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Reliability Assessment of Manufacturing Processes

Tatyana Karaulova
Tallinn University of Technology, Department of Machinery, Tallinn, Estonia,
tatjana.karaulova@ttu.ee

Marina Kostina
Tallinn University of Technology, Department of Machinery, Tallinn, Estonia,
pribytkova.marina@gmail.ee

Eduard Shevtshenko
Tallinn University of Technology, Department of Machinery, Tallinn, Estonia,
eduard.sevtsenko@ttu.ee

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Abstract
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 current paper, we introduce a framework for the fault analysis of production process, which provides the recommendations of corrective actions for the elimination of critical faults for machinery manufacturing. The central part of the proposed framework is an extension of the standard Failure Mode and Effect Analysis (FMEA) with a fault classifier and the estimation of FMEA parameters. The Bayesian Belief Network (BBN) is used to classify FMEA faults. In order to fit the analysis the BBN template duplicates the faults classifier structure.

Key words: *Bayesian Belief Network (BBN), Failure Mode and Effect Analysis (FMEA), Process reliability.*

1. INTRODUCTION

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. 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. 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 [1]. A reliable production system ensures the sustainability of an enterprise in a dynamic business environment.

Process reliability is the capability of equipment and labour to operate without failure. The assessment enables us to identify the causes of failures followed by prevention and control. The goal of the current research is to extend the existing reliability assessment methods and integrate them into a common framework. The framework must be able to identify the most unreliable parts of a production process and to suggest the most efficient ways for the reliability improvement. Significant cost-saving opportunities for industrial enterprises can be achieved through the practical realization of reliability improvement of production facilities. When the process failure reasons are described, the reliability measures of manufacturing processes can be obtained from daily production data.

The most notable methodology dealing with this issue is the failure mode and effect analysis (FMEA). It is a dominant and systematic process for identifying potential failures before they occur, with the intent to minimize the risk associated with them [2]. It has been widely used in the various manufacturing areas as a solution to many reliability problems [3–5].

1.1 General 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 paper the framework for the analysis of production process failures is introduced, which also allows to define the most effective ways of their elimination.

In the centre of the framework (see figure 1) is FMEA - Failure Mode and Effect Analysis. The FMEA data may be also used by other methods of a process reliability analysis, therefore the FMEA analysis must be done as precisely as possible. The most significant parameters of FMEA are evaluated by experts. It is especially important for the fault severity parameter. In order to determine the current number of failures (occurrence) the FMEA data are regularly refreshed by ERP data.

Also in the current paper it is proposed to extend the FMEA table by classifier of faults. Based on this classifier a network template is created in Bayesian environment, that will be filled by FMEA data and used for decision support (Figure 1).

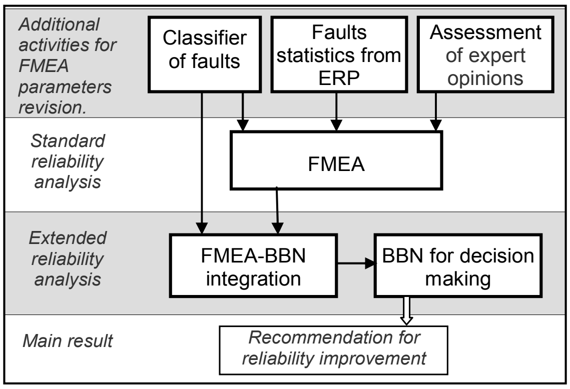

Figure 1. The framework of a manufacturing processes reliability assessment

The framework of manufacturing processes reliability assessment consist of the following levels:

- Additional activities for FMEA parameters revision;
- Standard method of reliability analysis;
- Extended reliability analysis.

2. RELIABILITY ASSESSMENT METHODS FOR MANUFACTURING PROCESSES

Reliability theory is the foundation of reliability engineering. Reliability engineering provides the theoretical and practical tools that enable to assess the probability and capability of parts, components, equipment, products and systems to perform their required functions for desired periods of time without failure, in specified environments and with a desired confidence. There are several standard methods for reliability estimation according to the handbooks of reliability prediction and design [6, 7].

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 [8].

2.1 The Failure Mode and Effect Analysis

FMEA is a reliability procedure which documents all possible failures in a system design within specified ground rules. It determines, by the failure mode analysis, the effect of each failure on the system operation and identifies single failure points, which are critical to the mission success or crew safety [9]. FMEA is the best analytical technique, because it establishes the links between causes and effects of defects, as well as it enable to discover the proper action [10].

In general the FMEA is a systemized group of activities designed to:

- recognize and evaluate the potential failure of a product/process and its effects,
- identify actions, which could eliminate or reduce the chance of a potential failure occurrence,
- document process

The purpose of the FMEA is to take actions to eliminate or reduce failures, starting with the highest-priority ones. It may be used to evaluate risk management priorities for mitigating known threat-vulnerabilities. In the FMEA failures are prioritized according to three dimensions:

1) How serious their consequences are,
2) How frequently they occur,
3) How easily they can be detected.

Used properly- the FMEA methodology allows to identify and document the potential system failures and to predict the consequences resulted. It would enable to determine the actions that would reduce severity and occurrence, but increase the detection of the potential failures. The composite risk score for each unit operational step is the product that combines three of its three individual component ratings: Severity (S), Occurrence (O) and Detection (D). The rating is scaled from 1 to 10 for each category [11]:

The occurrence is related to the probability of the failure mode and cause. A '10' on the occurrence table corresponds to a failure happening with every other part. A '1' corresponds to one failure in a million parts.

The severity index measures the seriousness of the effects of a failure mode. Thus, a severity index is assigned to the end effect of a failure. A '1' on the severity index corresponds to a failure that does not affect anything, a '5' corresponds to a performance loss, a '7' corresponds to machine shut down, and a '10' corresponds to a life threatening failure.

The detection index is generated on the basis of the likelihood of detection by relevant design reviews, testing, and quality control measures. A '1' on the detection index corresponds to a failure mode that is almost certain to be detected and a '10' corresponds to a failure that is almost impossible to detect.

Taking the product of these three indices (occurrence, severity, and detection) generates a risk priority number (RPN). The RPN represents the risk associated to each failure mode.

$$RPN = (S) \times (O) \times (D) \quad (1)$$

The RPN is a measure of a design risk. The RPN is also used to rank the order of the processes' concerns. The RPN will be between "1" and "1,000." For higher RPNs a team must undertake efforts to reduce this calculated risk through the corrective actions.

Advantages of FMEA:

- Identifies connections between reasons and effects;
- Takes into account the failure severity;
- Demonstrates the outcomes of previous unknown event;
- It is a systematized analysis;
- Provides focus for an improved testing and development;
- Minimizes late changes and the associated cost;

In our research the outcome of the FMEA is a list of recommendations that enables to reduce the overall risk to an acceptable level that can be used as a source for designing of a control strategy.

2.2 Assessments of Expert Opinions

Assessments of expert opinions are used for more precise estimation of severity parameter in FMEA. This approach is needed 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, 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 [12], 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 [13]. 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 [14].

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 $W \geq 0{,}7$ -0,8 opinions are consistent,
If $W <0{,}2$ - 0,3 opinions are not consistent,
If W=0,3 - 0,7 average consistency.

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

where *n* – a number of experts; m - a number of objects of expertise; S - a sum of squared deviations of all the examination objects' rank.
S may be defined as:

$$S = \sum_{i=1}^{n}\left(\sum_{j=1}^{m} x_{ij} - \frac{1}{2}m(n+1)\right)^2. \qquad (3)$$

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

2.3 Classifier of Faults

Classifier of faults is used for the arrangement of faults in machinery enterprises. It helps engineers by the codes of faults to define quickly the causes of faults. These codes must be included to FMEA. On the base of this classifier it is possible to build Bayesian Belief Network (BBN) for the process, because structure of BBN is the same as structure of classifier with the faults from FMEA of the process.

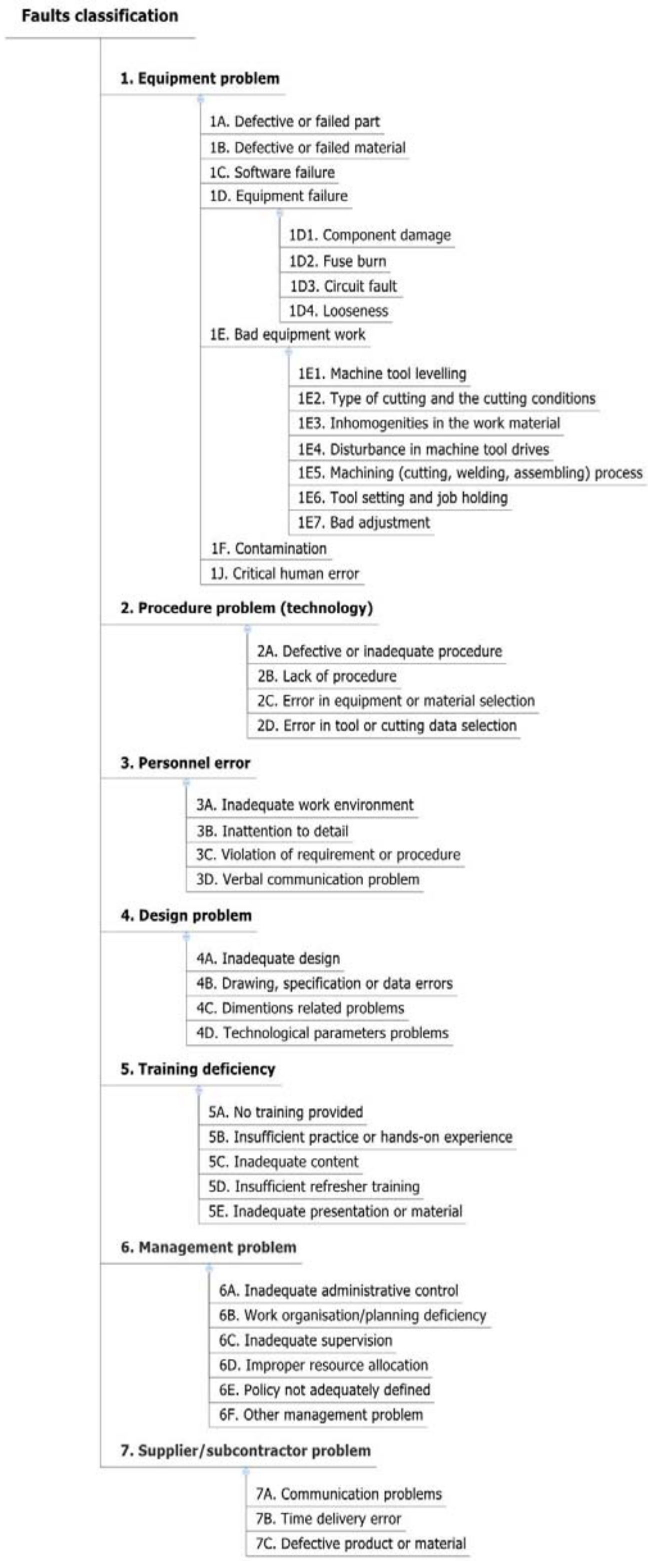

Figure 2. Faults classification for machinery enterprises

Reliability engineering is dealing with analysis of the causes of the faults in factories. For this reason standard DOE-NE-STD-1004-92 is used as a base [15].

We have adapted the classifier from this document for the machinery enterprises, see Figure 2. 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 major cause categories are:

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 elements are sufficient to describe any failure. Two new fields are added to standard FMEA structure, as “Failure class” and “Cause code”, in Figure 3, they are marked by “*”.

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

Figure 3. The header of FMEA table

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

2.2 Bayesian Belief Network

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 [16, 17].

Why did we decide to use the BBN in our research? It is the most appropriate tool for decision making, because the structure of BBN template includes the same faults, as classifier. Reliability engineers create the same structure of BBN and include in an every node the probability of particular cause errors by using the existing FMEA, cause codes,. 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 [18] is the synthesis of two separate sources of information - see Figure 4 for a schematic representation of this process. The result of combining the prior information and data in this way is the posterior probability.

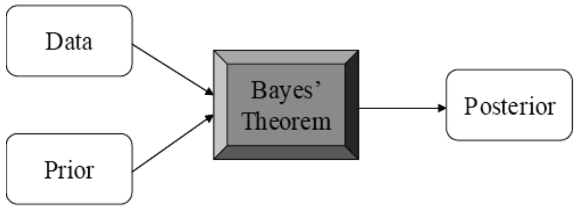

Figure 4. Synthesis of information by Bayes' theorem [18]

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 [19]:

- 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.

In this research the Bayesian Belief Network (BBN) is used to analyze the effect that the improvement of different fault groups will cause.

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):

$$P(H \mid E) = \frac{P(E \mid H)P(H)}{P(E)} \qquad (4)$$

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.

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:

$$P(H \mid \bigcap_j E_j) = \frac{\prod_{j=1}^{n} P(E_j \mid H)P(H)}{\prod_{j=1}^{n} P(E_j)} \qquad (5)$$

This article presents the use of Bayesian belief networks (BBNs) as a decision support tool to achieve sustainability of production process.

3. DATA TRANSFER FROM FMEA TO BBN

In Figure 5 the process reliability assessment flow is shown in details and it consists of 9 steps.

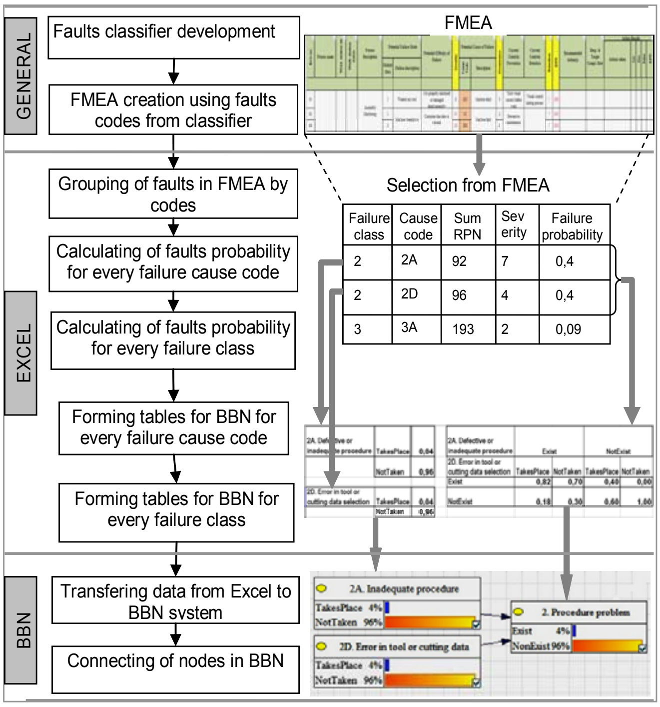

Figure 5. Process of data transfer from FMEA to BBN

Step 1 (GENERAL part) – Faults classifier development. It is done only once and can be implemented at any machinery enterprise.

Step 2 (GENERAL part) – FMEA elaboration. 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.

Step 4 (EXCEL part) – Calculating of failure probability for every failure cause (Figure 6). The probability of error for every failure cause is calculated based on data received from FMEA by equation 6:

$$P_{PR} = \frac{\sum RPN_{PC}}{\sum RPN_{Total}} \times 100\% \qquad (6)$$

where:

P_{RP} – probability of production route errors,

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

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

Failure cause code	Failure description	RPN Sum	Probability of failure	Severity		Severity in Bayes	
				Min	Max	Min	Max
1C	Software failure	287	0,13	7	10	0,7	1
1D	Equipment failure	442	0,20	7	8	0,7	0,8
1J	Critical human failure	68	0,03	2	5	0,2	0,5
2A	Defective or inadequate procedure	92	0,04	7	8	0,7	0,8
2D	Error in tool or cutting data selection	96	0,04	4	8	0,4	0,8
3A	Inadequate work environment	193	0,09	2	10	0,2	1
3B	Inattention to detail	468	0,21	3	8	0,3	0,8

Figure 6. Failure probability for every failure cause

Step 5 (EXCEL part) – Calculating of faults probability for every failure class according equation 7 in case of 2 events:

$$P(AUB)=P(A)+P(B)-P(A \cap B) \qquad (7)$$

where:

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

If we calculate probability for 3 events, we use the same but broadened equation 8:

$$P(AUBUC)=P(A)+P(B)+P(C)-P(A \cap B)-P(A \cap C)-P(B \cap C)+P(A \cap B \cap C) \qquad (8)$$

If it is required we can also calculate probability for more quantity of events.

Step 6 (EXCEL part) – Forming of tables for BBN: the probability is calculated for every failure cause. An example is introduced in Figure 7.

2A. Defective or inadequate procedure	TakesPlace	0,04
	NotTaken	0,96
2D. Error in tool or cutting data selection	TakesPlace	0,04
	NotTaken	0,96

2A. Defective or inadequate procedure	Exist		NotExist	
2D. Error in tool or cutting data selection	TakesPlace	NotTaken	TakesPlace	NotTaken
Exist	0,82	0,70	0,40	0,00
NotExist	0,18	0,30	0,60	1,00

Figure 7. Tables for BBN

Step 7 (EXCEL part) – Forming of tables for BBN: the probability is calculated for every fault group. Here probabilities are affected by the state of the other nodes depending on causalities.

Step 8 (BBN part) – Transfer of tables through FMEA-BBN. Universal format of data is used for storing and transferring them from Excel to Bayesian environment (in section 3.1 there is more detailed description of this process).

Step 9 (BBN part) – Connecting of nodes in BBN after this step Bayesian network is ready to be analysed.

3.1. FMEA-BBN integration module

Figure 8 describes the common scheme how data from the FMEA comes to BBN system.

The following approach is used in current research:

1. The template based on common classifier must be created in BBN system. This operation must be done once. In developed template is given in Figure 9, which is based on the faults classifier, shown in figure 2.

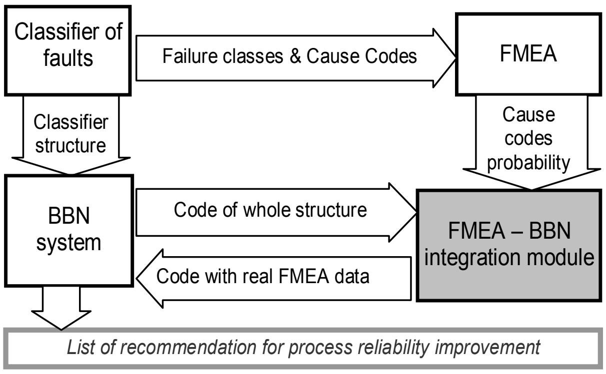

Figure 8. FMEA-BBN integration

2. Code generation for the structure of the classifier. This will be done using the opportunities of the BBN system.

3. By using special software module (FMEA-BBN integration module) this code of classifier is compared with data received from FMEA through the Excel tables. From text of the generated code file cause codes (1a, 1b, …7c) which was not found in the text must be deleted. When the cause code is existing, then software module locate its probability of faults to proper place in the text. 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 then to calculate the posterior probability after the corrective actions are applied. In figure 10 the main functions of the FMEA-BBN integration module are shown.

3.2. Implementation of corrective actions in BBN

A BBN is a directed graph whose nodes represent the (discrete) uncertain variables. BBN is drawn based on failure probabilities withdrawn from FMEA. This network (Figure 11) represents possible states of the given failures and their corresponding errors. The probability of any node being in one state or another without current evidence is described in Figure 7. Probabilities on some nodes are affected by the state of another nodes depending on casualities. This BBN can answer questions like: if personnel error exists, was it more likely to be caused by inadequate work environment, inattention to detail, or violation of requirements.

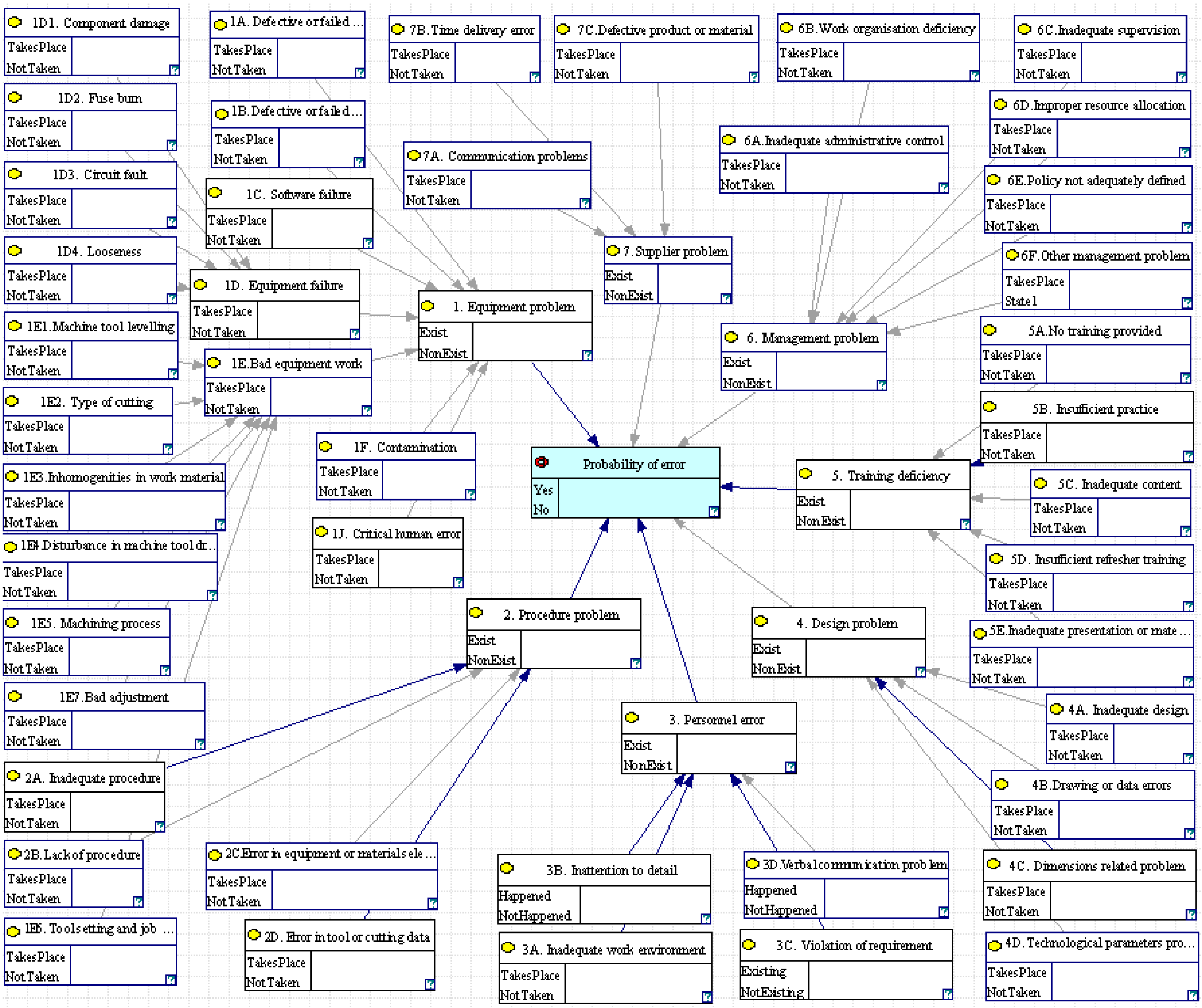

Figure 9. Common structure of faults classifier

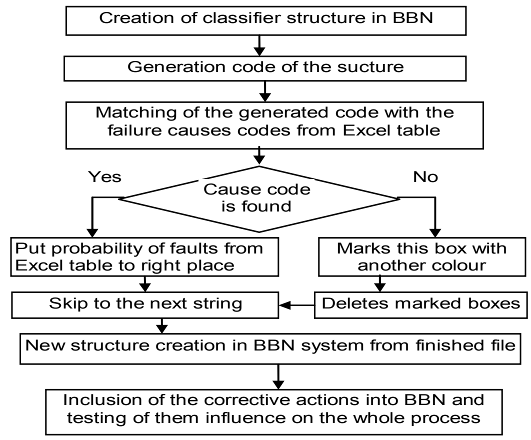

Figure 10 Functions of the FMEA-BBN integration module

After the primary network is completed we are ready to start using the reliability improvement module. According to Figure 12, personnel error (3th failure class) is the most probable failure type. Particularly, inattention to details which is one of personnel errors has the highest probability. Therefore, firstly the corrective actions are focused on this failure with intention to decrease its influence. In our case study four corrective actions are planned: (a) Poka-Yoke, (b) visual instruction, (c) additional training and (d) improvement of route card. All proposed corrective actions and path how they influence the top event is shown in Figure 11. Influence of every corrective action on personnel error and final probability of error at top event is represented in Figure 12.

In order to perform the analysis the probability of errors is calculated in Excel based on FMEA [20] for every corrective action are imported to the BBN. Moreover, influence of every corrective action on failure severity is also taken into consideration.

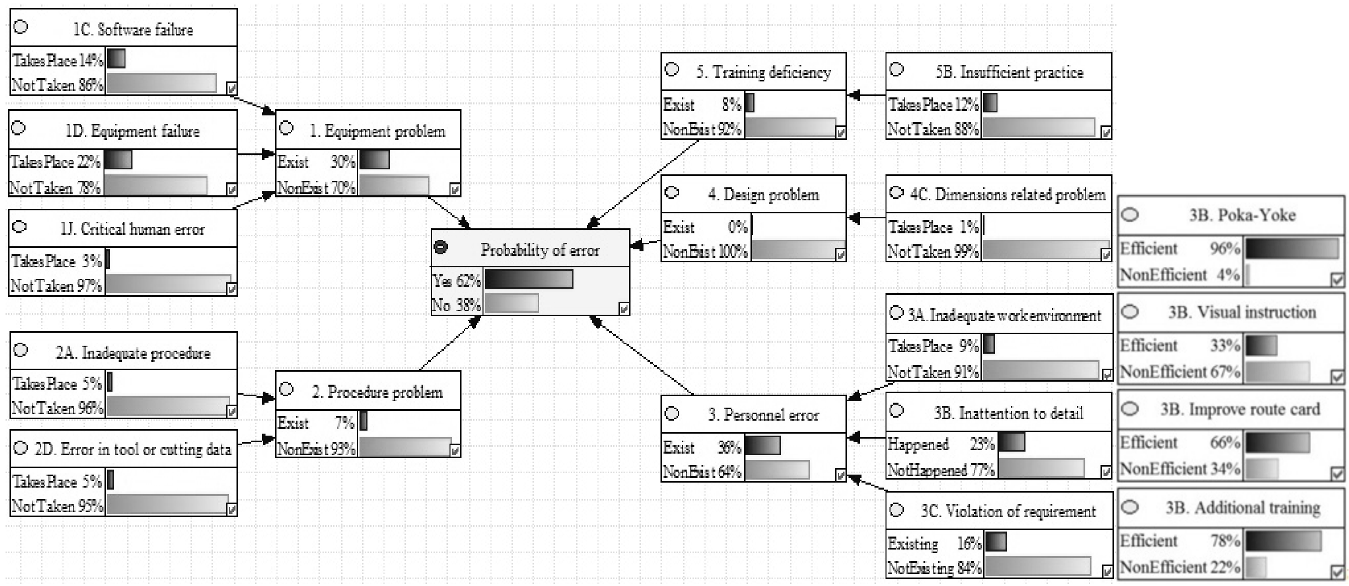

Figure. 11 An example of Bayesian Belief Network

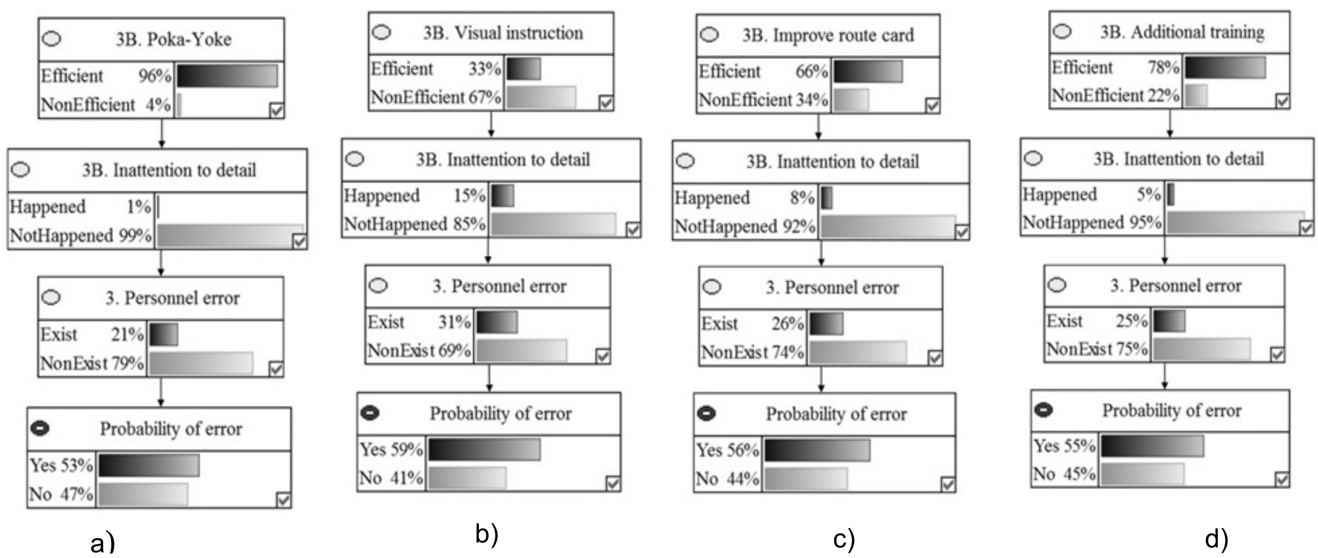

Figure. 12 Corrective actions and path of their influence in the process

As analysis shows the most effective corrective action for the Personnel errors elimination is implementation of Poka-Yoke – with probability of success of 96%. From one side Poka-Yoke is the most reliable decision of the problem, but from another side this is the most expensive decision as well. Apparently, the final decision what corrective action to implement will be made by the decision makers considering information received from the analysis as well as costs of each action and the policy of enterprise.

During decision making process it is important that the information required for decision making was presented in user-friendly format. The final required information is presented in Table 1. The table represents the influence of corrective actions on Personnel error and severity value changes.

Table 1. Influence of corrective actions on Personnel error where max severity is applied (worst case scenario)

Failure cause	Corrective action	Influence on failure cause	Influence on severity
Inattention to detail	Poka-Yoke	15 %	7
Inattention to detail	Visual instruction	5 %	0
Inattention to detail	Improve route card	10 %	0
Inattention to detail	Additional training	11 %	0

6. CONCLUSION

The Customers demand for high quality, reliable products is increased. Without measure of process losses a companies can´t estimate how much money they're loose monthly due to unreliable production processes. Process reliability is a method for identifying problems, which have significant cost reduction opportunities for improvements.

Traditionally, reliability has been achieved through extensive testing and use of techniques such as probabilistic reliability modelling. These are techniques are used in the late stages of development. The challenge is to design based on quality and reliability requirements in the early stage of development cycle.

Many processes have extra capacity. You'll never find the hidden losses unless you look for it with new tools and new approaches described in this paper. Reliability analysis FMEA gives to 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 article we argue that Belief Bayesian Networks provide an attractive solution to the problems identified above. BNN enable us to combine FMEA data that are available (faults probability and severity) with qualitative data and subjective judgments about the process. Hence BBN provide a method of modelling process losses and measuring the effectiveness of recommendations using for process reliability improvement. In current research the framework for the analysis of the production process was developed. It enables companies to analyse processes as a whole as well as its parts for efficient forecast of the production process improvement. The reliability analysis framework was developed for machinery manufacturing enterprises. Bayesian Belief Network enables to calculate the posterior probabilities for each fault group based on the error of the manufacturing processes probability.

In our future work we are going to develop a reliability analysis module and to connect it with ERP system for reliability estimation for every manufacturing operation that enables to select the most reliable production route for new product.

7. ACKNOWLEDGEMENTS

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Procena pouzdanosti proizvodnih procesa

Karaulova T., Kostina M., Shevtshenko E.

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Apstrakt

Pouzdanost proizvodnih procesa je ključni problem koji osigurava stabilnost proizvodnog sistema. On poboljšava kvalitet proizvoda i smanjuje proizvodne gubitke. U ovom radu predstavljamo okvir za analizu grešaka proizvodnog procesa koji pruža preporuke za postupke poboljšanja eliminacije kritičnih grešaka u proizvodnji mašina. Centralni deo predloženog okvira je dodatak standardnoj analizi načina i efekata loma (FMEA) sa klasifikatorom grešaka i procenom FMEA parametara. Bajesova mreža verovatnoće (BBN) se koristi za klasifikaciju FMEA grešaka. Kako bi odgovarala analizi, BBN osnova duplicira strukturu klasifikatora grešaka.

Ključne reči: *Bajesova mreža verovatnoće (BBN), analiza načina i efekata loma (FMEA), pouzdanost procesa.*