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Reliability estimation for manufacturing processes

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Analysis and modelling

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.
Design/methodology/approach: FMEA is in the centre of the proposed framework,a reliability analysis type, the most widely used in enterprises. The current research suggests to extend the FMEA by introducing a classification of faults. In this procedure, Bayesian Belief Network is employed to analyze faults.
Findings: An integrated modelling method based on a system modelling and complemented with a reliability evaluation mechanism has the capability to analyse and design manufacturing systems. The tool developed to analyse a production process, enables companies to analyse the process as a whole as well as its parts and achieve efficient prognosis for the production process reorganization.
Research limitations/implications: The reliability analysis framework is developed for machinery manufacturing enterprises.
Practical implications: The reliability assessment tool helps engineers quickly and with accurate estimate most unreliable places of production process and indicates ways of their elimination with great efficiency.
Originality/value: Expansion of FMEA method, application of Bayesian Belief Network for process reliability estimation, usage of reliability estimation during production route creation.
Keywords: Process reliability; Failure Mode and Effect Analysis (FMEA); Bayesian Belief Network (BBN)

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1. Introduction

The globalisation of markets, growth of customers' expectations, widening competition in all spheres of relation between the customer and the supplier are the factors which at present extort the quality exhibiting in the strategy of the enterprise. Quality in the competitive world means the necessity of fulfilment of commited and waited customer's requirements who occupies the leading position on the market [1]. Quality of production process means reliable and sustainable process. Therefore the common objective of industrial enterprises is to increase the overall production reliability. In another words, they look for output maximization of their current resources, by reduction of wastes in equipment and process reliability. Equipment and process reliability jointly create reliable production.

The system reliability assessment and prediction has become an increasingly important aspect of the process operating different stages. It is important to develop efficient reliability assessment techniques for complicated systems with several methods and different failure mechanisms, in order to ensure adequate performance under extreme and uncertain demand [2]. Reliability requirement for production process ensures the sustainability of the whole enterprise.

The goal of the current research is to develop a reliability assessment method. The main task of the paper is to show data transferring from FMEA to BBN and further realisation of decision making. The system must identify the most unreliable parts of a production process and suggest the most efficient ways for the reliability improvement. Significant cost-saving opportunities for industrial enterprises can be achieved through the reliability improvement of the facilities for their practical realisation. When the process failure criteria are established, the reliability of manufacturing processes can be obtained from daily production data.

2. Methods for process reliability improvement

Reliability theory is the foundation of reliability engineering. Reliability engineering provides the theoretical and practical tools whereby 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, can be specified and predicted [3]. There are several standard methods for reliability estimation according to the Electronic Reliability Design Handbook (MIL-HDBK-338B) [4], one of them is Failure Mode and Effect Analysis (FMEA). FMEA is the best analytical technique, because allow for establishing links between causes and effects of defects, as well as searching, solving and with drawing the best decisions concerning applying proper action [5].

2.1. Failure Mode and Effects Analysis (FMEA)

This part is the core of this research. FMEA (Failure Mode and Effect Analysis) is in the centre of the proposed framework-, other methods are based on data from this analysis. Therefore this analysis must be implemented as precisely as possible, especially it is important for such parameter as fault severity.

FMEA is a reliability procedure which documents all possible failures in a system design within specified ground rules. It determines, by failure mode analysis, the effect of each failure on system operation and identifies single failure points, which are critical to mission success or crew safety [6,7].

In general 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 potential failure occurring,
- 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 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.

Good FMEA methodology allows for the identification and documentation of potential failures of a system and their resulting effects. It also allows for the assessment of the potential failure to determine actions that would reduce severity, reduce occurrence, and increase detection. The composite risk score for each unit operation step is the product of its three individual component ratings: Severity (S), Occurrence (O) and Detection (D). This composite risk is called a risk priority number (RPN). This number is then used to rank order the various concerns and failure modes associated with a given design as previously identified in the FMEA.

$$RPN = (S) \ x \ (O) \ x \ (D) \qquad (1)$$

The RPN is a measure of design risk. The RPN is also used to rank order the concerns in processes (e.g., in Pareto fashion). The RPN will be between “1” and “1,000.” For higher RPNs the team must undertake efforts to reduce this calculated risk through corrective action(s).

Advantages of FMEA:

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

Disadvantages of FMEA:

- Amount of data can be too much,
- Analysis can be too complicated,
- Environmental conditions and maintenance aspects might not be examined [4].

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

2.2. Classifier of faults

Classifier of faults is needed for ordering the 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.

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 [8]. The assessment phase includes analyzing the data to identify 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. External Phenomena

Those seven elements are sufficient to describe any failure. We have adapted the classifier from this document for the machinery enterprises, see Figure 1.

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

In FMEA structure two new fields are included, as "Failure class" and "Cause code", in Figure 2, they are marked by "*".

2.3. Bayesian Belief Network (BBN)

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 [9,10].

Why did we decide to use BBN in our research? It is most suitable tool, because structure of BBN is the same as structure of faults classifier. Reliability engineers using only existing cause codes from FMEA can create the same structure of BBN and include the probability of particular cause errors to every node. Bayesian networks are the natural successors of statistical approaches to Artificial Intelligence and Data Mining. Particularly suited to taking uncertainty into consideration, they can as easily be described manually by experts in the field.

A key feature of Bayesian statistics is the synthesis of the two separate sources of information - see Figure 1 for a schematic representation of this process [11]. The result of combining the prior information and data in this way is the posterior distribution.

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 [12,14]:

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

In this research the Bayesian Belief Network (BBN) is used to analyze what effect 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 hypothesis H given that evidence E is present or P(H|E), is

$$P(H|E)=\frac{P(E|H)P(H)}{P(E)} \tag{2}$$

where

$P(H)$ is the probability of the hypothesis 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.

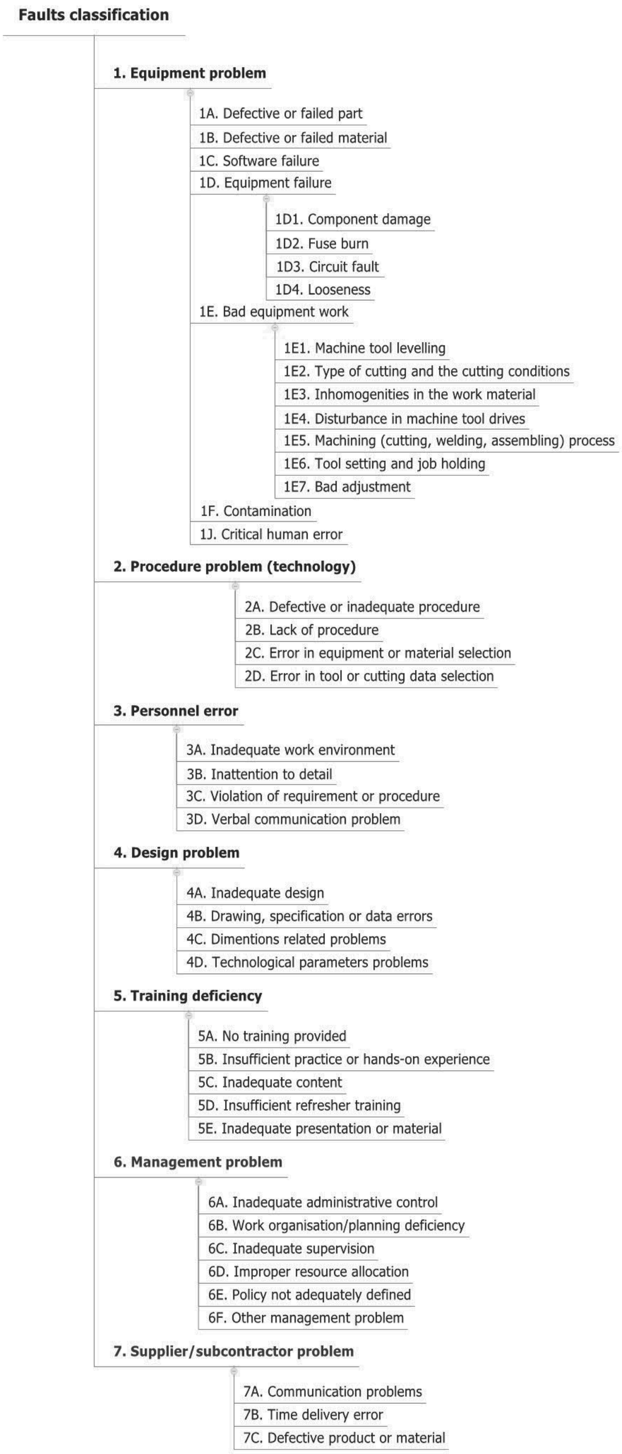


Fig. 1. Faults classification for machinery enterprises

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)	Expected Action Results			
				* Failure class	Failure description			* Cause Code	Description							Severity	Occurrence	Detection	RPN

Fig. 2. The header of FMEA table

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 [13]:

$$P(H|\bigcap_{j} E_j) = \frac{\prod_{j=1}^{n} P(E_j|H)P(H)}{\prod_{j=1}^{n} P(E_j)} \qquad (3)$$

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

3. Case study of process reliability improvement

3.1. General remarks

Reliability of production processes is a key issue for ensuring the stable system operation, increasing of a product quality, and reducing of a production losses. In this paper the tool for the analysis of failuress in a process is proposed which also allows defining the most effective ways of their elimination.

In the current paper it is proposed to extend the FMEA by introducing a classifier of faults. On a base of this classifier a stucture of network is created in Bayesian environment for decision support and also transferring of failures data from FMEA is carried out (Figure 3).

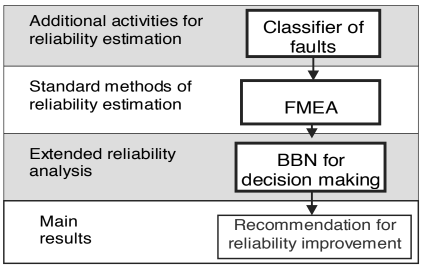


Fig. 3. Process reliability assessment

Decision support systems are built based on data extracted from various data sources. During the decision making process, it is important to present the intermediate results in user-friendly formats, such as search or calculation results, illustration with pictures, diagrams, summaries with tables, graphs, etc., and graphical illustration of casual-effect relationships [15,16].

According to the recommendations for reliability improvement the required level of reliability is achieved and a decision maker chooses the most suitable production route, provides it with the list of recommendations and finally this production route is imported to ERP system and then into production process.

3.2. Data transformation from FMEA to BBN

In Figure 4 the process reliability assessment flow is shown in details and it consists of 9 steps.

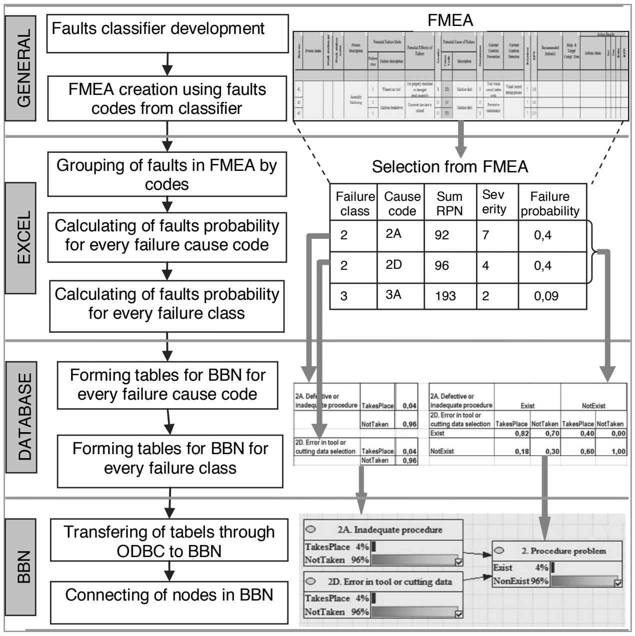


Fig. 4. Detailed process of reliability assessment

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. This process starts from analysis of production system operations and particular enterprise requirements. 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. This step is required for further work with failure codes.

Step 4 (EXCEL part) - Calculating of failure probability for every failure cause. This information will be used in BBN (Figure 5). The probability of error for every failure cause is calculated on base of data from FMEA by Equation 4:

$$P_{PR} = \frac{\sum RPN_{PC}}{\sum RPN_{Total}} \times 100\% \quad (4)$$

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

Fig. 5. Detailed process of reliability assessment

Step 5 (EXCEL part) - Calculating of faults probability for every failure class.

Step 6 (DATABASE part) - Forming of tables for BBN: every failure cause with its probability. An example is introduced in Figure 6.

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

Fig. 6. Tables for BBN

Step 7 (DATABASE part)- Forming of tables for BBN: every fault group with its probability. Here probabilities are affected by the state of the other nodes depending on causalities.

Step 8 (BBN part)- Transferring of tables through ODBC to BBN. Universal format of data is used for storing and transferring them from Excel to Bayesian environment.

Step 9 (BBN part)- Connecting of nodes in BBN or building of BBN. This is the final step when Bayesian network is ready to be analysed.

3.3. BBN example

A BBN is a directed graph whose nodes represent the (discrete) uncertain variables [14]. BBN is drawn based on failure probabilities withdrawn from FMEA. This network (Figure 7) 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 6. 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.

After the primary network is completed we are ready to start using the reliability improvement module. According to Figure 7, personnel error (3^{th} failure class) is the most probable failure type. Particularly, inattention to details which is one of personnel errors has the highest probability. Therefore, corrective actions are first of all focused on this failure causes aiming to decrease it as much as possible. 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 8. Influence of every corrective action on personnel error and final probability of error at top event is represented in Figure 9.

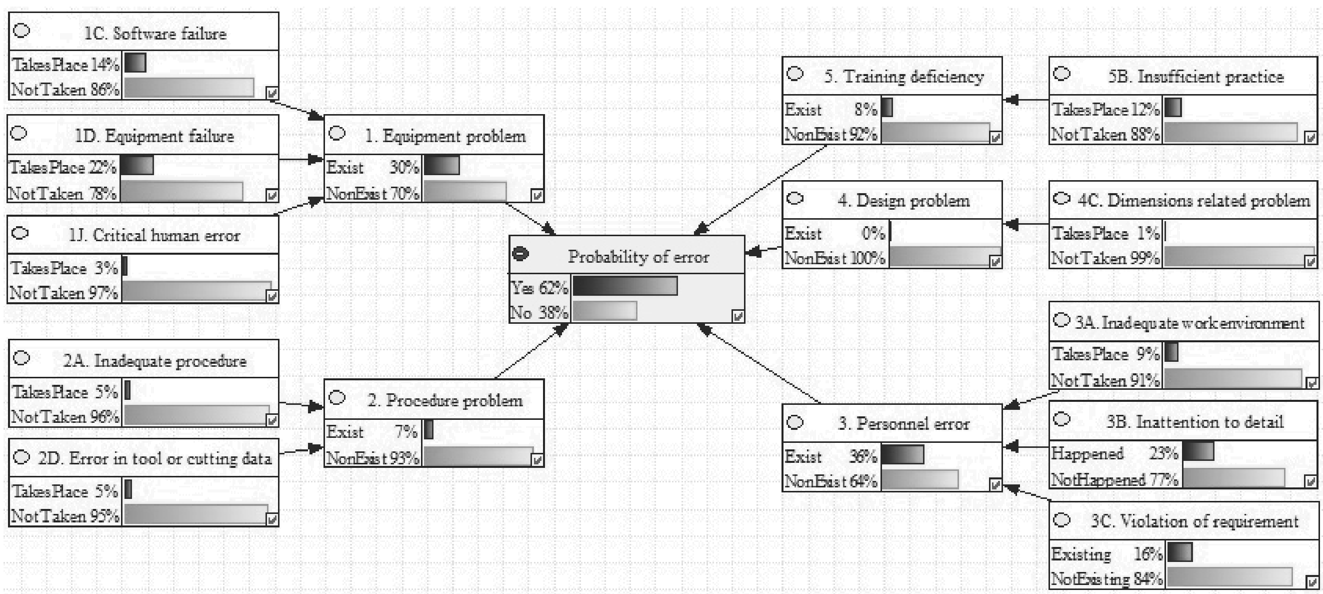


Fig. 7. An example of Bayesian Belief Network

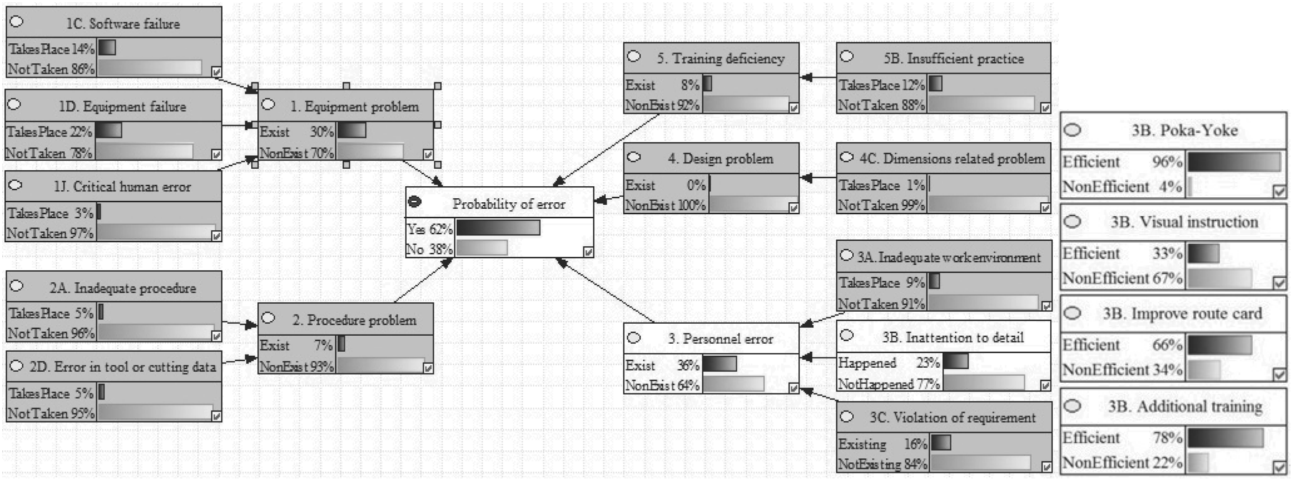
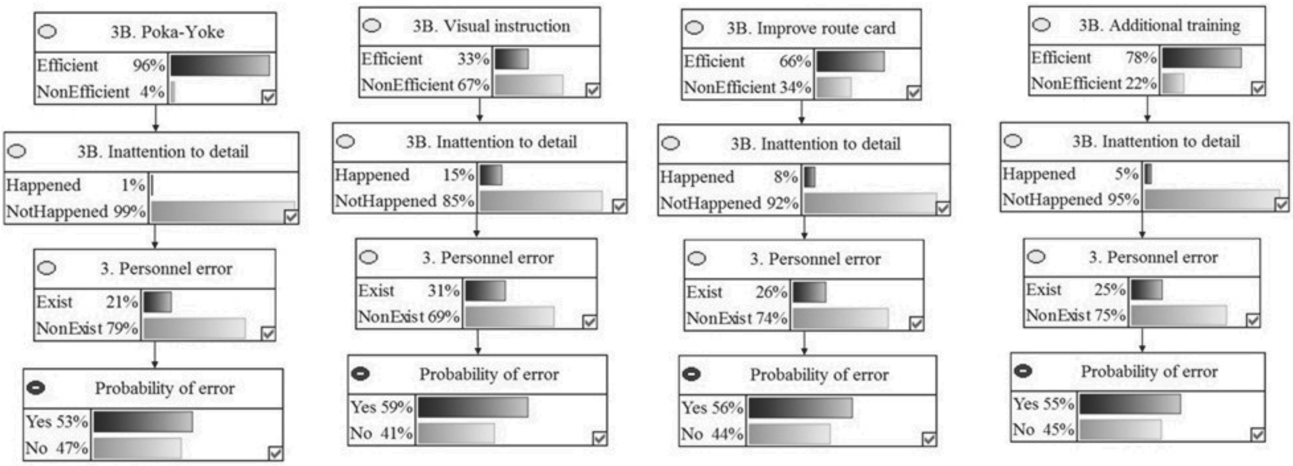


Fig. 8. 4 planned corrective actions and path of their influence in the process



a) b) c) d)

Fig. 9. Posterior probabilities when implemented: a) Poka-Yoke, b) visual instruction, c) improvement of route card, d) additional training

In order to make this analysis, RPN of corrective action was taken from FMEA, probability of error for every corrective action was calculated and imported to the Bayesian model. Moreover, influence of every corrective action on failure severity is also taken into consideration. As it was mentioned before in Figure 9 are presented available corrective actions and their influence on the corresponding failure class and finally on probability of error on top event. As analysis shows the most effective corrective action for Personnel errors elimination is Poka-Yoke implementation - with probability of success of 96%. From one side Poka-Yoke is the most reliable desicion 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 got from the analysis as well as costs of each action and the policy of enterprise. As it was mentioned in the paragraph 3.1, during decision making process it is important that required for decision making information was presented in user-friendly format, so final required information is presented in Table 1. The table represents the influence of corrective actions on Personnel error and change of severity value.

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

4. Conclusions

Customers are placing increased demands on companies for highly qualified and reliable products. Without measuring of process losses companies do not have an idea of how much money they are missing each month from unreliable production processes. Process reliability assessment is a method for identifying and resolving problems, which has significant opportunities for cost reduction and for improvements.

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

Failure Modes and Effects Analysis (FMEA) is a methodology good for analyzing potential reliability problems as early in the development cycle as late when a process is already started. However by performing this analysis earlier in the process designing, it is easier to take actions to overcome some 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. FMEA can also capture historical design information for use in future product improvement. It can be used to perform the crucial step of anticipating what might go wrong with a product. While anticipating every failure mode is not possible, the design team should formulate as extensive a list of potential failure modes as possible.

Many production processes have extra capacity. It is difficult to find it without any analysis. New tools and new approaches described in this paper may help to find the hidden losses in a process and make it more reliable. Reliability method FMEA gives us not only quantitative assessment of operations failures in the process, but also 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. BBN enable us to combine failures probability and severity, the data which is available from FMEA, with qualitative data and subjective judgments about the process. Hence BBN provide a method of modelling process losses and measuring the effectiveness of recommendations used for process reliability improvement.

The tool developed in this research to analyse the production process enables companies to analyse processes as a whole as well as its parts separately and get efficient prognosis for production process improvement.

The production process reliability analysis framework was developed for machinery manufacturing enterprises. Bayesian Belief Network makes it possible to calculate posterior probabilities of each failure on the error probability of the manufacturing processes. I

In our future work we are going to develop a reliability analysis module and to connect it with ERP system for estimation of every operations reliability and selection the most reliable production route for a new product.

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