RESEARCH IN LOGISTICS & PRODUCTION

ISSUES ON PRODUCTION PROCESS RELIABILITY ASSESSMENT – REVIEW

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Abstract: The paper discusses a problem of reliable performance of production processes. Reliability analyses of production systems regard considering many different factors and requirements. As a result, basic definitions connected with production system/process have been defined. Later, there has been also presented the literature review in reliability engineering, what gives the possibility to present a comparison analysis of known reliability models for production systems performance. Based on the presented literature summary, the multidimensional definition of production process reliability is developed with short example of its implementation possibilities. The work ends up with summary and directions for further research.

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1. INTRODUCTION

In today's changeable and uncertain environment the manufacturing companies have to be flexible and dependable in order to meet customers' expectations. Such challenges as shorter life cycles of products and technologies, shorter delivery times, high level of products customization, increased product variety, high product quality expectations, or demand variability necessitate that manufacturing system/process reliability is to be considered as a major performance parameter (Dai et al., 2015; Lin & Chang, 2012; Tubis 2010).

Reliability of a production system depends both on its configuration and on the way it is managed in operation. Thus, reliability modelling process of production system performance needs the existence of various problems connected with e.g. possible machines and equipment unreliability recognizing and analyzing. Moreover, the main reliability characteristics of production systems mostly depend on the maintenance activities being performed in these systems. Following this, assessing reliability of complex systems composed of a large number of components is a difficult task (Elsayed, 2000; Plewa 2009). On the other hand, the effective performance of production process also needs development of methods for reliability estimation and prediction. However, there can be found many different approaches and aspects of production process reliability which are under investigation in the analysed literature (Dhillon, 2005; Jodejko-Pietruczuk & Plewa, 2014). Thus, this research area still demands examination of real manufacturing systems performance and development of new complex framework for production process reliability modelling and assessment. As a result, the study is aimed at the summary of recent research in the area of production system/process reliability assessment. Based on the developed state of the art, authors propose the definition of production process reliability that adheres to the requirements of reliability engineering of technical system, as well as takes into account the specific character of manufacturing systems and supply chains performance.

Following the introduction, the paper is organized as follows: First, there are defined basic definitions connected with production system/process. Literature overview in the research area is also discussed. Later, the reliability engineering issues and production systems/processes reliability assessment problems are investigated. This gives the possibility to propose the multidimensional definition of production process reliability with short example of its implementation. The work ends up with summary and directions for further research.

2. DEFINITION OF PRODUCTION PROCESS RELIABILITY – LITERATURE REVIEW

Manufacturing is continuously evolving since its development from the age of craft production to mass production, and later on to lean production and agile manufacturing (Chlebus, 2000). That development provokes the increase in interest in such concepts as robustness, flexibility, productivity, quality, vulnerability, resilience, and dependability (i.e. reliability, availability and supportability) what may be confirmed by the authors of such recent works as (Elsayed, 2000; Inman, et al. 2013; Jain et al., 2013; Li et al., 2013; Mondal et al., 2014; Savage & Carr, 2001). Following this, there exist many definitions of production system/process terms in the known scienfitic works.

Following (Mazurczak & Gania 2011), a production system may be interpreted as static and dynamic combinations of founds that transform entrance supplies (processes, objects of work, means of work, information) into exits, which may appear materially (goods and services, as well as production waste) or informationally. The main function of any production system is to performance production processes. Based on (Black, 2007) this system is defined as a complex arrangement of physical elements (machine tools, tooling, materials-handling equipment, people) characterized by measurable parameters. The main target of such a system is to satisfy internal and external customers' needs.

The process is a sequence of steps or events designed in such a way that the result of it is to produce a product or service (Lee & Rosenblatt 1987; Liwowski & Kozłowski, 2007). This term may be also defined in several other ways, as e.g. (Nowakowski, 2011):

- a phenomenon relating to a fragment of reality that meaning transformation of the status of this part of the reality,
- a sequence of elementary changes in the part of reality that pass in time,
- successive flow of related changes that constitute stages, phases, stages of reality changes,
- flow, development, and a transformation of something.

Taking one step further, the production may be defined as an adaptation and transformation of objects of work into final product with the use of means of operation and manpower (Pająk, 2006). Thus, production process may be defined as planned operation plan that being implemented gives the possibility to provide the customer with the products that satisfy his requirements (Pająk, 2006). Following (Lee & Rosenblatt 1987) production process is a sum of all activities that involve materials and goods gradually undergoing changes, that cause successive development of features of products, directed by its intended use. The end of the production process occurs when all the necessary features of given product have been achieved. The main function of production process is to modify the process inputs (various resources as information, raw materials, peoples) into the process outputs (final product or service) (Głowacka-Fertsch & Fertsch, 2004; Hamrol, 2015). The production process is also affected by external and internal disruptions and has to satisfy specified customer requirements (Fig. 1).

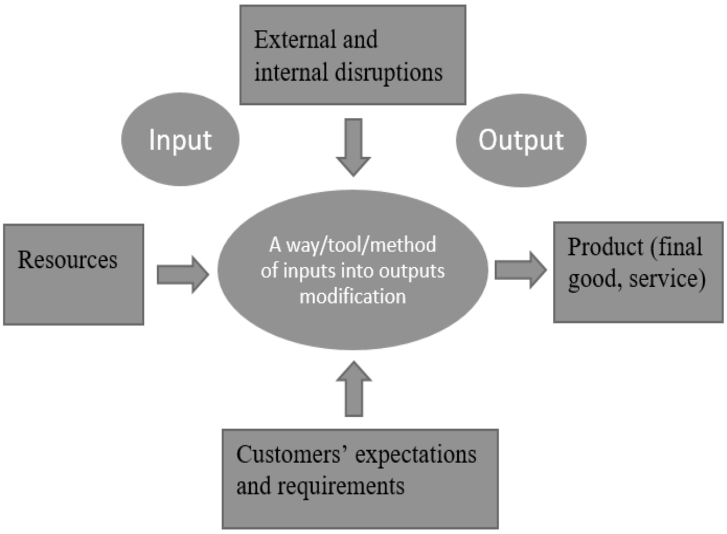

Fig. 1. The main elements of production process; Own contribution based on (Hamrol, 2015)

Based on work (Liwowski & Kozłowski, 2007), the production processes can be classified according to many different criteria. For example, taking into account the work organization, there can be distinguished four types of production:

- production line – production is organized in such a way that the product passes sequentially from one location to another,
- continuous flow – type of production line, from which the product cannot be removed before the end of the sub-process,
- custom manufacturing – products are manufactured based on customers' orders,
- manufacturing fixed position - the product does not change its position during production process performance.

Today's production companies suffer many disruptions connected with external sources (e.g. suppliers unreliability) or internal problems occurrence. This situation requires proper identification of elements, which may influence the effective performance of a given system (Fig. 2).

Taking one step further, the production process interactions, its stability, manufacturing lead time or changes in production technology are mostly unpredictable and usually hard to measure. Thus, one of the challenging issues facing many production systems is process unreliability and its impact on the operation of the manufacturing organization (Moinzadeh & Aggarwal, 1997).

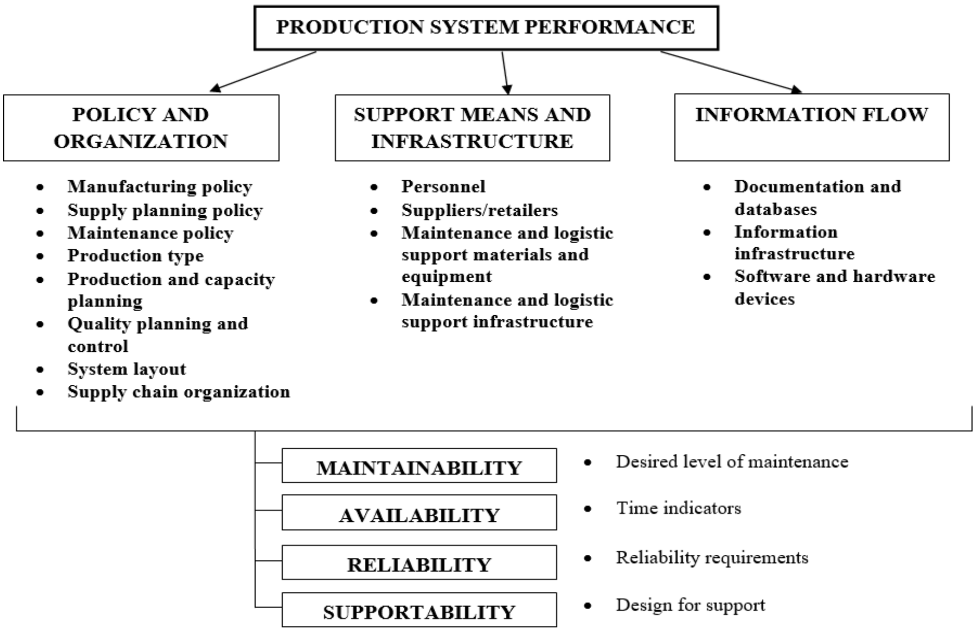

Fig. 2. Reliability, availability, maintainability and supportability in achieving production system performance; Source: Own contribution based on (Blanchard, 2004; Inman, et al. 2013; Nowakowski, 2006)

In the reliability literature the meaning of technical system reliability (and availability) is known. According to (Gulati et al., 2010) reliability is defined as the probability that equipment, machinery or systems will perform their required functions satisfactorily under specific conditions within a certain time period. Following (Ważyńska-Fiok & Jaźwiński, 1990), reliability can be defined as a property of the system to maintain the ability to perform present function at a certain time and under certain conditions, in spite of specific subset of system components' possible failure occurrence. The main factors which affect this system's characteristics are (Jodejko-Pietruczuk et al., 2013):

- system configuration (series, parallel, k-out-of-n),
- number of units/components in a system,
- random time to failure,
- maintenance policy,
- random repair time.

For a manufacturing system, reliability is usually treated as a performance indicator that provides information of overall system capability (Lin & Chang, 2013, 2012), productivity or quality (Elsayed, 2000; Dai et al., 2015) and as a measure of production time (Chakraborty & Ankiah, 1989). Thus, following the literature, reliability of production process can be seen from different aspects, such as:

- time (timely completion of manufacturing orders),
- quantity (successive performance of scheduled production),
- quality (of service/products),
- cost (economical effective production).

Taking one step further, the production process reliability may be also defined according to the business-oriented approach that determines the correct performance of a logistic system in terms of 7R formula implementation (Ballou, 2004): Right product, Right quantity, Right quality, Right place, Right time, Right customer, and Right price. Thus, according to this approach the reliable performance of any logistic system means delivery: the correct product, to the correct place, at the correct time, in the correct condition and packing, in the correct quantity, with the correct documentation, to the correct customer (MIL-HDBK_502, 1997).

This variety of production processes reliability issues has motivated researchers to propose various techniques and models for its assessment. The most known solutions are reviewed in the next Section. Later, based on the given literature summary there is developed a multidimensional definition of production process reliability.

3. ASSESSMENT OF PRODUCTION PROCESS RELIABLITY

The complexity and multifaceted nature of production systems performance made that there can be found a lot of work covering issues of reliability engineering in the recent literature. Assessment problems in this field have gained much interest since 1960s (Dhillon, 2005). Thus, various approaches have been developed in order to assess and optimize the production processes performance. According to (Dhillon, 2006, 2005), the main reliability assessment methods that also may be use for production processes analysis performance mostly include:

- Failure Mode and Effect Analysis (FMEA),
- Fault Tree Analysis (FTA),
- Network Reduction method,
- Decomposition method,
- Common Cause Failure Analysis method.

The known production process/system reliability models may be classified into five main groups:

- Models based on reliability index assessment,
- Models with maintenance (of production machines),
- Models based on quality engineering approach,
- Models with inventory requirements,

- Extended production models (include e.g. production strategies implementation (e.g. just in time system) or optimization models (e.g. Economic Production Quantity models).

Moreover, in the literature the reliability of the production process is defined in various ways. One of the first work dedicated to the problems of system reliability modelling is (Curtin, 1959), where author uses the Monte Carlo approach to predict and evaluate system reliability. Later, Mayne (1960) shows two reliability models of good and bad periods on production lines. He takes into account quality control and need of reworks in the case of "bad" periods and production delays connected with those "bad" periods. In the same year, Hosford (1960) provides definitions of such concepts as dependability, reliability, availability, and proposes interval model of production. Lefkovitz (1977) demonstrates design rules of manufacturing systems with taking into account the disturbances. He focuses on avoiding breakdowns, time and costs of rework, controlling quality and production processes and on a total cost of production. Two years later, Meyer, Rothkopf and Smith (1979) analyse connection of demand and average inventory level and its effect on repair time and time of breakdowns.

In the 1980s., Blumenthal, Greenwood and Herbach (1984) focus on the problem of aging of equipment and tools, and its impact on the failure of the production process. Buzacott and Yao (1986) in their analytical models show the importance of flow control, routing, and sequence of the production process. They also show the impact of set-up times of machines to process performance. In the same year, Filus (1986) checks dependence between system load and failures of the system and machines. De Maré and Rosander (1988) describe several case studies for different types of production systems. Chakraborty and Ankiah (1989) present an assessment of the production system using the Monte Carlo method.

Davy, White, Merritt and Gritzmacher (1992) develop a set of knowledge about JIT and propose a simple model of JIT production system. Chen and Yao (1992) propose fluid model of continous production system with random disruptions. They also describe the factors affecting the production process performance. Berg, Posner and Zhao (1994) build a comprehensive production model, which includes data such as input demand, system capacity, capacity machines, inventory and reliability of the machines. Moinzadeh and Klastorin (1995) investigate the relationship between reliability of production process, costs of stopping production, and costs of rework in the case of appearing defective items as a final product. Denardo and Lee (1996) in their article are focused on quality, inventory buffer and need of rework in a serial production line. In the article of Moinzadeh and Aggarwal (1997), reliability is defined as a time between breakdowns. Authors control also operating costs and inventory level. Denardo and Tang (1997) divide production process for stages and check reliability of each stage based on demand, inventory level, and customer service. They use inventory buffer and restoration factor as a performance indicators.

Table 1. Summary of the presented literature overview

Reliability criteria	Curtin (1959)	Hosford (1960)	Mayne (1960)	Lefkowitz (1977)	Meyer et al. (1979)	Blumenthal et al. (1984)	Filus (1986)	Buzacott, Yao (1986)	de Maré, Rosander (1988)	Chakraborty, Ankiah (1989)	Davy et al. (1992)	Chen, Yao (1992)	Berg et al. (1994)	Denardo, Lee (1996)	Moinzadeh, Klastorin (1995)	Moinzadeh, Aggarwal (1997)	Denardo, Tang (1997)	Iravani, Duenyas, Olsen (2000)	Tsou, Chen (2005)	Graves et al. (2010)	Pan, So (2010)	Louit et al. (2011)	Lon and Chang (2013, 2012)	Kao (2012)	Lodding et al. (2014)	Dai et al. (2015)
Aging						+																				
Breakdown of machines		+		+	+		+			+			+			+		+				+				
Cost of lose/ penalty															+			+								
Costs															+	+			+		+					
Critical parts																						+				
Customer service																	+									
Demand					+								+				+				+		+			
Efficiency of process																								+		
Inventory level					+				+		+	+	+	+		+	+	+			+	+				
Lead time																					+					
Maintenance								+										+				+				
Manpower										+	+															
Operational Effectiveness	+																									
Process failure						+		+																		
Production Delays			+																						+	
Quality			+	+						+	+			+	+											+
Repair time		+			+		+		+	+			+													
Reworks			+	+										+	+											
Spare parts							+			+												+				
System load							+																			
Total costs of production				+																						
Waste reduction											+															
MODEL / METHOD	Monte Carlo approach	Interval model of production	Reliability models of good and bad periods of production	Hierarchical control approach	Markov model of production-storage system	Reliability test on serial production	Model of dependence between a failure and a system load	Control of flow in production process	Case of parallel, sequentially and simultaneously production	Monte Carlo simulation	Draft of JIT model	Model of continous production with fluid flow	Model of production including capacity, demand, machines	Model of linear quality of production stages with rework	Quality model with non-defective items	Bottleneck production – model of breakdowns	Model of production recovery with production stages	Markov decision process	Poka-Yoke model	Production models by Bayesian and Markov methods	Model of deterministic and stochastic demand	Risk models for spare parts	Stochastic flow network model, decomposition method	Input and output oriented models	Backlog and sequence deviation	Knowledge network with ANP

Iravani, Duenyas, Olsen (2000) analyse production and inventory system in terms of failure of a system, maintenance, costs of potential lose, and penalties for delays. They check time dependence of breakdowns between inspections and limited availability of repair crew. Later, Tsou and Chen (2005) use Poka-Yoke to increase reliability of production and decrease production defects. Their main indicators are production costs and quality costs. Pan and So (2010) connect efficiency and reliability of supply and production processes with inventory, costs, lead time, and demand. Graves, Anderson-Cook and Hamada (2010) describe a few reliability models for production systems. They use Bayesian method and Markov methods. Louit, Pascual, Banjevic and Jardine (2011) present reliability approach to maintenance. They focus only on critical parts and their cost and availability, as well as their breakdowns and downtime periods. In 2012, Lin and Chang consider a manufacturing network performance by measuring its capability as a probability of demand satisfaction. They use decomposition method and provide two models: a stochastic-flow network model with reworking action and the same failure rate for all the machines, and the second model, where the failure rates are different. This problem is later continued in work (Lin and Chang, 2013). Kao (2012) decomposes parallel production system and shows its strong and week areas. He focuses on a total effectiveness of a system and demonstrates input and output oriented models. The review of RAMs analysis in food production lines is given in (Tsarouhas, 2012). The problem of lateness modelling with the use of control variables and sequence deviations is analysed in (Lodding et al., 2014). Authors in their work focus on the possibilities of schedule reliability improvement. More recently, Dai et al. (2015) introduce a knowledge network of process scenarios based on the analytic network process (ANP) implementation.

Table 1 summarizes the presented literature review providing a comprehensive comparison of the investigated models taking into account the implemented method or modelling solution and reliability criteria.

4. MULTIDIMENSIONAL APPROACH TO PRODUCTION PROCESS RELIABILITY DEFINITION

Based on the approaches presented in the Sections 2 and 3, to finally propose a production process reliability definition one can focus on its model (Fig. 3).

In the area of production systems performance, the primary aim of the production process is the implementation of all activities related to the manufacturing of the finished product from raw material to a product. It always refers to an explicit product and it is associated with a specific, assigned to it, workstation (Hamrol, 2015). This allows defining the basic elements and participants of the production process given in the Fig. 3. As a result, the production process reliability may be defined as an ability of a production system to completely fulfil the production plan of fully valuable final products in a specified period of time under stated conditions. The given process conditions regard to the five main areas:

- machines and equipment performance and their failures occurrence possibility (connected with a number of uncertain factors, such as e.g. an uncertain degree of machine deterioration, inherent uncertainty in material and equipment quality, unavailability of operators, inadequate equipment usage) – that includes e.g. failure intensity calculations, maintenance tasks optimization,
- maintenance and logistic support infrastructure performance and their failures occurrence possibility – that takes into account e.g. the reliability of suppliers/retailers or logistic processes reliability,
- information flows and information reliability,
- possibility of the occurrence of unwanted random hazards/threats (internal and external type),
- processes of decisions making by policy makers and human factor reliability.

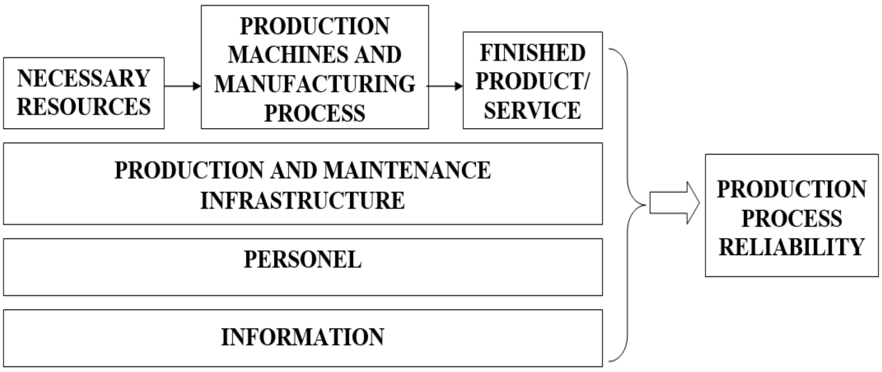

Fig. 3. Model of production process

The complex reliability analysis should cover the investigation all of the mentioned areas providing a valuable contribution to processes performance improvement. However, today's manufacturing companies usually are focused on the implementation of quality engineering approach (Elsayed, 2000) or a mixed approach – quality engineering with reliability considerations (Savage & Carr, 2001) in order to improve their efficiency or productivity. The benefits from more comprehensive approach are then ommited. Such a situation may be connected with e.g.:

- a lack of awareness of management board of the advantages of complex reliability approach implementation,
- a lack of data necessary to implement such a multidimensional assessment approach,
- a lack of guidelines of reliability accurately assessment for the system under different operating conditions.

The short example of performed reliability analysis of the chosen production process, that is presented below, provides reader with the most commonly used methods and tools in this area. It serves to illustrate what is the scope of the presently conducted analyses in this area.

The production process performance analysis is developed for the manufacturing company from the welding industry being focused on the production for the automotive industry. The main areas of investigated company's production are different types of welded structures and frame structures. There are also produced heavier structures such as frames, lifting frameworks or buckets for construction equipment. Everything is manufactured according to the individual customer projects.

The company has invested in modern production machines, like e.g. numerically controlled welding robots, or CNC machining centres. In the company, there are separated production and non-production areas that are also divided into workstations. Currently, there are almost 100 workstations at the production hall. The performed reliability analysis is carried out for one of the production area – paint shop area that covers the workstations for wet painting, powder painting, completion process, and assembly of products. The chosen painting process had the highest number of customer complaints, this is why the analysis is mostly focused on its performance.

In the analyzed company, the production process reliability is defined by the reliability index that corresponds to the number of reported complaints of external type (products rejected by company's customers). This means that the process reliability is related to the quality of the final product. At the same time, the range of covered analyzes is fully consistent with quality engineering approach.

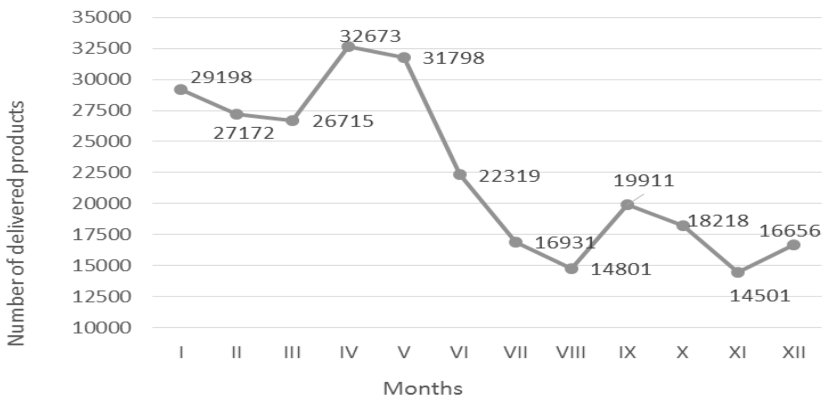

Fig. 4. Number of delivered products to company's final customers (in 2014)

The company's database includes information about all complaints (both, the internal and the external type), definition who detected the occurred error/problem, as well as place and date of the identified defect/problem. This gives the possibility to carry out additional analyses to define the problems' causes and the possible ways of their elimination. Other registry applies corrective and preventive actions. Below, there is presented chosen results of performed reliability analysis for the data from 2014.

In the 2014, company delivered to their customers about 270 900 products that fulfill their requirements (Fig. 4).

At the same time, there were 65 customers' complaints that regard to the problems occurred during the analysed production processes performance. There were identified 226 products that did not satisfy the customers requirements. Based on this, in the Fig. 5, there is presented the reliability index for the analysed production process.

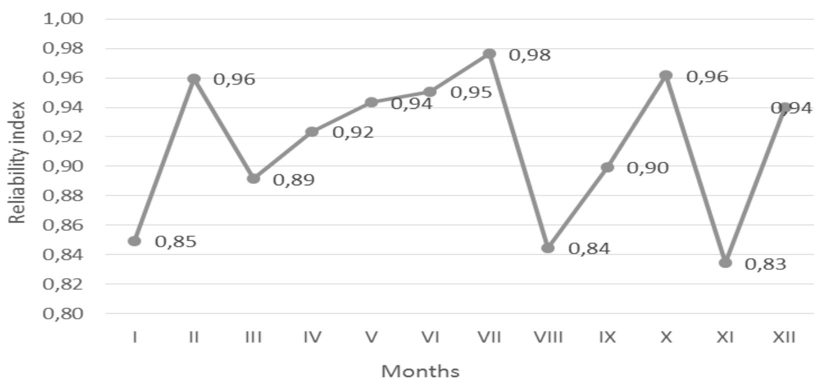

Fig. 5. Reliability index for analysed production process in 2014 (for external complaints)

The average reliability index for this production process is high and equal to 0.91. However, the obtained results were strictly connected with high level of internal complaints – high number of products with identified defects by production employees (Fig. 6). Internal detection of performed production process faults ranged from 0% in December, to 500% in June (in the relation to the number of customer complaints).

In the next step of reliability analysis performed by the given company, there are investigated the causes of occurred customers' complaints. There are used simple quality tools as Pareto-Lorenz analysis, Ishikawa diagram and What if? method.

Following this simple example of production process reliability assessment, the definition of process reliability is strictly equated to final product's quality. Other criteria like non-delayed production performance, proper performance of supporting infrastructure or information reliability are ommited. The reliability conditions identified in this Section (e.g. machines performance, human factor) are analysed indirectly with the use e.g. Ishikawa diagram or What if? method.

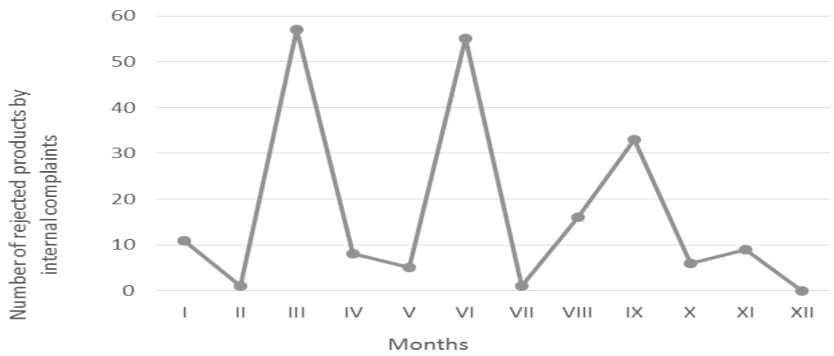

Fig. 6. Number of rejected products by production employees before delivering them to the customers (internal complaints) in 2014

On the example presented above, there are briefly indicated these performance areas that usually are analysed (e.g. product quality, machines and equipment performance) and those which are not tested due to e.g. the lack of data (human errors, information flow unreliability). Following this, the performed reliability analyses are not standarized and do not adhere to the continuous improvement concept. However, analysis of existing procedures for the assessment process is the first step to propose a new method that allows for full reliability analysis implementation, which will be the subject of authors' further research.

5. CONCLUSIONS

The analysis shows possibilities of reliability assessment for real production systems performance. More detailed statistical analysis of the problem is very limited by the lack of certain information. Often, the data are regarded as private or secret and results of analysis are impossible to be published. On the other hand, usually such information is not stored, so the analyses cannot be performed.

The presented article shows the first attempt for development and investigation of production process reliability assessment method that helps decision managers in their every-day work. Taking into account the subjectivity of expert opinions, lack of information, and the variety of approaches to reliability assessment problems, authors conclude that this research area still demands further investigation and development of new complex framework for production system reliability measurement.

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