability. So we get the new program code corresponding to the data of FMEA.

4. On the base of new program code is possible to create new structure in BBN system and to calculate probability of failure after the corrective actions are applied. In Figure 4.5 the main functions of the FMEA-BBN integration module are shown.

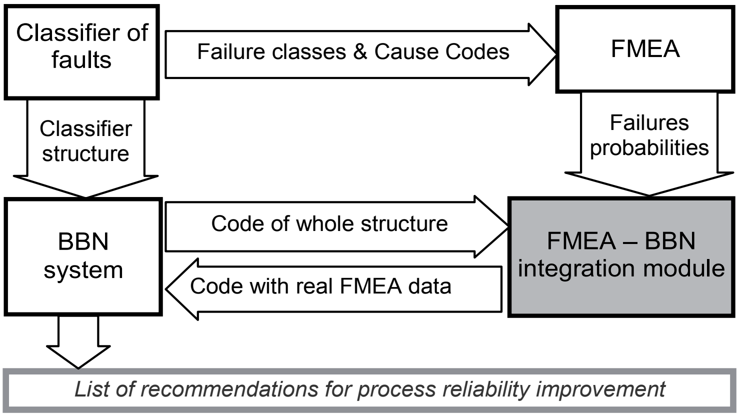


Figure 4.5 FMEA-BBN integration process

The algorithm of integration process is shown in Figure 4.6.

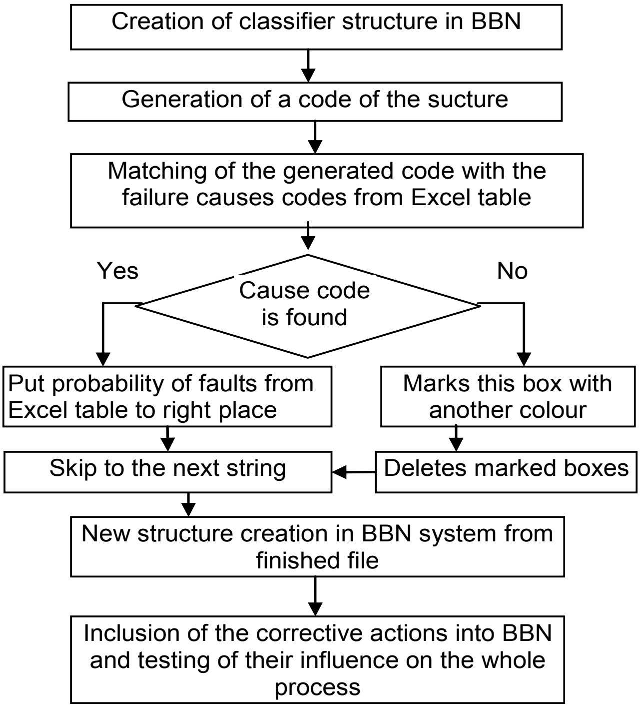


Figure 4.6 The algorithm of integration process

On the base of the classifier of faults a template of all possible failures is created in BBN system. In the frame of the research the GeNIe 2.0 system was used for realisation of BBNs. (see Fig. 4.7).

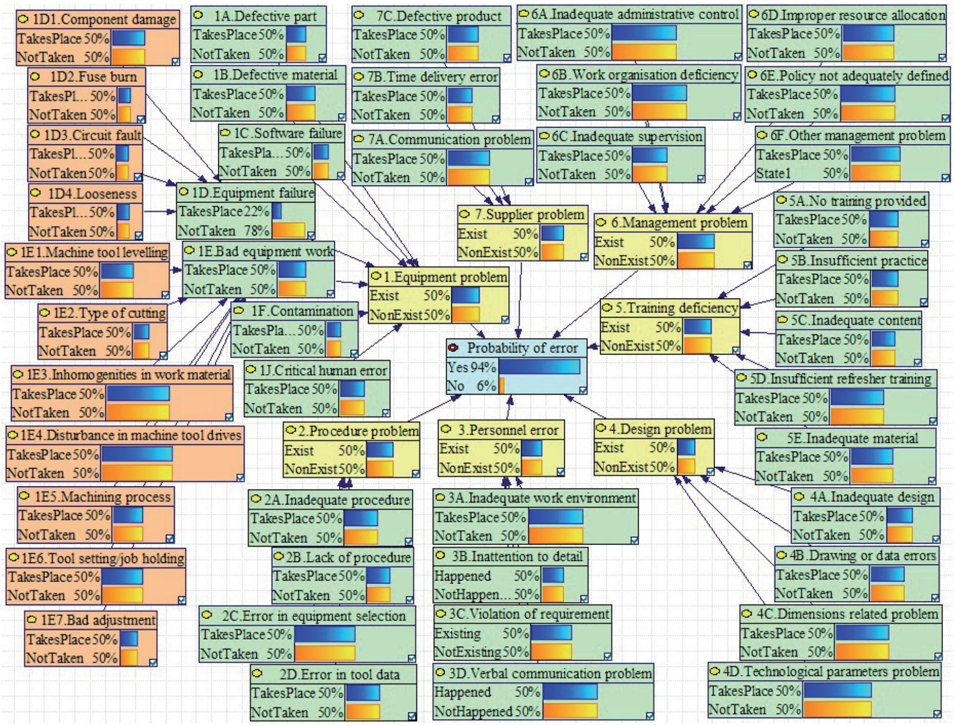
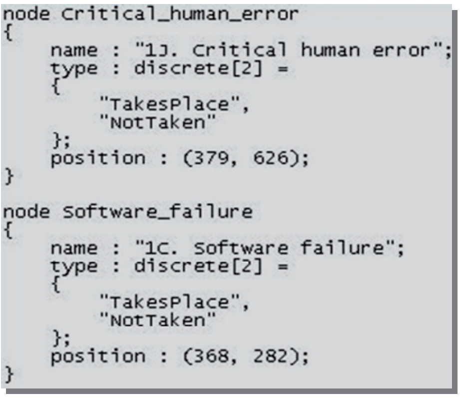


Figure 4.7 A template of the classifier of faults in BBN

The generated code of this template is stored in *.xdsl* format. A fragment of this code is represented in Figure 4.8.



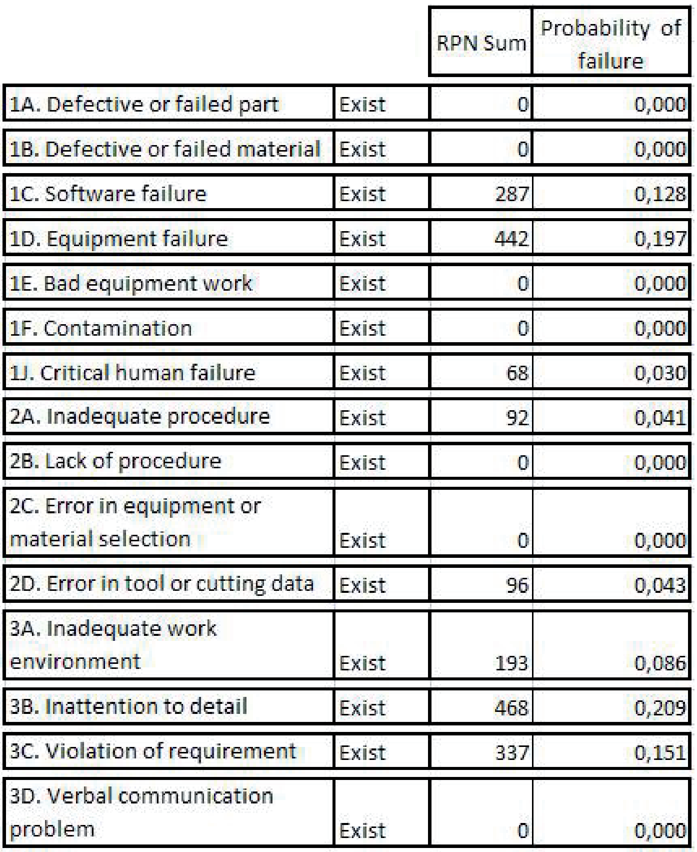
```
node Critical_human_error
{
        name : "1J. Critical human error";
        type : discrete[2] =
        {
                "TakesPlace",
                "NotTaken"
        };
        position : (379, 626);
}

node Software_failure
{
        name : "1C. Software failure";
        type : discrete[2] =
        {
                "TakesPlace",
                "NotTaken"
        };
        position : (368, 282);
}
```

Figure 4.8 A fragment of the template in *.xdsl* format

The integration module gets information about probabilities of all failures from FMEA and starts scanning the generated code of the template in order to find and leave active failures with some value of probability (for example, 1C, 1D, 1J, 2A and so on, see Fig.4.9) which have come from FMEA and delete failures with zero probability from FMEA (for example, 1A, 1B, 1E and so on in Fig. 4.9).

After the whole code of the template is scanned and all failures with zero probabilities are removed from it, a new BBN is created. The set of the nodes corresponds with data in the concrete FMEA. However it is still not a final network. In order to get the correct working network it is needed only to connect nodes between each other by arrows.



		RPN Sum	Probability of failure
1A. Defective or failed part	Exist	0	0,000
1B. Defective or failed material	Exist	0	0,000
1C. Software failure	Exist	287	0,128
1D. Equipment failure	Exist	442	0,197
1E. Bad equipment work	Exist	0	0,000
1F. Contamination	Exist	0	0,000
1J. Critical human failure	Exist	68	0,030
2A. Inadequate procedure	Exist	92	0,041
2B. Lack of procedure	Exist	0	0,000
2C. Error in equipment or material selection	Exist	0	0,000
2D. Error in tool or cutting data	Exist	96	0,043
3A. Inadequate work environment	Exist	193	0,086
3B. Inattention to detail	Exist	468	0,209
3C. Violation of requirement	Exist	337	0,151
3D. Verbal communication problem	Exist	0	0,000

Figure 4.9 Data from FMEA about probabilities of failures for the integration module

The prepared on the basis of transferred from FMEA data BBN is represented in Figure 4.10.

The information with probabilities of failures is calculated starting from the bottom levels to the top level. In the current example probability of an error on the top level is 14%. On the basis of this number a decision maker decides whether to implement some corrective actions or not. As usually 14% probability of error is not satisfied thus it is decided to implement some corrective actions and consequently to improve reliability of the whole process.

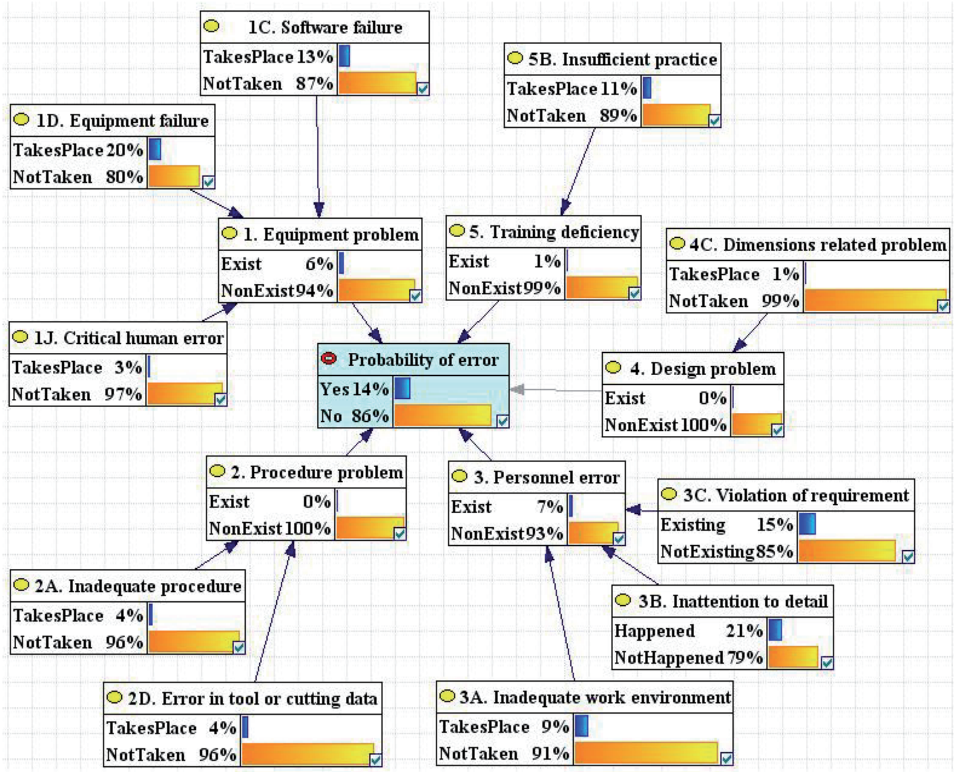


Figure 4.10 The BBN of the current case study

4.2 Decision making for reliability improvement

The process of decision making for reliability improvement is carried out according Figure 4.11.

First of all is required to find out a failure class to work with, failure class with the worst probability of error. In the current example the failure class with the worst reliability has 7% probability of failure and is the class number 3 – Personnel error, so is required to start improving reliability from this class.

Inside the Personnel error class the worst failure cause is 3B – Inattention to details. It has 21% probability of failure.

Now it is right moment to go back to FMEA. In FMEA is needed to filter this failure cause, find out what failure mode inside this failure cause is the worst according to RPN and finally check what corrective actions are available for this type of failure.

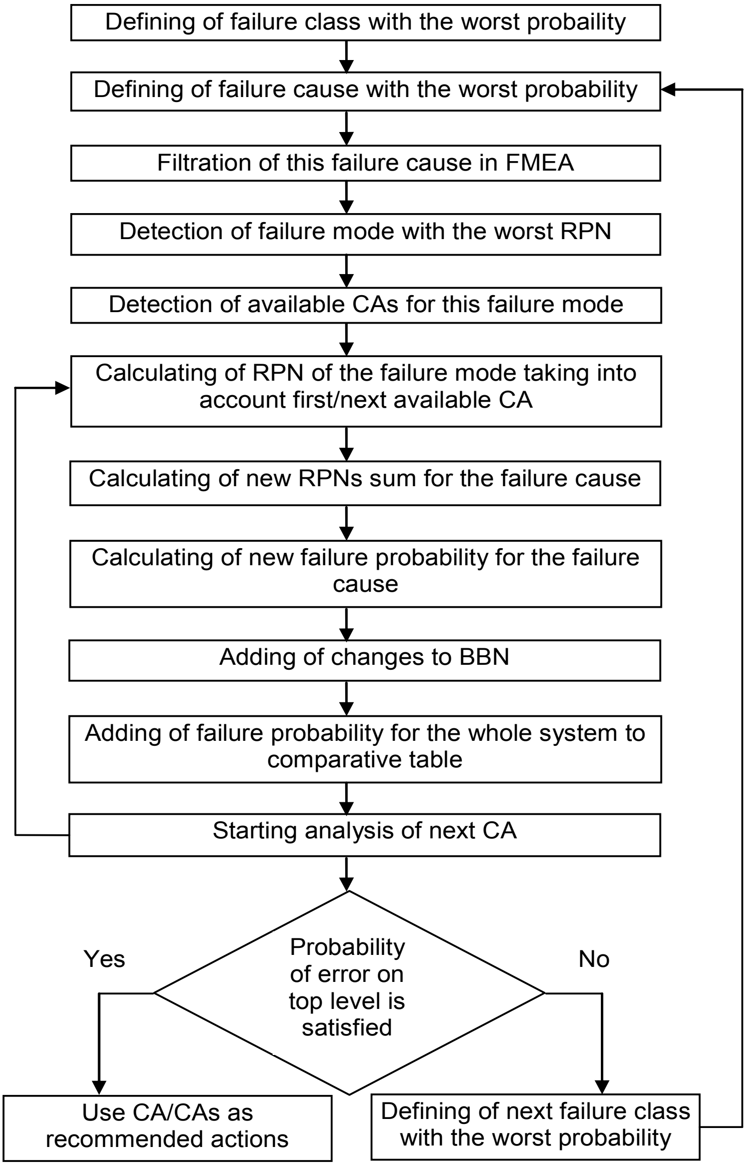


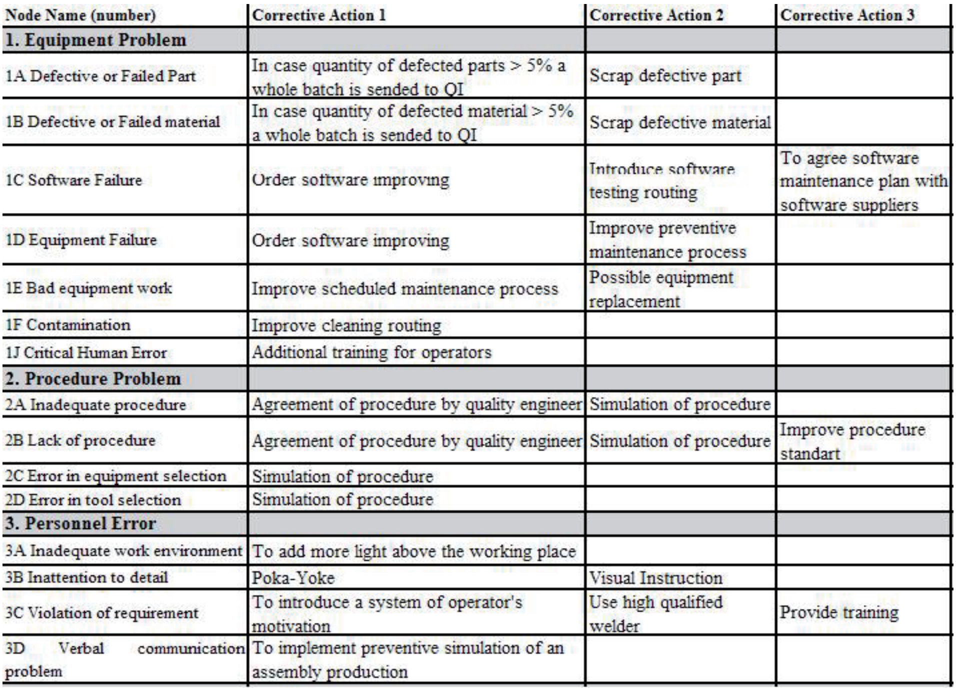
Figure 4.11 The BBN of the current case study

After filtration of 3B error in FMEA (see Fig. 4.12) is needed to find out what the most critical failure mode in this group is. In the example the most critical failure mode is “Not properly placed” which gives RPN 192.

	Proces		Potential Failure Mc		Potential		Potential Cause		O		Current	D	R	Recommended Action(	Action			
3	Alignment	201	3	Wrong detail dimensions	Detail will not fit and will not	3	3B	Operator fault	3		Machine scope	3	27					27
8	Chamfering	301	3	Detail not fixed when it	Detail clould be damaged	3	3B	Operator fault	3		Visual control	2	18					18
11			3	Too much cutted material	Damaged detail	7	3B	Operator fault	4		Visual or measuring control	3	84	To improve route card by adding hilighted window with chamfer degree	7	1	3	21
14			3	Not enough cutted material	Detail should be reworked	4	3B	Operator fault	2		Visual or measuring control	3	24					24
17	Sawing	401	3	Wrong dimension (the length is too long)	Rework. Additional scrap	3	3B	Operator fault	3		Visual control	2	18	To improve route card with highlighted window for important dimensions	3	1	2	6
20			3	Wrong dimension (the length is too short)	Detail may go to scrap	5	3B	Operator fault	3			2	30	To improve route card with highlighted window for important dimensions	5	1	2	10
26	Bending	501	3	Wrong die or punch	Damage of die and punch or	8	3B	Operator fault	3		Operator competence	2	48					48
29	Rolling	601	3	Detail overrolling	Detail will need additional time to repair	3	3B	Operator fault	3		Operator competence	3	27	Additional training for an operator	3	1	2	6
35	Machining	1101	3	Not properly placed	Wrong machined detail/assembly. Repair -	8	3B	Operator fault	3		Visual or measuring control	8	192	Implement Poka-Yoke	1	1	8	8

Figure 4.12 Filtered 3B failure cause in FMEA

The next step is to clarify what CAs are available for this failure mode. All available CAs are in the special CAs list which is prepared beforehand by FMEA team and can be any time replenished by new CAs. Part of the list is introduced in Figure 4.13.



Node Name (number)	Corrective Action 1	Corrective Action 2	Corrective Action 3
1. Equipment Problem			
1A Defective or Failed Part	In case quantity of defected parts > 5% a whole batch is sended to QI	Scrap defective part	
1B Defective or Failed material	In case quantity of defected material > 5% a whole batch is sended to QI	Scrap defective material	
1C Software Failure	Order software improving	Introduce software testing routing	To agree software maintenance plan with software suppliers
1D Equipment Failure	Order software improving	Improve preventive maintenance process	
1E Bad equipment work	Improve scheduled maintenance process	Possible equipment replacement	
1F Contamination	Improve cleaning routing		
1J Critical Human Error	Additional training for operators		
2. Procedure Problem			
2A Inadequate procedure	Agreement of procedure by quality engineer	Simulation of procedure	
2B Lack of procedure	Agreement of procedure by quality engineer	Simulation of procedure	Improve procedure standart
2C Error in equipment selection	Simulation of procedure		
2D Error in tool selection	Simulation of procedure		
3. Personnel Error			
3A Inadequate work environment	To add more light above the working place		
3B Inattention to detail	Poka-Yoke	Visual Instruction	
3C Violation of requirement	To introduce a system of operator's motivation	Use high qualified welder	Provide training
3D Verbal communication problem	To implement preventive simulation of an assembly production		

Figure 4.13 List of available CA

In the current example there are 3 columns with possible different CAs for each failure mode however the number of CAs can be infinite. To continue with the case study it was found out that 3B is the worst failure.

According to the list of available CAs there 2 available corrective actions in case of this failure mode are

1) Implement Poke-Yoke, and
2) Visual instruction

Now one by one, both corrective actions need to be added to the BBN in order to see how each of them will influence probability of fault on the top level.

In the Figure 4.12 is shown in the column “Recommended Action” which CA was chosen and in the column “Action Results” how it influences RPN of the failure mode. Implementation of Poke-Yoke very strongly improves RPN: 1(S) x 1(O) x 8(D) = 8. To calculate efficiency of the corrective action simple ratio is required:

$$E_{CA} = 1 - \frac{RPN_{CA}}{RPN} \tag{4.4}$$

where

E_{CA} – efficiency of CA

RPN_{CA} – RPN of the failure mode after CA implementation

RPN - RPN of the failure mode before CA implementation

Using the Equation 4.5 the efficiency of Poke-Yoke implementation is:

$$E_{Poke-Yoke} - 1 - \frac{8}{192} - 0{,}958 \tag{4.5}$$

Taking into consideration this condition probability of “Inattention to details” failure should be recalculated. The following Equation 4.6 should be used in this case:

$$P(F)_{CA} = P(F) - P(F)E_{CA} \tag{4.6}$$

where

$P(F)_{CA}$ – probability of failure mode after CA implementation

$P(F)$ – probability of failure mode before CA implementation

Using the Equation 4.6 the probability of “Inattention to details” after Poke-Yoke implementation is:

$$P(3B)_{CA} = 0.209 - 0.209 * 0.958 = 0.009$$

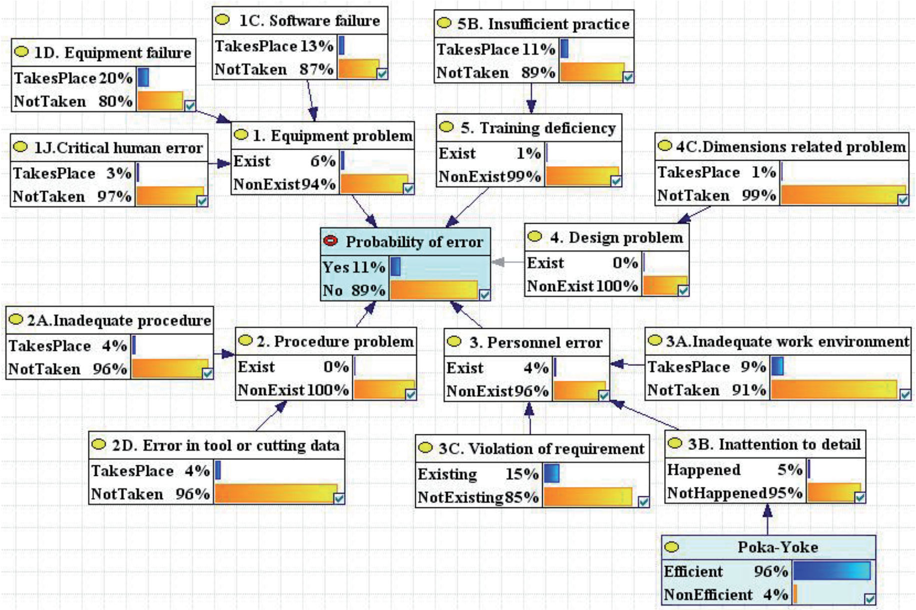


Figure 4.14 The BBN after implementation of Poke-Yoke

When all required calculations are done and changes in BBN are performed, it is seen that this corrective action has improved probability of failure on the top level of the production process by 3%. Probabilities of “Personnel error” class and “Inattention to details” were improved by 3% and 16%, respectively (See Fig. 4.14).

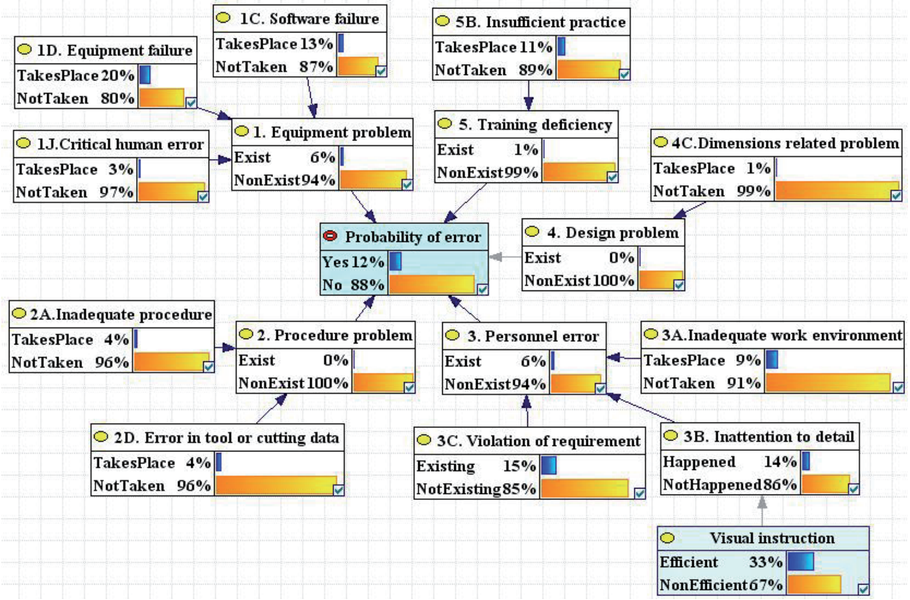


Figure 4.15 BBN after implementation of visual instruction

The analysis of first CA “Poke-Yoke” is done, now is required to perform the same analysis for the next CA - “visual instruction”. The result of implementation of this CA is represented in Figure 4.15.

Calculations of the probabilities are performed according to the same scheme as in example with Poke-Yoke. RPN of implementation of the visual instruction was estimated like 8(S), 2(O) and 8(D) what gives RPN=128. According to the Figure 4.15, probability of the top level failure is reduced by 2%. Probabilities of “Personnel error” and “Inattention to details” are reduced by 1% and 7%, respectively.

Summary table with information about influence of corrective actions on the production process is represented below.

Table 4.1 Influence of different CA on the production process

Corrective action	Efficiency of corrective action	Improvement of probability of failure for “Inattention to details”	Improvement of probability of failure for “Personnel error”	Improvement of probability of failure for top level
Implementation of Poke-Yoke	96%	16%	3%	3%
Implementation of visual instruction	33%	7%	1%	2%

When probability of failures in case of using of different corrective actions is calculated, decision maker needs to decide what action to use in a production process. His decision can depend on different aspects: efficiency of corrective action, price, time and complexity of implementation and so on. However this aspect is not considered in the frame of this thesis.

4.3 Conclusions of Chapter 4

In this chapter practical implementation of the elaborated methodology is introduced in details. It is argued that BBN which is built based on imported data from FMEA provides an attractive solution to the problems of prioritisation of failure modes and selection of corrective actions for these failure modes. BBN enables to combine FMEA data with quantitative data and subjective judgments about the process. Hence BBN provides a method of modelling process losses and measuring the effectiveness of recommendations for process reliability improvement. On practice it looks like calculating of probabilities of each fault group and is resulted in discovering the most critical fault group. Each corrective actions is analysed from its efficiency point of view. This scheme can be implemented plenty of times until the desired result is achieved. Decision makers may benefit from its output to make the most relevant decision in their manufacturing processes.

CONCLUSIONS

The main objective of the research was reached and the effective methodology for production process reliability growth was elaborated. Integration of FMEA, as a reliability estimating tool, and BBN, as a decision making tool, into common framework allowed creating this methodology. The elaborated tool allows quickly and with great precision estimating the most unreliable places of a production process and making decisions for reliability improvement of a production system.

In the framework of the doctoral theses were achieved:

1) Were defined the contemporary trends in the field of reliability of manufacturing processes in industrial enterprises, main aims and activities, of reliability engineering, which enable to support a reliable production processes (C*hapter 1*).

2) An overview of existing commonly used methods for reliability estimation was performed (*See section 2.2*). Aims and benefits of each method were defined and done explanation why FMEA was selected as a main method for the research. This method gives relationship between failure mode and cause of this failure. This is very important for the current research because we got an opportunity for further analysis of the problem and failure cause elimination (See section 2.3).

3) The main idea of the methodology was represented as a framework (*See section 3.1*). It was shown that the whole methodology contains two main parts: main reliability analysis and extended analysis. The main reliability analysis contains the core of the research – FMEA-BBN approach. This part of the framework makes possible to find the most effective solutions for process faults elimination. Combination of these methods allows making a full-fledged analysis of a production system and to reveal the weakest places of the system.

4) The part of extended reliability analysis represents connection of the FMEA-BBN approach with the standard methods for reliability estimation. This allows conducting additional analysis of the system that can be performed using modelling of the process and other reliability techniques like FTA and RBD (*See section 3.3*).

5) During the research the classifier of faults was elaborated specially for machinery enterprises (*See section 3.2.2*). The main idea of the classifier is specification of failure causes in FMEA; in BBN the structure of the classifier served as a basis for network building.

6) Assessment of expert opinion was considered as a tool for qualification of severity and detection parameters ranking is case when FMEA team members have discrepancy in their opinions (*See section 3.2.1*).

7) Practical implementation of the proposed methodology was carried out (*See section 4*). Using the concrete example was represented how suggested FMEA looks like, how to calculate probability of failures, transfer data from FMEA to BBN and finally make an analysis of the system and implement

corrective actions. Reliability prediction is possible through using of BBN. By using scenario analysis, reliability (output of the BBN) can be predicted based on values of the input variables for the BBN. Besides, BBNs in the area of reliability management appears to be much broader than the application of FMEA.

8) During the research mechanism of data transferring from reliability analyzing system to decision making system was elaborated (*See section 4.1.4*). This mechanism realizes automated transferring of failures and probabilities from FMEA to BBN what makes work of practitioners much easier.

In the current research the framework for the analysis of the production process was developed which provides a systematic approach for management of reliability of manufacturing processes in machinery industry. It enables companies to analyse a process as a whole as well as its parts for efficient forecast of a production process improvement. The reliability analysis model supports selection process of corrective actions. It is carried out on a base of the Bayesian Belief Network approach which enables to calculate probabilities of failures and to select the appropriate recommendations for work station reliability improvement without the significant increase of production cost.

Novelty of the research

The new methodology for improvement of production process reliability on a base of FMEA is proposed. This methodology allows making the most effective decisions for implementation of corrective actions. To fulfil this:

- FMEA is improved – the classifier is elaborated and severity and detection parameters can be specified by assessment of expert; the mechanism of occurrence renewing is proposed;
- The mechanism of automated data transferring from FMEA to BBN is elaborated;
- BBN is used for decision making concerning selection of corrective actions. Reliability management can be obtained through BBNs in the form of decision support. Decision support by BBNs can basically be provided through scenario analysis.

Significance of the research for science and national economy

- As a result of the project implementation, enterprises receive a set of recommendations that, when implemented, result in production efficiencies and cost savings.
- A process for production that bolsters sustainable consumption and production by minimising waste has become an increasingly important corporate strategy in the global business arena.

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LIST OF PUBLICATIONS

1. Karaulova, T., Kostina, M., Shevtshenko, E. *Reliability Assessment of Manufacturing Processes*. International Journal of Industrial Engineering and Management (IJIEM). (2012).

ISSN: 2217-2661

Web address: http://www.iim.ftn.uns.ac.rs/casopis/volume3/ijiem_vol3_-no3_3.pdf

Abstract: Reliability of production processes is a key issue that ensures the stability of production system operation. It helps to improve product quality and reduce production losses. In current paper, we introduce a framework for the fault analysis of production process, which provides the recommendations of corrective actions for elimination of critical faults for machinery manufacturing.

Written mainly by T. Karaulova with contributions from M. Kostina and E. Shevtshenko.

2. Kostina, M., Karaulova, T., Sahno, J., Maleki, M. *Reliability Estimation for Manufacturing Processes.* Journal of Achievements in Materials and Manufacturing Engineering (AMME). (2012), Vol.51, issue 1, pp. 7-13

ISSN: 1734-8412

Web address: http://www.journalamme.org/papers_vol51_1/5111.pdf

Abstract: Purpose of the current research is to develop a reliability assessment method with an extension of the existing ones and pooling them to a common framework. The system must identify the most unreliable parts of a production process and suggest the most efficient ways for the reliability improvement.

Written by M. Kostina with contributions from J. Sahno and M. Maleki. Supervised by T. Karaulova.

3. Karaulova, T., Kostina, M., Sahno, J. *Framework of Reliability Estimation for Manufacturing Processes.* SCIENTIFIC JOURNAL "MECHANIKA". (2012). Accepted

ISSN: 2029-6983

Abstract: In this paper a framework is introduced which has in the centre FMEA - a reliability analysis type, the most widely used in enterprises . In the paper it is proposed to extend the FMEA by introducing a classificator of faults and an estimation of expert opinions for the FMEA parameters. By using the Pareto analysis, it is possible to extract from the FMEA the most critical process failures and transfer them for further analysis to BBN.

Written mainly by Karaulova T. and Kostina M. with contributions from Sahno J.

4. Pribytkova, M., Sahno, J., Karaulova, T., Shevtshenko, E., Maleki, M, Cruz-Machado, V. *Reliability analysis module development for production route elaboration*. Proceedings of TMCE 2012, pp.1013-1026

ISBN: 978-90-5155-082-5

Web address: https://www.etis.ee/ShowFile.aspx?FileVID=58167

Abstract: This paper is intended for readers interested in production routes reliability improvement and related decision making in manufacturing enterprises. The proposed framework facilitate decision making process through the reliability analysis module, which combines the data stored in ERP system with data received from failure mode and effects analysis table. The reliability analysis module structure shows how to extract the knowledge, required for selection of appropriate corrective action, which improves the reliability of production route.

Written by Kostina M., Karaulova T., Sahno J., Shevtshenko, E. and Maleki, M. Supervised by Cruz-Machado, V.

5. 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 19-21st April 2012, Tallinn, Estonia: 8th International Conference of DAAAM Baltic Industrial Engineering, Tallinn, Estonia, 19-21 April 2012, pp.567 - 572.

Web address: http://innomet.ttu.ee/daaam/proceedings/pdf/sahno.pdf

Abstract: Knowledge Management (KM) for production routes (PR) selection in manufacturing enterprises is important for reuse of historical data for production reliability process improvement. In this paper, we propose a new Data Mart (DM) structure as a part of KM framework for storage and reuse of PR data. In the case study we introduce how the developed framework can be used in a manufacturing enterprise.

Written mainly by Sahno J. with contributions from Opik R., Kostina M., Paavel M. And Shevtshenko E. Supervised by Wang Y.

6. Karaulova, T.; Pribytkova, M.; Sahno, J.; Shevtshenko, E. *Design of reliable production route system*. In: Annals of DAAAM for 2011 & Proceedings of the 22nd International DAAAM Symposium: Vienna, Austria: DAAAM International Vienna, 2011, pp. 539 - 540.

ISSN: 1726-9679

Web address: https://www.etis.ee/ShowFile.aspx?FileVID=51373

Abstract: This paper is intended for the companies interested in the practical experience of the Information Management Systems. The presented architecture of production route design describes the process of production data collection, definition, integration and extraction for specified project. The introduced reliability analysis module enables to assess and apply technological route for new orders, to minimize the production time and cost.

Written mainly by Karaulova T. with contributions from Kostina M., Sahno J. and Shevtshenko E.

7. Bjorklund, S.; Pribytkova, M.; Karaulova, T. *Development the maintenance plan: maintenance activities on operational level.* 2010. Proceedings of the 7st International Conference of DAAAM Baltic Industrial Engineering (pp. 286 - 291)

Web address: http://innomet.ttu.ee/daaam10/proceedings/PDF/Bjorklund.pdf

Abstract: This article focuses on the operational level of production enterprise activities and considers the suitability of failure mode and effects analysis (FMEA) which is a central element of Reliability Centred Maintenance (RCM), and periodic maintenance problem (PMP) solving for the case production line. FMEA provides the data for PMP in the context of failures and bottlenecks in machines and equipment. PMP uses operational research methods to find optimal maintenance plan. This combination of two methods (RCM/FMEA and PMP) becomes a powerful tool for reducing total cost of maintenance and diminishing the frequency of production line failures.

Written by Bjorklund S. and Kostina M. Supervised by Karaulova T.

8. Pribytkova, M.; Poljantsikov, I.; Karaulova, T. *Influence of variability on a reliable production process.* 21st DAAAM international symposium, Croatia, Zadar, 20-23rd October, DAAAM International Vienna, 2010, pp. 0329 - 0330.

ISSN: 1726-9679

Web address: https://www.etis.ee/ShowFile.aspx?FileVID=41775

Abstract: In this article the influence of variability on a reliable production process is considered. In case variability comes out of the allowed borders the production process becomes unreliable. This process leads to degradation of main production process characteristics: time of production output and product's quality. To track variability one of the best analysis to use is Statistical Process Control (SPC), which allows revealing hidden problems in process and determining causes of these problems before a failure occurs.

Written by Kostina M. with contributions from Poljantsikov I. Supervised by Karaulova T.

9. Karaulova, T.; Pribytkova, M. Reliability Prediction for Man-Machine Production Lines. 2009, DAAAM International Scientific Book (pp. 487 - 500)

ISSN: 1726-9687

Web address: https://www.etis.ee/ShowFile.aspx?FileVID=39012

Abstract: Nowadays the requirements on reliability of the complex mechanisms and machines are constantly rising. Suppliers, who are able to "manage" reliability of developed and manufactured mechanisms and machines, have significant competitive advantages. Present paper introduces the reliability analysis of prototype production line process. The modelling method was used for process analysis considering complex dependences among various parts of the system.

Written mainly by Karaulova T. with contributions from Kostina M.

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Inglise keel	Kõrgtase

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Töötamise aeg	Tööandja nimetus	Ametikoht
2006 - ...	AS Norma	Tootmisinsener

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