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IMPROVEMENT OF PRODUCT RELIABILITY DURING THE PRODUCTION PROCESS IN THE AUTOMOTIVE INDUSTRY USING IMPROVED FMEA ANALYSIS

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Abstract: Product reliability plays the most important role during the car purchase by customers. In order to satisfy customers need it is necessary to product be reliable during the product life cycle. One of the important phases of the product life cycle is production process phase. In order to assure product reliability in automotive industry Failure Mode and Effect Analysis (FMEA) is used. FMEA for product reliability during the production process proposed by automotive industry standard (IATF 16949) is process FMEA (PFMEA). This analysis is in use in automotive industry for a few decades, but still contains certain number of shortcomings. Three groups of PFMEA shortcomings are identified: Shortcomings related to human factor, risk estimation and evaluation shortcomings and procedural (structural) shortcomings. In order to overcome procedural shortcomings, study of integration of lean approach into PFMEA is proposed. This research is supported by case study conducted in one company for producing electronics and cables for automotive industry. In order to improve risk estimation and evaluation process, integration of safety and financial risk into severity index is proposed. Solving of this problem is achieved by invention of new specialized tables for safety severity risk and cost severity risk. New involved risks (with existing) are weighted by application of fuzzy AHP methodology supported with Order Weighted Aggregation (OWA) method in order to achieve more precise results much easier. Testifying of applied methodology is done by case study in automotive company for producing leather upholstery for automobiles. Proposed improvements improved significantly product reliability during the production process, as well as FMEA analysis itself. Problem is that these improvements increased complexity and time-consumingness of PFMEA. In order to overcome this new problem, comprehensive software solution which contains proposed improvements and comprehensive database, is proposed.

Keywords: Reliability, Failure Mode and Effect Analysis (FMEA), Process Failiure Mode and Effect Analysis (PFMEA), Automotive industry, Production process, Lean approach, Fuzzy AHP, Database, Software solution.

Unaprjeđenje pouzdanosti proizvoda u fazi procesa proizvodnje u automobilskoj industriji primjenom poboljšane FMEA analize

Sažetak: Pouzdanost proizvoda igra najvažniju ulogu kod kupaca prilikom odabira automobila za kupnju. Da bi se ostvarila ova potreba kupaca, potrebno je da proizvod bude pouzdan tijekom svog životnog ciklusa. Jedna bitna faza u kojoj proizvod treba zadovoljiti kriterij pouzdanosti je faza procesa proizvodnje. Za potrebe osiguravanja pouzdanosti u automobilskoj industriji koristi se analiza grešaka i otkaza poznatija kao (FMEA). FMEA analiza za osiguravanje pouzdanosti proizvoda u fazi procesa proizvodnje, a koja je propisana standardom za automobilsku industiju (IATF 169491) je procesna FMEA ili PFMEA analiza. Ova analiza je u upotrebi u automobilskoj industriji već nekoliko desetljeća, a još uvijek sadrži određeni broj nedostataka. Identificirane su tri grupe nedostataka PFMEA: nedostaci nastali uslijed utjecaja ljudskog faktora, nedostaci procjene i vrednovanja rizika i proceduralni (strukturalni) nedostaci. U cilju otklanjanja proceduralnih nedostataka predložena je i provedena studija integracija vitkog (*lean*) pristupa podržana studijom slučaja provedenoj u tvrtki za proizvodnju elektronike i kabela za potrebe automobilske industrije. Za potrebe unapređenja procjene i vrednovanja rizika predloženo je integriranje sigurnosnog i financijskog rizika unutar procjene ozbiljnosti rizika (*severity*). Rješavanje ovog problema je postignuto uvođenjem novih tablica za ozbiljnost sigurnosnog rizika i ozbiljnost financijskog rizika. Novi uvedeni rizici su ponderirani primjenom Fuzzy AHP metode podržanom Order Weighted Aggregation (OWA) metodom radi lakšeg dobivanja rezultata. Testiranje primjenjene metodologije je testirano studijom slučaja u jednoj automobilskoj tvrtki koja se bavi kožnim tepisiranjem. Predložena unaprjeđenja su omogućila znatno poboljšanje pouzdanosti proizvoda u tijeku procesa proizvodnje i same PFMEA analize, ali su dodatno povećala kompleksnost i dugotrajnost analize. U cilju otklanjanja ovog problema predloženo je rješenje u vidu sveobuhvatnog softvera koji sadrži predložena rješenja i centraliziranu bazu podataka.

Ključne riječi: Pouzdanost, Analiza otkaza i posljedica (FMEA), Procesna FMEA (PFMEA), Automobilska industrija, Proces proizvodnje, vitki (lean) pristup, Fuzzy AHP, Baza podataka, Softversko rješenje.

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This dissertation comes as a result of a blend of people, events, situations, as well as my multi-year, spiritual, mental and physical work. It can also be said it is the result of the desire to solve the real problems encountered in the industry by using a scientific approach. Therefore, it represents a blend of knowledge gained in the academic sphere and experience gained in practice, commonly applied to solving a real problem in industry.

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List of Abbreviations

Abbreviation	***Description***
AIAG	Automotive Industry Action Group
AGREE	Advisory Group on Reliability Electronic Equipment
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
APQP	Advanced product quality planning
ART	Adaptive Resonance Theory
BRIC	Brazil, Russia, India, China
BRM	Boolean representation method
COPRAS-G	Grey-complex proportional assessment
DEA	Data Envelopment Analysis
DEMATEL	Decision Making Trial and Evaluation Laboratory
DFMEA	Design Failure Mode and Effect Analysis
ELECTRE	Elimination and Choice Expressing Reality
EPDS-1	Shortage for software prototype related to FMEA
ER	Entity Relationship
ERP	Enterprise Resource planning
FER	Fuzzy Evidential Reasoning
FFIP	Functional-Failure Identification and Propagation
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode and Effect Criticality Analysis
FTA	Failure Tree Analysis
GRA	Grey Relation Analysis
JIT	Just in Time
IATF	International Automotive Task Force
ICBM	Intercontinental Ballistic Missile
IFS	Intuitionistic Fuzzy Set
ISM	Interpretive Structural Modelling
ISO	International Standardization Organization
IT	Information Technology
MCMD	Multi-Criteria Decision Making

MCS	Minimum cut sets theory
ME-MCDM	Multi-Expert Multi-Criteria Decision Making
MFP	Module-based Failure Propagation
MTBR	Mean Time Between Repair
MTTR	Mean Time To Repair
MULTIMORA	Multi-Objective Optimization by ratio Analysis
NASA	National Aeronautics and Space Administration
OWA	The Order Weighted Aggregation
OWGA	The Order Weighted Geometric Aggregation
PDCA	Plan, Do, Check, Act
PFMEA	Process Failure Mode and Effect Analysis
PPAP	Production Part Approval Process
PROMETHEE	Preference Ranking Optimization Method for Enrichment Evaluations
QFD	Quality Functional Deployment
QUALIFLEX	One of MCDM methods
SMED	Single Minute Exchange of Die
TFN	Triangular Fuzzy Numbers
TOPSIS	The Technique for Order of Preference by Similarity to Ideal Solution
TPM	Total Productive Maintenance
TPS	Toyota Production System
UPN	Utility Priority Number
USA	United States of America
VIKOR	One of MCDM
WIFA	Project related to improvement of knowledge-based system
WLSM-MOI	Partial ranging method

List of Indices

Index	***Unit***	***Description***
S		Severity
O		Occurrence
D		Detection
RPN		Risk Priority Number
S_S		Safety severity index
S_Q		Quality severity index
S_C		Cost severity index
EC_F	€	Expected cost of failure
C_F	€	Cost of failure
p_F		Probability that failure will occur
C_{FI}	€	Internal cost of failure
C_{FE}	€	External cost of failure
P_S	€	Profitability of implemented solution
C_{IS}	€	Cost of implemented solution
p_D		Probability that failure will be detected
I_A	€	Solution implementation availability
B	€	Available budget
A_F		Amount of failures occurred during the production process
C.I.		Consistency coefficient
I		Total number of identified failures
i		Failure
J_i		Total number of identified failure effects
j		Effect
k		Mathematical description for severity index (lowest)
k'		Mathematical description for severity index (highest)
$W_{kk'}$		Matrix for severity definition
$l_{kk'}$		Lower bound of matrix for severity definition
$u_{kk'}$		Upper bound of matrix for severity definition
$m_{kk'}$		Model value of matrix for severity definition
w_k		Weight vector

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1. INTRODUCTION

1.1 Motivation

The automotive industry represents one of the most important economic sectors in the world in terms of revenue. Boston consulting group department from Detroit forecasted that in 2014. car sales will increase in BRIC[1] countries as well as in the third world countries[2], while in the developed countries will decrease [2]. Reason for this might be that increasing number of young people is deciding to use alternative ways of transport, rather than buying a car. This idea is coming from research study conducted in 2014. on the car consumer population from all over the world [3]. However, the statistics have shown different results. Last 10 years, from 2007. until 2017., trend of automobiles production is in increase (see Figure 1.1) [4].

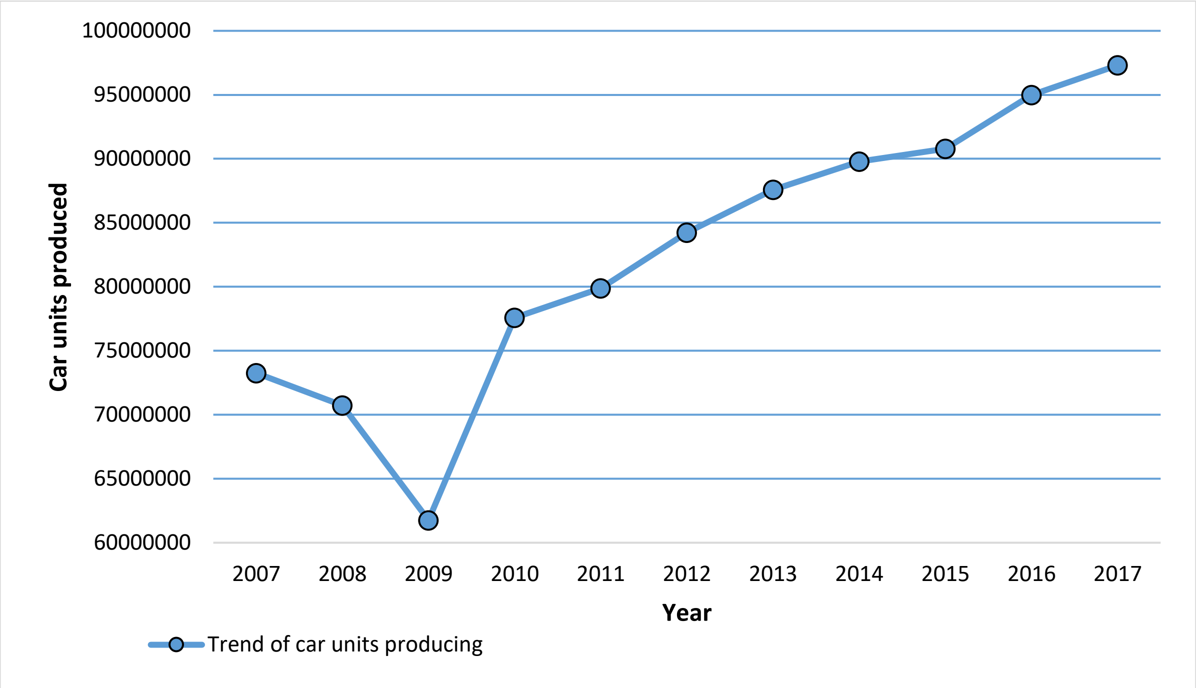

Figure 1.1. Trend of car production for last 10 years [4].

Based on the before mentioned statistical research and the fact that new model of cars are developed all over the world, which are supported by alternative energy sources (Hydrogen, electricity, etc.), which will replace oil and gas cars in the future, conclusion is that the automotive industry will keep growing on the global market in the future.

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[1] *BRIC* is an acronym for the economies of Brazil, Russia, India, and China combined. These are fastest growing economies on the world in nowadays [1].

[2] *Third world countries* – This term is often used to describe developing countries of Africa, Asia, Latin America and Oceania.

According to the study of relevance during the car selection by customers, reliability plays the most important role [5]. Product reliability is a characteristic which should satisfy whole product life cycle, through all of the phases. One of the important stages in which product reliability have to be assured is production process. In the automotive industry, many companies are using whole programs for reliability and quality management like Lean or Six Sigma concepts. Nowadays, product reliability during the production process in automotive industry is very important from many reasons, but especially because of the customers. Customer wants product delivered just in time, with right quality and acceptable price. Reliability in this case means that predefined conditions will be satisfied. To achieve this goal, product has to be failure[3] free during the whole production process. Recommendation of author Stamatis [6] is that these types of failures which can reduce product reliability should be controlled with source quality system, rather with prevention than detection. In automotive industry, Failure Mode and Effect Analysis also known as FMEA, is used for this type of failures. Type of FMEA related to production process is Process Failure Mode and Effect Analysis (PFMEA).

FMEA analysis in general, was first stipulated by QS 9000 for automobile industry in 1994., which is replaced by ISO/TS 16949 in 2006. ISO/TS 16949 was active until recently, and PFMEA was mentioned in six clauses of this standard. Relatively recently, in 2016. ISO/TS 16949 was replaced by IATF 16949 (Quality management system for organizations in the automotive industry) the new standard for automotive industry. In this new standard PFMEA was mentioned even 18 times, which is much more compared with previous standard. According to this, it can be concluded that relevance of PFMEA in automotive industry is in increase. From 1994. until today, three standards for automotive industry have changed and PFMEA stayed the same in its traditional form proposed by Automotive Industry Action Group (AIAG)[4] in their manual “Potential Failure Mode and Effect Analysis”. The first version of this manual was published in 1993., second in 1998., third in 2002 and forth and active one in 2008.

Besides these mentioned trends, additional motivation for this dissertation was obtained during the first year of doctoral studies and during the time of employment in one automotive

[3] *Failure* in this case presents state which deviating from the preferred state in which product should be. Under failures are considered: defects, deviations, shortages, malfunction, etc.

[4] *AIAG* – Automotive Industry Agency Group is agency for the automotive industry founded by big three American corporations: Ford Motors, Chrysler and General Motors.

company which is producing electronic components and cables for automobiles. At the position of project leader one of the main tasks was conduction and revision of PFMEA for new and existing products, as well as the product reliability improvement during the production process. In this environment, many problem occurred during the conduction of PFMEAs. Some of these problems were:

- Team was not motivated enough to participate in PFMEA realization. Therefore, PFMEA leaders had to conduct PFMEA by themselves. This is very subjective and its up from rules proposed for automotive industry in course of PFMEA. Therefore, this classed PFMEA as an additional formality and its main purpose was neglected.
- Maintenance of PFMEA is time-consuming and complicated, especially in term of failure occurrence (O) index which was not fit with O index measured during the time.
- Fixing of a PFMEA results to satisfy external auditors. This problem is a direct result of lack of understanding for necessary implementation of solutions from the top management. In this situation, PFMEA leader is in delicate situation between external pressure by auditors and internal constraints by top management of a company.

Similar problems were identified in literature, as well as another problems related to PFMEA structure and way of risk calculation, but also in PFMEA procedure. In summary, PFMEA analysis is widely applied in the automotive industry and its use is in increase for last years. Besides that, PFMEA still has many constraints and there is space for lot of improvements, also.

1.2 Short review of the current state

After confronting with mentioned problems in previous sub-chapter, help was searched in the various literature related to FMEA generally and PFMEA. Johnson and Khan [7] conducted research in 2003. in which similar problems were identified. Research was conducted with 200 companies from automotive industry located in The United Kingdom and The Central Europe. Besides already existing problems, a set of new problems was put on the list, which appears during the PFMEA realization. On many of the problems related to FMEA various solutions were proposed from different authors. All these solutions are applicable on the PFMEA as well. That is confirmed by Liu et al. [8] review study on FMEA from 2012. He predicted that trend of writing of scientific papers related to FMEA will be in increase during the next period of time, which is approved with many other papers related to FMEA published after 2012 until nowadays by various authors. Some of mentioned methodologies for resolving of FMEA disadvantages are: artificial intelligence, multi-criteria decision making (MCDM), integrated approaches, mathematical programming and other approaches. Lot of these approaches considerably improve FMEA, but make it more complicated at the same time.

These solutions make FMEA realization and management much easier. All these solutions are applicable on the PFMEA as well. The problem with many of solutions is in the breaking of the traditional PFMEA framework for automotive industry[5] as well as in increase of time-consumingness and complexity of conduction. In order to achieve better product reliability during the production process, automotive industry needs modified PFMEA approach which will cover constraints of the traditional PFMEA, nevertheless this modified approach has to be transformed back to traditional PFMEA framework for automotive industry as it is presented on Figure 1.2. One of the main reasons for this is in external auditors. They are only qualified to review traditional PFMEA, while modification can confuse them.

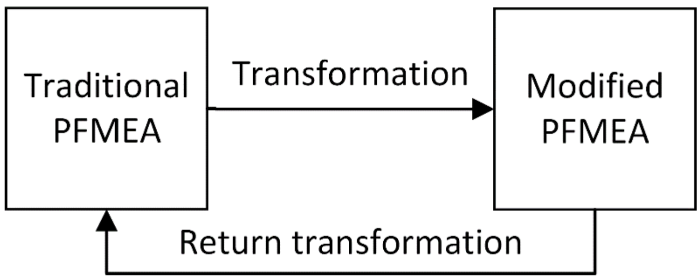

Figure 1.2. Transformation of PFMEA for automotive industry.

Besides this problem related to traditional PFMEA framework, there are three more classified group of problems identified during the wider literature review (this will be more detail presented in the sub-chapter 3.2). These groups of problems are: procedural problems, risk estimation and evaluation problems, and problems related to human factor.

1.3 Hypothesis

According to before mentioned motivation and current state, two hypothesis arise:

Hypothesis 1: With integrating lean approach methodology into procedure for PFMEA realization for the needs of the automotive industry, more reliable results can be achieved.

Hypothesis 2: With integrating cost and safety factors into severity (S) index of PFMEA for automotive industry, better risk estimation can be achieved as well as increment of reliability

[5] *Traditional PFMEA framework for automotive industry* is proposed by AIAG in their manual "Potential Failure Mode and Effect Analysis" (active version is 4th from 2008.).

estimation for severity of the failure effect caused by failure mode which appears in the production process.

Both of hypotheses are related to product reliability increment during the production process.

1.4 Description of research methodology

For confirmation of before mentioned hypothesis, an extended research should be taken, which includes two phases.

In the first phase of the research lean approach and it's applicability to be integrated into PFMEA procedure has to be checked. Lean tools, methods and techniques which can be integrated into PFMEA procedure have to be checked as well. After the integration of lean approach into PFMEA, case study should be conducted to check consistency of the integration. This will be done by comparison of current state of one already realized PFMEA in a company from automotive industry, with another state after application of lean integrated approach. Finally, results should be compared and presented.

The second phase of the research is related to improvement of PFMEA structure by improvement of traditional risk priority number (RPN) and involvement of hidden risk factors that influence on S index. Basic idea is to split S index on three new indices related to safety, quality and costs. New tables should be invented for all of the three indices. Table should be scaled (1-10) values for different risk severities. After definition of new severity indices, all of the three new indices have to be weighted. After weighting S index should be reduced to the scale from (1-10) again, in order to keep traditional PFMEA framework for automotive industry. Three basic indices for definition of RPN (S, O and D) should be weighted additionally. At last, case study should be conducted in order to test new approach. Comparison of the traditional approach for PFMEA conduction in automotive industry and new approach with improved S index, should be done last.

During the application of these proposed methodologies and conduction of the researches, traditional PFMEA framework for automotive industry should be kept. One additional problem which may appear is that these improvements can make PFMEA more complicated and time-consuming for conduction. This can lead to decrease of product reliability. To avoid this additional complication software decision making system with comprehensive database, should be developed.

1.5 Expected scientific contribution

Expected scientific contribution that as a result of this dissertation is presented as follows:

- Hybrid approach of integrating Lean approach into PFMEA procedure (the reverse approach was used until now) will be used for the first time. Therefore, decrease of deficiencies of PFMEA is expected. With improvement of PFMEA procedure, reliability of the product will be improved.
- Reliability of failure assessment will increase by integrating of cost and safety aspect into traditional S index. Therefore, traditional PFMEA framework for the automotive industry will be kept.
- More realistic state of RPN will be achieved by integration of new S indices into traditional S index. This improvement will lead to the increase of the product reliability as well because of better prioritization.
- New tables for definition of new S indices will be founded.

2. RELIABILITY: REVIEW ON PRODUCT RELIABILITY DURING THE PRODUCTION PROCESS IN AUTOMOTIVE INDUSTRY

In wider sense, reliability is a feature of some object to stay in the predefined state during the time. Reliability plays very important role in automotive industry. This claim is approved by Bertsche [5] in the study of criteria of relevance during the car purchase (See Figure 2.1). In this study, 11 criteria were observed: reliability, fuel consumption, price, design, standard equipment, maintenance cost, resale value, service network, delivery time, prestige, and good price by trade-in. Criteria were evaluated with a scale from 1 (very important) do 4 (unimportant). Reliability is at the first place with value (1.3), according to surveyed and interviewed customers. Only costs are considered to play more important role than reliability in some cases.

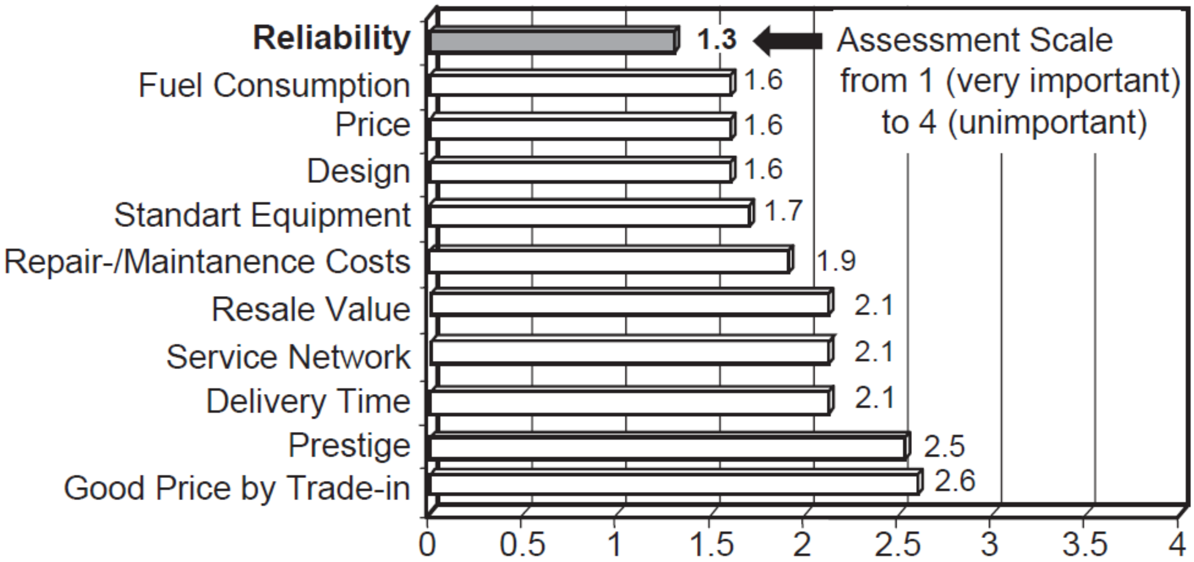

Figure 2.1. Car purchase criteria [5].

According to the before mentioned study it is obvious that customer wants reliable product. In order to achieve this, product should be reliable during the whole product life cycle. Topic of this thesis is related to product reliability during the production process phase. This implies that production process has to be reliable. Production process reliability some authors define as a operational reliability [9, 10]. Term operational reliability, was used for the first time by Duran in 2000. According to his definition, operational reliability is flexible optimization process of human factor, process and technology in order to achieve availability[6]

[6] *Availability* is probability that the item is in a state to perform as required at a given instant [11].

and additional value of production goods. Operational reliability consists of four key elements (as it is presented on Figure 2.2): Human reliability, equipment maintainability, equipment reliability and process reliability.

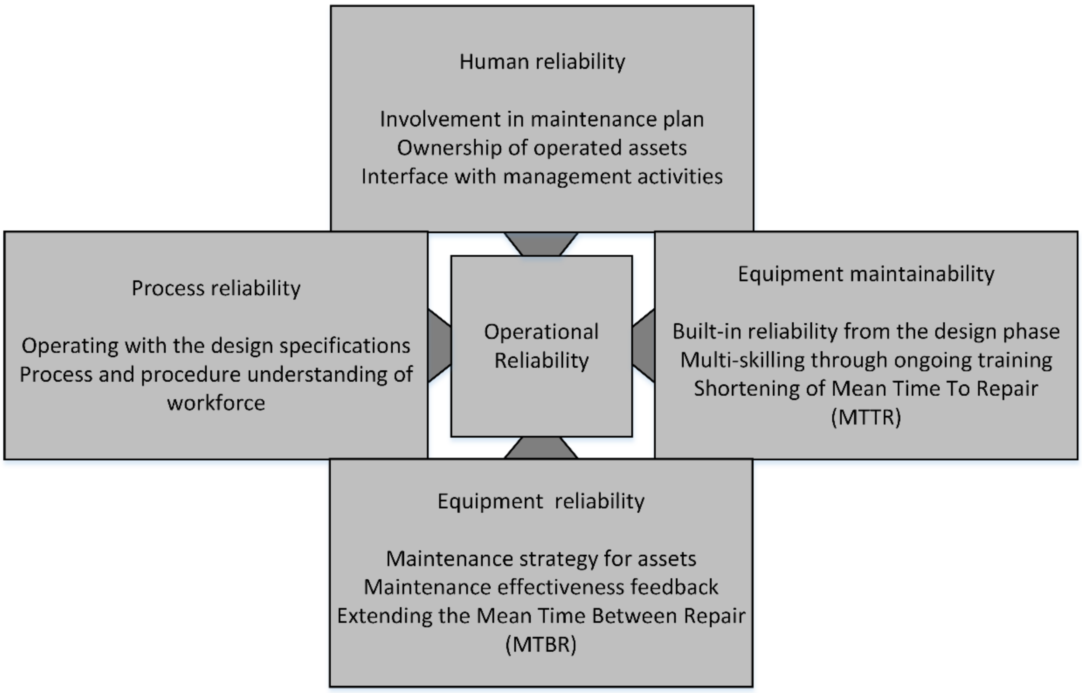

Figure 2.2 Operational reliability according to Duran (2000) [9, 10].

Unreliable product during the production process can lead to additional costs and wastes, especially if defected product comes to the customer/consumer before failure is detected. Therefore, both qualitative and quantitative methods should be used to avoid these situations. Quantitative methods usually used for estimation and improvement of product reliability in the production process in automotive industry are statistics and probability theories. On the other hand, the most used qualitative method for providing product reliability during the production process in automotive industry is PFMEA.

According to Birolini [11] there are ten basic activities to conduct in order to ensure product reliability during the production process:

1. Product configuration management. Documentation, control and accounting introduction and review, after already introduced changes and modifications.
2. Selection and qualification of production facilities and processes.
3. Monitoring and control of the production procedures.
4. Protection from damage during the production process.

5. Systematic gathering, analysis and control of the failures which appear during the production process.
6. Quality and reliability ensuring during the procurement (documentation review, input control, supplier audit, etc.).
7. Calibration of measuring and testing equipment.
8. Performances inside process and final testing.
9. Representation of critical components and circuits.
10. Cost optimization and time scheduling for testing and displaying.

According to the mentioned activities, the conclusion is that one of preconditions for reliable product is reliable production process. Therefore, focus will be on the qualitative and quantitative methods which can be used to improve product reliability during the production process in automotive industry by improving production process reliability.

Historical development of production process reliability in automotive industry may be divided on two periods of time. The first period is related to mass production and the need for reliability engineering during the production process to improve mass production. It was first introduced in Ford Motors Corporation during the 20th century. This company was mainly focused on product development rather than production process development. This was the reason why reliability concept was not taken into account more seriously. The second period considered breakthrough of Japanese car manufacturers (especially Toyota) on American market with products of right quality and acceptable price. This was enabled by improved and reliable production process. Instead of mass production and unnecessary stocks, Japanese car manufacturers produced only by the customer order. During the time, this way of business and production has bought Japanese companies on the top of the world car manufacturers list. Nowadays, popular Japanese production process reliability concept is known under the name Lean. Therefore, it could be said that serious need for production process reliability appeared during the 1980s.

2.1 The reliability engineering

In general, reliability can be defined as ability of an organization[7] to fulfill previously defined terms and requirements with customer during the certain period of time. Usually, reliability can be observed by two sides: side of the customer/consumer and side of the producer. By

[7] *Organization* in this context represents wider term to describe enterprises, companies, corporations, etc.

the customer/consumer side, the most important is that all predefined terms and characteristics related to product/service are fulfilled. By the producer side, according to Birolini [11] reliability means that product will be produced according to the predefined customer demands. Usually, main demands from a customer are: right quality, acceptable price and product delivered on time.

According to literature, reliability is usually defined as a probability that object[8] will satisfy required function/s without failure mode during the certain period of time, under certain conditions [12]. Basic skills required for efficient reliability engineering management are: engineering knowledge and experience applied during the development or production process. According to that, in dependence of stage where product is currently located, reliability engineering may be qualified or quantified with different tools, methods and techniques.

O'Connor [12] identified four basic reliability engineering goals listed according to the priority:

1. Application of professional and scientific engineering techniques in order to prevent or reduce failures.
2. Identification and removal of failure cause.
3. Finding a way to confront failures, even if their causes are not identified.
4. Application of methods for reliability estimation of the new state, but for analysis of data about reliability as well.

In the next subchapter, a historical review on development and use of term reliability engineering and reliability in general will be made. Additional review on appearance and definition of standards related to reliability in industry will be made as well.

2.1.1 Historical review on the development of reliability engineering

Many authors agree with a fact that reliability engineering could not be even imagined without statistics and probability theories. Probability was used for the first time on games and gambling in 17th century. It could be said that, it was the period when first conditions for reliability engineering estimation were obtained. A theory, first set by scientist Pascal, was upgraded by another scientist Laplas in 1812. Laplas provided a set of new techniques, but he

[8] *Object* in this context considering observed object for which reliability is estimated. Therefore, in dependence of observed aspect it could be: product, system, process, equipment, worker, etc.

also extended the application of probability theory for solving practical problems like: demographic, population estimation, life assurance, etc. [13].

The first serious need for reliability engineering occurred in the middle of 19^{th} and at the start of 20^{th} century. The cause was the appearance of mass production of standardized products in the big amounts. Companies which first implemented that way of production were Springfield's armory in 1863. and automotive corporation Ford Motors in 1913. [13]. During that time, quality was not at the primary place for these companies. Market was oriented on producing big amounts of products. According to that, degree of product unreliability was much higher than in nowadays.

In general, it could be said that statistics and mass production were key drivers for reliability engineering appearance. It was just a matter of time, when the need for reliability management will increase. The event which accelerated reliability engineering appearance was World War II. Increased need for vacuum tubes (invented in 1906. by Lee de Forest) motivated engineers to pay more attention on them. These tubes were highly unreliable in that time, but in the same time very important.

Reliability engineering originated as a discipline in the middle of 1950s in The United States of America (USA) [12]. Rapid development of electronic industry led to the need for evolution of development and production of electronic components. This event increased unreliability and complexity of production. Therefore, department for defense and electronic industry of USA established together an *Advisory Group on Reliability of Electronic Equipment* (AGREE) group in 1952. Mission of AGREE was to [14]:

1. Recommend measures for equipment reliability increment.
2. Help during the implementation of reliability program in government and civil agencies.
3. Propagate about reliability.

AGREE immediately started with complex researches on electronic equipment. Therefore, their way of examination becomes a standard way very soon, because it was the most effective in that time. The first officially reliability engineering appearance as a discipline obtained in AGREE report from 1957. Immediately after this, department for defense from USA published AGREEs report for testing again, but this time under the name "Reliability Qualification and Production Approval Tests", as a military standard – MIL-STD-781 [12].

Saleh and Marais [13] have identified two ways of reliability engineering progress in 1960s:

1. Increased specialization inside reliability engineering as a discipline. This way was divided on three subways:
   - Enlarged application of statistical techniques like: redundancy modelling, Bayesian statistics, Markov analysis, etc.
   - Physics of failures on components (from where reliability physics were founded).
   - Structural reliability related to integrity of buildings, bridges and other civil and construction objects.
2. Reliability movement from componential level to level of activities inside a system (system reliability, process reliability, efficiency, availability, etc.). This way ensured rapid development of complex engineering systems for military and aerospace program needs, like: *ICBM*, *F-111*, *Mercury*, *Gemini*, *Apollo*, etc.

In 1970s, reliability played a key role in development of new technologies, system safety and software [13]. According to Knight [15] main changes in electronic technologies were inducted by large scale devices. This increased the need for increment of reliability. Three fields of possible improvements were proposed [13]:

1. Reliability on system and safety level (especially in gas and oil as well as in chemical industry).
2. Development of software reliability.
3. Warranty reliability (mainly oriented to Military industry).

In 1980s, Great Britain started with implementation of reliability standards. British standardization institution has developed a BSS 5760 standard under the name "*Guide on Reliability of Systems, Equipment and Components*" [13].

Only one decade later In 1990s, implementation of reliability standards became trend all over the Europe. Series of European Dependability[9] Standards developed during the 1990s, later on were integrated in International Standardization Organization (ISO). One example of these standards was ISO/IEC 60 300 standard which describes concepts and principles of the dependability management system [13]. Reliability from 1990s was also marked by rapid development of technology and availability of computers to wider community [16].

[9] *Dependability* is a reliability form, which besides reliability implies sustainability, availability and safety as well.

2.2 Production process

Production is one of the key segments of industrial activities with around 20-30% of total value of produced goods or provided service [6]. Rao [17] defined production as a use of mechanical, electrical and chemical processes with changes of geometry, characteristic and/or shape of a goods in order to achieve final product or semi-product. According to the need, production may be classified on production for producing for assembling of already produced parts (assembling - presented on Figure 2.3) and on production of certain parts (manufacturing – presented on Figure 2.4) [18]. Some of activities during the production process are: documentation management and product design, material selection, planning, manufacturing or assembling process, quality assurance, maintenance, etc.

Figure 2.3. Production process: assembling.

Assembling process represents one of the two mentioned types of production and its main activities are: handling, joining and control [19]. Another type is manufacturing process. This process has become very complex because of rapid development of technology, especially during the last years.

Figure 2.4. Production process: manufacturing.

Manufacturing process related to production of the final goods may be classified in five subcategories [17]:

1. Processes for changing of material shape. For this type of manufacturing process mechanical and heating forces are usually used in order to change geometry of material. Some of that processes are: casting, warm and cold deforming (like minting, extrusion, rolling, clamping, etc.), operations for sheet metal processing (like perforation, bending, cutting, etc.), plastic molding, etc.
2. Processes for processing of the parts with certain dimensions. These processes are: conventional machining (drilling, molding, grinding, reaming, milling, honing, polishing, turning, etc.) and nonconventional machining (like waterjet cutting, plasma cutting, etc.).
3. Processes for surface processing. These processes are: cleansing operations (like removing of a dirt, oil and similar substances from part surface), surface operations (like blasting, diffusion, Ionian transplantation, etc.), lubrication operations (like galvanization, anodizing, etc.) and thin layer deposition processes (like physical and chemical vapor deposition).
4. Processes used to join parts. These processes are: welding, soldering, sintering, pressuring, tempering, dowelling, etc.
5. Processes for material properties improvement. These processes are: annealing, normalization, etc.

2.3 Methods for production process reliability analysis and improvements

There are two types of methods for the product reliability estimation during the production process: quantitative and qualitative.

Quantitative methods are based on statistical methods and probability theories. Therefore, these methods are functioning only with already known data. Quantitative methods are based on reliability prediction, determination of the rate of the failures, reliability and probability analyzing, etc. Some of these methods are: Boolean analysis, Markov analysis, Failure Tree Analysis (FTA), etc.

On the other hand, qualitative methods are based on failure; failure effect and failure cause detection. The way of detection is usually defined by expert opinion. Some of the most frequently used methods are: FMEA, sequence analysis of the next event, lists, FTA (may be quantitative analysis as well), etc. FMEA is the most used qualitative method, especially in automotive industry.

After the implementation of some analytical methods, preventive and corrective actions, there is still possibility that system may deviate caused by different factors which influence on production (like human factor). It is very important to control these deviations by implementing the methods of continuous improvement. Implementation of these methods and techniques decreases the possibility for new failure occurrence, but in the same time increases product reliability and production productivity. Some of these methods are [12]:

- Simple graphs. Graphs are usually used to identify and solve deviations. Some representative examples of that graphs are Pareto graph (also known as a Principle 80/20) and graph of the cause and effects (also known as Ishikawa graph or fishbone).
- Control plan. Control plans are usually used after implementation of preventive and/or corrective actions during the production process, especially if there are some special characteristics (proposed by customer or defined by supplier/manufacturer/customer). Some of these characteristics are: temperature fluctuations, deviations inside a process before and after settings, change of the operators, material change, etc. It is very important to follow the time and date on the control plan in order to identify cause of these deviations.

- Multi-dependency graph. This graph is used for identification of the main deviations during the production process in case that production process is influenced by many different factors. It is usually used for process development and/or problem solving. It is very efficient for deviation amount decrease which should be included into statistical analysis.
- Statistical methods. These methods can be used for deviation amount decrease during the production process. Basically, they are used for production process improvement, but for initial process and/or production design as well.
- Zero failure. Nowadays, this method is more like conceptual or aspirational. This approach to quality control is developed in USA in 1960s. Some of the concepts related to these methods are Lean and Six Sigma.
- Quality circles. This methodology first appeared in Japan in 1950s. Nowadays, it is spread all over the world. This method is based on educating workers to follow quality features, but to analyze problems and suggest solutions to management as well. Workers are organized in small workgroups headed by group leader. These groups are restricted by authorization. Therefore, workers still may implement some of the solutions without authorization of management, but only in their domain. Solutions which are not in their domain have to be presented to management. Workgroups are learning seven quality tools[10] in order to solve problems easier. In order to make workgroups functional it is needed to get familiar with *Kaizen* (Japanese word for continuous improvement).

2.4 Reliability during the production process in automotive industry: current state

Nowadays, there are few popular concepts of production. Lean and Six Sigma are the most popular in automotive industry. Lean was founded as a need for radical changes of production process in automotive industry. Therefore, inside Toyota Company, different methods, techniques and tools were developed for failure detection and prevention during the production process. This led to the production process reliability increment. On the other hand, Six Sigma is a concept in which all quality methods, techniques and tools are gathered in order to achieve better reliability, efficiency, productivity, and business in general. The purpose of both concepts in streaming to achieve absolute reliability of the product or

[10] *Seven quality tools* are: 1. Brainstorming; 2. Data gathering; 3. Data analysis methods; 4. Pareto graph; 5. Histogram; 6. Ishikawa graph; 7. Graph of statistical process control.

annulment of the failures during the production process. Lean is based on the principle "zero failure", while Six Sigma concept has span from one to the 6^{th} Sigma where 6^{th} Sigma presents "zero failure".

Reliability in the automotive industry is formally defined by international ISO 9000 (Quality management systems – fundamentals and vocabulary) and IATF 16949 international standard for quality management related to automotive industry. In ISO 9000, reliability is defined in general by clause "3.5.3 dependability", as one of the terms used to describe quality characteristics [20]. In IATF 16949 production process reliability is mentioned in few clauses.

Quantitative methods for reliability analysis and estimation in the automotive industry are not defined by standards. Their use usually depends on level of development of a company. The most frequently used qualitative method for reliability analysis and risk[11] estimation during the production process in automotive industry is PFMEA. This analysis is proposed by automotive standard IATF 16949. The usage of PFMEA for automotive industry is specified by reference manual "Potential FMEA" founded by big three USA companies, Ford Motors, Chrysler and General Motors. More attention should be put on implementation and usage of PFMEA in the automotive industry, because there are lots of studies showing that PFMEA is not absolutely reliable analysis. This is contradictory, because primary function of this analysis is reliability and risk estimation. One of the biggest problems for this analysis lays in dependence on human factor. Besides this key problem, PFMEA contains more conceptual problems leading to the impracticability during the usage. These problems are converting PFMEA to just another administrative process. Recommendation by AIAG [21] is that PFMEA should be supplemented by new data during the time, especially after changes. Therefore, this triggers the need for PFMEA to be both qualitative and quantitative analysis. This is the reason why many companies use software and databases for PFMEA.

[11] *Risk* as a term is defined by many authors on different way. Some considering risk as a probability that damage will occur. Some as a probability that injury on the workplace and/or losses will occur. Anyway, the most number of risk definitions contains two basic elements: 1. Probability that risk will occur and 2. Consequences made by risk (costs, injuries, losses, etc.). It could be said that risk in this case presents probability that some failure will occur leading to the unwanted influence on the product, production process or environment (equipment, human factor, infrastructure, etc.)

2.5 Reliability during the production process in automotive industry: Future trends

According to the fact that technology is in increase nowadays more than ever before, production systems, but production processes as well, are going to be more complex. Increased complexity of the production process in general, leads to the product reliability deviations as well. Therefore, the need for more comprehensive solutions for production process reliability management will increase in the future. Zio [16] predicted the need for more practical and efficient application as well. According to the literature review, conclusion is that future trends in production process reliability in automotive industry will be:

- More detailed regulation frameworks in order to define the influence of reliability methods influence.
- Inclusion of the safety factor (more specifically) during the production process, but also definition of influence of the produced product on customer/consumer after the production process.
- Inclusion of the costs during the production process reliability analysis. Some costs like business costs and warranty costs, costs due to the scrap or rework, etc. are not included in reliability estimation.
- Inclusion of the time needed to realize production process reliability analysis. Sometimes is needed to include more employees in the reliability analysis, which is usually and extra activity for employees.
- Comprehensive database in order to collect and process all data needed to ensure reliable production process. This database may be of a big help for decision making, but for risk calculation and failure prediction as well. Database should be also used to centralize all product and failures together in order to improve failure prediction.
- Appropriate software to link all these before mentioned elements of reliability improvement together. Functionality of all these elements separately or partially may be very difficult and unreliable. Therefore, there is a need for comprehensive software solution which will make control and reliability estimation much easier, but it will decrease data processing as well.

3. FAILURE MODE AND EFFECT ANALYSIS (FMEA)

In order to understand role of the PFMEA for automotive industry and PFMEA in general it is necessary to understand FMEA first. Founding of the FMEA and historical review, fields of the application of the FMEA, FMEA types, etc. FMEA is in use for many years, applied in many different fields, but still contains many different shortcomings. In this chapter, whole and comprehensive review of all these shortcomings of the traditional FMEA will be made. Literature review will be done as well, in order to identify all used solutions for improvement of FMEA shortcomings. After introducing of FMEA in general, PFMEA for automotive industry will be explained more detailed, with regard to further research.

3.1 FMEA in general

FMEA (or sometimes referred in the literature as FMECA[12]) is analysis for the failures which occur in the different conditions, but also of failure effects caused by failure modes. FMEA is inductive method with bottom-up approach. The main objective of PFMEA is to identify potential failures, evaluate causes and effects of failure modes. At last, for all these potential failures, appropriate solutions should be proposed and implemented in order to decrease number of failures and to increase product reliability. Therefore, FMEA is not just an analysis, but improvement tool as well. Final goal is failure free product, increased reliability and safety of the product, and customer/consumer satisfaction. This analysis is a living document. This means that it should be constantly updated by new data, especially after some changes on product design or production process. It should be considered that FMEA may be used both preventively and correctively, but preventively is much more important.

The First version of FMEA analysis was provided in 1949 for the USA military needs under the name military procedure MIL-P-1629, and that was the first documentation of this analysis at the same time [22]. From mentioned military procedure later on (1974.), two more military standards were founded: MIL-STD-1629 and MIL-STD-1629A. This analysis during that time was used as a technique for failure mode definition in systems as well as for failure effects caused by failure modes. FMEA realization concept was different from nowadays FMEA realization concept. The first formal use of FMEA analysis known today was in 1965 for

[12] *FMECA* or Failure Mode, Effects and Criticality Analysis is form of the FMEA specialized for criticality risk solving. Sometimes are these two methods equated in the literature. This is very wrong, because this two analysis are principally very similar, but purpose of use is different.

aerospace industry needs. Concretely, NASA used it for "*Apollo*" space project [22]. Later, from 1965 this analysis was actively used for aero-space industry needs, but also for nuclear industry needs [7]. One decade later in early 1980s FMEA was applied for automotive industry need, first time by Ford Motors in 1973 informally. Formally, five years later in 1977. Ford Motors implemented this method as a preventive method for quality management in the both design and production process [23]. In 1984 USA automotive corporations Ford Motors, Chrysler and General Motors published manual "Potential Failure Mode and Effect Analysis handbook" for FMEA usage. This handbook was very complicated for usage, because of the divergence between two different regulations. Therefore, suppliers had many problems due to usage of FMEA. These problems trigger AIAG to link all regulations into one unique manual adjusted to all suppliers, which resulted with publishing of "Potential Failure Mode and Effect Analysis" in 1993. Second revision was published in February 1995, third in July 2001 and fourth and still active one in June, 2008. [21].

Nowadays, FMEA in widely used and it can be said that FMEA has become standard practice in many companies all over the world [22]. Onodera [24] identified over 100 different application of FMEA in Japan in 1997. Many other authors highlighted wider application of FMEA in various industries. Some of them are: among the most common are automotive and aerospace industry [6, 8, 22-36], military industry [6, 8, 22, 25, 26, 28, 36-38], electrical components production industry [8, 22, 27, 28, 33, 34], nuclear industry [6, 8, 26-28, 31, 32, 37], medicine and medical equipment production industry [6, 8, 28, 34, 36-39]. In addition to the before mentioned application, use of FMEA is also present in: retail, mechanical, construction, chemical and service industries, in companies for hardware and software development, information systems, food production companies, plastic injection companies, in power plants, civil engineering, telecommunications, etc. [6, 8, 21, 27-29, 38-42].

FMEA is usually conducted with multidisciplinary team by fulfillment of predefined FMEA form (FMEA report). Traditional RPN is achieved by multiplying three different indices – S, O and D (as it is presented in Equation 1). Usually, each of three indices may have value (1-10) on the predefined scale. According to this, RPN may go (1-1000). There are examples with (1-5) scale, also [6]. According to the rule which probably was adopted from automotive industry, corrective actions are mandatory when RPN exceeds value 100 or any of previously mentioned three indices exceeds value 8.

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

In the early beginning of this analysis, FMEA was the unique analysis. The use of FMEA for the automotive industry purpose, it was split on two types. Two main types are defined according to the stage where the product currently is located. That could be design or production process stage. According to this FMEA, the analysis related to design stage is a Design Failure Mode and Effect Analysis (DFMEA) and FMEA related to process is PFMEA. One of the differences between these two types is that for DFMEA the end user is a customer, but for PFMEA it can be the next user in a production process. PFMEA is more complicated and time-consuming then DFMEA, also.

Nowadays, there are many different types of FMEA analysis. Some of them are [6]:

- System or concept FMEA. This is FMEA used for system function checking. Usually is conducted in the earliest phase before definition of certain hardware.
- Already mentioned DFMEA and PFMEA used in design and production process phase.
- Service FMEA. This FMEA is used as standard technique for components and system evaluation during the conceptual phase of the product design phase. Main purpose of this analysis is improvement of the product serviceability.
- Environmental FMEA. This FMEA is used for weather conditional evaluation. Usually is conducted in order to check conditions of analyzed design, process, machines, etc.
- Machine FMEA. Is conducted in order to check state of the machines, tools and equipment. Usually is extension of the DFMEA.
- Software FMEA. This one is the same as Machine FMEA but specialized for software.
- Properties FMEA. This type of FMEA is more methodological for product properties converting, proposed by customer into coordinated design and verification plan for integration of process cascade goals and tool robustness.

3.2 FMEA shortcomings

Even if FMEA is defined by different standards and it is around 60 years in use, there are still shortcomings related to this analysis. FMEA shortcomings can be sorted in the three groups relating to the nature of the problems occurring at FMEA. These shortcomings are: shortcomings related to human factor influence on FMEA, risk estimation and evaluation shortcomings and procedural shortcomings. These shortcomings are respectively listed from the most important to the less important. FMEA Shortcomings are being mapped on PFMEA shortcomings.

3.2.1 Shortcomings related to human factor influence on FMEA

Human factor is the main problem occurring at FMEA. FMEA reports are usually fulfilled according to the subjective opinion of the FMEA team, which makes FMEA hardly controllable. Credibility of the determination of failures, failure effects, causes, risk priority indices (S, O and D) and RPN is almost totally dependent of the expert opinion. This leads to the relativity of the production process reliability. Some problems related to this type of the FMEA shortcomings are:

- Decision making problems. This type of problem occurs during the whole FMEA realization process. From the start when FMEA team is formed, over decision making during the failure identification and evaluation process, to the solution implementation process.
- Problems with human factor unconscientiousness during the FMEA realization [7, 43]. These problems occurs frequently in many industries, but especially in the automotive industry. Main reason for this problem occurrence is in lack of the common culture and philosophy inside a company. FMEA is a living document which should be updated constantly. Therefore, it is highly recommended for FMEA to be realized by conscientiousness employees. Some additional problems which may influence on this problem are lack of motivation and time.
- FMEA realization is time-consuming [44]. Therefore, this analysis becomes boring during the time.
- A lack of appropriate training [7]. In order to realize FMEA on more efficient and effective way, experience is necessary. But wrong experience may lead FMEA team in the wrong direction long-termly. Study realized on 150 automotive suppliers showed that PFMEA is not appropriately understood by PFMEA teams, which is the main reason why FMEA is observed as an additional administrative work. Authors noticed that surveyed employees often interfere with failure causes and effects, sometimes even failure modes. Preventive (or corrective) actions were implemented only when RPN or S, O or D indices were up from the acceptable line. These factors indicate on lack of the appropriate training.

3.2.2 Risk estimation and evaluation shortcomings

Risk estimation and evaluation framework of the FMEA contains many problems identified by many different authors. There is a whole review study about these problems conducted by Liu et al. [8] based on the review of around 75 scientific articles. Problems related to this type of the FMEA shortcoming are:

- RPN constraints [21, 8]. These constraints are presented in the AIAG's reference manual for automotive industry as well as in Liu et al. review study. Liu et al. [8] stands out 7 the most important RPN constraints identified by many different authors [8]:
  1. Different combinations of S, O and D indices may result in the same RPN value, but risks may be totally different.
  2. Mathematical formula for RPN calculation is questionable.
  3. RPN cannot be used for measuring of the effectivity of the corrective actions
  4. RPN values are not constant.
  5. Mathematical formula for RPN is very sensitive on changes during the risk evaluation.
  6. RPN elements have many doubled factors
  7. RPN considers only three risk factors.
- Problems related to S, O and D indices [7, 38]. Problem with subjectivity related to S, O and D indices may be divided on three separate problems for each of three. S index is severity of the failure effect, usually observed from the quality aspect or in some cases from safety aspect. Other factors which may influence on severity (like a cost or time spent on FMEA realization) are not counted. O index may even be the biggest problem, because it is totally dependent on probability and prediction. D index is the least problematic from all of the three indices, even if some authors see this index as a problem during the definition of its value [46]. In addition to the separate observation of each of the three indices, Liu et al. mentioned three constraints related to these indices in his review paper [8]:
  1. Relative importance between S, O and D indices is not considered. This means that these indices should not have the same weights. For example, RPN value (RPN=128) with values of the S, O and D indices (respectively 8, 8 and 2) may have lower value from RPN value (144) with value of the S, O and D indices (respectively 4, 6 and 6). This

is misbalanced and first RPN is more problematic than second, even if the second has higher RPN value.

2. These three indices are very complicated for evaluation. They are usually defined by crisp values. Therefore, there is no clear definition of the risks.
3. Each of the indices is evaluated by different meaning. Therefore, their multiplication is questionable.

- Costs are not included into FMEA [7]. Costs caused by failures may be numerous. All failure which pass true production process and arrive to the customer/consumer unseen are financial threat for a company. There are no costs included into severity decision making process, also. In addition to the costs related to customer/consumer, there are also cost caused by failures which influence on the company itself.

3.2.3 Procedural shortcomings

Procedural FMEA shortcomings are partially depended on a human factor, but on the FMEA structure as well. It could be said, that this type of shortcomings occurs during the interaction of the human factor on the FMEA structure (or FMEA report). This type of shortcoming was noticed by Johnson and Khan [7] and named as a "FMEA analysis management". Some of the problems relating to this type of FMEA shortcoming are:

- Limited space for FMEA report fulfillment. Space for the fulfillment of the FMEA report is constrained and any wider explanation in the field may lead to the opacity.
- It is not possible to use FMEA report again [25].
- Interdependence between different failure modes and effects is not considered [8].
- Wrong approach to failure root cause identification [43].
- There is no failure standardization principle and that is the reason for failure repeating in FMEA reports [43].
- FMEA report fulfillment is time-consuming process [32, 43]. Time is very important influence factor for FMEA, because of its influence on human factor. FMEA realization is not primary job for employees, but additional time-consuming activity.
- The continuous improvement is not mentioned in this approach. Therefore, failures are usually improved or solved only when RPN or some of S, O or D indices passes the border line.

3.3 Literature review on FMEA

FMEA is actively in use over 60 years. Therefore, there is a lot of papers published related to this topic. There are few review (state-of-the-art) papers addressing different groups of problems and solutions related to FMEA. First review paper was presented by Bouti and Kadi (1994) [46] about critical issues of FMEA. This was a comprehensive study with 250 articles about different categories related to FMEA and its specific use in product design and production process till 1994. Some of categories of the papers noted in this review study are: description and reviews, performance evaluation or comparison with other techniques, FMECA enhancement, automation, combination with other techniques, and specific application. A study that continued on the previous study is conducted by Sutrisno and Lee (2011) [47] for the period from (1994 - 2010). This study is practically extension of the previous study but with enlarged focus on the analysis of service sector. Reviewed Researches were addressing: improvement in estimating of RPN, modification of FMEA method in service operation, and expansion of FMEA study in various service area.

As a difference to a before mentioned review studies, Liu et al. (2012) [8] presented review study with 75 papers published from (1993 – 2012) in prestigious international journals. In this study different methodologies were observed for solving of FMEA constraints. Most of the methodologies reviewed in before mentioned study match up in this review study. This study is divided on five different groups according to the type of methodology approach used by different authors. Approaches presented in study are: Multi-criteria decision making (MCDM), artificial intelligence, mathematical programming, hybrid approach and other approaches (like cost based FMEAs) (see Table 3.1).

The most used approach is artificial intelligence with 40% of totally applied methods. The MCDM approach holds the second place with 22.5%, other approaches are on the third place with 17.5%, integrated approaches with 11.25% are on the fourth place, while mathematical programming with its 8.75% is on the last, fifth place.

Fuzzy expert system is posted as one of better and mostly used approaches. Besides lot of advantages, this approach has also many disadvantages, which leaves space for future research [8].

From 2012 till 2016, interests for MCDM increased. Liu (2016) [48] presented new MCDM researches sorted in six groups (see Table 3.3).

Table 3.1. Classification of methods for improvement of risk estimation and evaluation [8].

Categories	Approaches	Amount
MCDM (22.5%)	ME-MCDM	1
	Evidence theory	2
	AHP/ANP	4
	Fuzzy TOPSIS	1
	Grey theory	7
	DEMATEL	1
	Intuitionistic fuzzy set ranking technique	1
	VIKOR	1
Mathematical programing (8.75%)	Linear programming	4
	DEA /Fuzzy DEA	3
Artificial intelligence (40%)	Rule-base system	1
	Fuzzy rule-base system	29
	Fuzzy ART algorithm	1
	Fuzzy cognitive map	1
Integrated approaches (11.25%)	Fuzzy AHP-Fuzzy rule based system	1
	WLSM-MOI-Partial ranking method	1
	OWGA operator – DEMATEL	1
	IFS-DEMATEL	1
	Fuzzy OWA operator-DEMATEL	1
	2-tuple-OWA operator	1
	FER-Grey theory	1
	Fuzzy AHP-fuzzy TOPSIS	1
	ISM-ANP-UPN	1
Other approaches (17,5 %)	Cost based model	6
	Monte Carlo simulation	1
	Minimum cut sets theory (MCS)	1
	Boolean representation method (BRM)	1
	Digraph and matrix approach	1
	Kano model	1
	Quality functional deployment (QFD)	2
	Probability theory	1

Table 3.2. The reviewed weighting methods for risk factors [8].

Categories	Weighting methods	Amount
Direct given	/	8
Subjective weighting	Direct assessment by experts	6
	AHP/ANP	10
Objective weighting	Ordered weight	3
	DEA	3
	Minimum cut set	1

From 2012. till 2016, interests for MCDM increased. Liu (2016) [48] presented new MCDM researches sorted in six groups (see Table 3.3).

Table 3.3. MCDM for FMEA from 2012 till 2016 [48].

Categories of MCMD	Approaches	Amount
MCMD based on distance	Measurement of distance	1
	GRA	6
MCDM based on compromise ranking	VIKOR	3
	TOPSIS	6
MCDM based on priority assumption	QUALIFLEX	1
	ELECTRE	1
	PROMETHEE	1
MCMD based on pair comparison	AHP	2
	ANP	1
MCMD based on hybrid approach	VIKOR i AHP	2
	VIKOR, DEMATEL i AHP	1
	ER i TOPSIS	1
	GRA i DEMATEL	4
	TOPSIS i DEMATEL	1
other MCMD approaches	MULTIMORA	1
	COPRAS-G	1
	ER	1
	DEMATEL	1
	Digraph and matrixes	1

These groups are: MCDM based on distance, MCDM based on compromise ranking, MCDM based on priority assumption, MCMD based on pair comparison, MCMD based on hybrid approach and other MCMD approaches.

The most recent review study on FMEA is conducted by Spreafico et al. (2017) [49]. This research covered scientific papers and patents published from 1978 till 2016. These authors classified research according to the authors (on industry or academia) and source literature (on scientific literature or patents). 220 scientific papers were identified (203 from academia and 17 from industry) and 109 patents (23 from academia and 86 from industry). These authors sorted FMEA problems and solutions into four groups: applicability, cause and effects representation, risk analysis and problem solving. Findings are that academia is more interested in applying of different methodology in order to solve FMEA constraints and problems, while industry is more oriented to implementation on practical solutions for risk evaluation.

3.4 PFMEA in the automotive industry

Early beginning of the use of PFMEA in the automotive industry is related to 1980s, when PFMEA become obligatory for suppliers of American automotive corporations Ford Motors, Chrysler and General Motors. PFMEA is type of FMEA used during the production process. Nowadays, usage of PFMEA is obligatory for all companies which producing parts for automotive industry, which is the main reason for PFMEA prevalence in industry as a reliability improvement tool. Some of the standards and manuals which were proposing and still proposing PFMEA in automotive industry are: *Advanced process quality planning* (also known as APQP), *Production Part Approval Process* (also known as PPAP), TE 9000, ISO 9000, QS 9000, ISO/TS 16949, IATF 16949, etc.

Besides the fact PFMEA is obligatory in automotive industry, there are still shortcomings occurring during the conduction. Therefore, it could be said that nowadays, PFMEA attracts interest for improvements by researchers. Besides shortcomings, PFMEA provides many advantages as well. Some of them were highlighted by Stamatis [6]:

- Reliance that all risks are identified during the early phase of the production process, or even before production process starts.
- Priorities and explanations for product or process improvement activities.
- Scrap, rework and cost reduction.
- Preservation and acquisition of knowledge about processes and products.
- Reduction of warranty costs.
- Documentation of Improvement activities and failures for some future processes.
- Potential failure mode identification.
- Potential failure effect identification.

- Determination of failures severity.
- Determination of potential failure cause/es.
- Implementation of the new design or control in order to stop the same failure occurring in the future.
- Collective activities identification in order to stop failure occurring.
- Priorities setting in order to implement corrective activities during the production process.

PFMEA conduction should be done in the team using a predefined procedure[13]. In the next subchapters, PFMEA procedure related to automotive industry will be presented. Moreover, PFMEA form and following PFMEA terminology explanation and PFMEA team will be given as well as directions for the future research.

3.4.1 PFMEA procedure

For PFMEA procedure conduction, certain step sequence is predicted. This sequence may be changed according to the company needs. Traditional (or conventional) PFMEA procedure for automotive industry is defined and proposed by AIAG (see Appendix A) [21].

Multi-disciplinary team should be formed before PFMEA conduction starts. Team is fulfilling basic data about PFMEA first, in order to be followed in documentation easier. After basic data definition, process flow chart should be defined in order to analyze failures related to each of the production process steps. Before PFMEA conduction starts, special characteristics defined by customer or defined during the design phase in DFMEA, should be checked also. After all of these steps are prepared, failure analysis may start After failure definition, failure effect caused by failures should be defined, as well as causes of the failures and current state check for preventive and corrective measures. Afterwards, the risk evaluation comes by defining S, O and D indices resulting with RPN. If some of RPN or S, O and/or D indices pass the acceptable border lines, corrective measures should be implemented (they should be implemented anyway, but especially in this case).

3.4.2 PFMEA report with following terminology

Conduction of the PFMEA is done by PFMEA report fulfillment. Traditional PFMEA report with minimal content of information is proposed by AIAG (see Appendix B) [21]. This form of the

[13] *Procedure* – In this case, under the term procedure is considered specification of the series of activities, actions and operations should be done in order to achieve certain output in the form of PFMEA report.

PFMEA report is the one most frequently used in practice, even if companies are free to adapt it according to their needs. The main reason for this is in external auditors which are educated according to the traditional PFMEA framework proposed by AIAG. Therefore, any modification on PFMEA should be transformed back into traditional PFMEA framework.

This report is based on two separate parts: heading and body. Heading of the PFMEA report contains basic data about object or process which for PFMEA is realized, while body of the PFMEA report contains procedural steps for PFMEA conduction. In further reading, each of the terms in the tables will be explained.

Body of the PFMEA report contains next data [21]:

- PFMEA number – is used to define number of the PFMEA analysis or for the document control.
- Item – Is a name or number of the system, subsystem or component which PFMEA is realized for.
- Process responsibility – Is a name of the process designer responsible for the process.
- Model year/Program – Model used while process is being analyzed.
- Key date – Initial PFMEA realization date (this date should not exceed the scheduled start of the production date).
- FMEA date – Date of the last revision of the PFMEA.
- Core team – Team members included in the PFMEA realization.
- Prepared by – Team leader responsible for the PFMEA.

Body of the PFMEA report is based on [21]:

- Process step/Function – This field may be based on one field, but two separate fields as well. Process step is a step in process flow chart. Function may be operating during the production process, depending on which way process flow chart is designed.
- Requirements – This field should be fulfilled if there are some special requirements demanded by customer, consumer or if there are some requirements defined during the product design phase.
- Potential failure mode – Is defined as an event or activity with a loss of the product function. This term is also known as a failure, malfunction or deviation.

- Potential Effect of failure – is effect (or consequence) that occurred during the failure mode with direct negative influence on customer/consumer satisfaction. These consequences may even have safety influence on the customer/consumer.
- Severity (S) – Defines severity level of the failure effect which reflects on customer/consumer. Severity is defined by crisp values (from 1-10) with different scenarios. These values are defined in table for severity proposed by AIAG (see Appendix C). The recommendation is when value of the S index is 9 or 10, corrective solution must be implemented. These two values of the S index are related to the safety.
- Classification – This field is for highlighting of the failures with special priority which may need to be evaluated additionally.
- Potential cause of failure mode – Failure cause is an indicator which leads to failure occurrence. Recommendation is to identify and solve cause failure, rather failure effect. PFMEA team often does not make difference between cause and effect, which may be very problematic for PFMEA.
- Occurrence (O) – Defines how many times failure occurred in certain amount of produced products or in one batch. Occurrence is defined by crisp values (from 1-10) depending how many times failure occurred. These values are defined in table for occurrence proposed by AIAG (see Appendix D). The recommendation is when value of the S index is 9 or 10, corrective solution must be implemented.
- Current process controls – There are two types of control considered under this term: current preventive control and current detection control. Under current preventive control, there are measures considered for failure cause removal or reduction of failure rate, while failure cause detection is considered under the current detection control.
- Detection (D) – D index presents level of production process capability to detect failures before passing true production process. Detection is defined by crisp values (from 1-10) with different scenarios. These values are defined in table for severity proposed by AIAG (see Appendix E). The recommendation is when value of the D index is 9 or 10, corrective solution must be implemented.
- Risk Priority Number (RPN) – This term is related to the assessment activity of risk priorities according to the total value achieved by multiplication of S, O and D indexes. RPN is not a value for definition of the need for preventive or corrective measures implementation, but

for setting of the priorities between failures which has to be implemented in terms of solutions. RPN value range for automotive industry goes from 1 to 1000. Priority risks which implementation of the solutions are obligated for risks with value higher than 100.

- Recommended actions – Implementation of the recommended actions is done in order to reduce values of the S, O and/or D indexes. These actions are usually recommended by PFMEA team.
- Responsibility and target completion date – Usually in this filed, there is a responsible person defined (or organization) for implementation of a recommended actions, with target date included. Person responsible for certain process controls efficiency of the implemented actions.
- Actions taken and completion date – In this field, conducted activities are highlighted with following date of the conduction.

3.4.3 PFMEA team

PFMEA is a team based analysis. According to IATF 16949, it is obligatory to be conducted in multidisciplinary team. This is provided in clauses 8.3.2.1 and 8.3.3.3 of IATF 16949 [50]. Relevance and reliability of the PFMEA conduction depends on experts from different fields. Therefore, it could be said that PFMEA is often based on multidisciplinary team, headed by team leader. According to some authors, recommended number of team members is from 4 to 6 [51, 52]. On the other hand, Stamatis [6] recommends from 5 to 8 (the best is 5) team members per PFMEA. Principally, PFMEA number of team members is relative and depends entirely on the production process needs. Besides regular PFMEA internal team internal members delegated from a company itself, additional external team members can be added. These external team members may be: Customers and/or suppliers, external service companies, DFMEA team members, even shop floor workers in some cases, etc. PFMEA team may be separate topic of research in order to improve PFMEA, because quality and reliability of the PFMEA mostly depends on human factor (in this case team members). More detailed instructions for team forming and team management can be found at Stamatis [6].

PFMEA conduction is done by team leader. PFMEA Team leader is usually set by company management, but in some cases may be elected inside a team. Common mistake about PFMEA team leader is opinion that PFMEA leader is function with decision making role. PFMEA team leader has the same rights and duties as other team members. Some of these duties are:

planning and conduction of the meetings, ensuring of the necessary resources, Provision of the PFMEA conduction reliability, etc. [51, 52]. Besides PFMEA leader, another important person for PFMEA conduction is process expert. This profile is very important for sharing of knowledge related to production process inside a PFMEA team. Ideal case is when PFMEA leader is a production process expert at the same time.

Team member has to pass special education related to PFMEA in order to conduct PFMEA on appropriate way. Additional education is not necessary (but is desirable) if team members have some certificates or experience in PFMEA conduction. All members have to pass education program if certain automotive company uses some unusual way of PFMEA conduction or some software solution. Besides education for PFMEA conduction, PFMEA team should pass education about team work as well.

3.4.4 International standards which contain PFMEA

Primary international quality standard which describes basic quality concepts and principles is ISO 9000 (active version of this standard is ISO 9000:2015). Preventive risk management is proposed by this standard [53]. According to Stamatis [6] PFMEA needs to fulfill specific requirements of the ISO 9001 (Quality management systems - requirements). Active version of this standard is ISO 9001:2015. Nothing changed from those times till nowadays. This also could be said for ISO 9004 (Quality management systems – Managing for the sustained success of an organization). Active version of this standard is ISO 9004:2010 [54]. Therefore, conclusion is that all mentioned standards (ISO 9000, ISO 9001 and ISO 9004) need FMEA, but it is not specifically defined.

Some quality standards particularly propose usage of PFMEA analysis for preventive risk management during the early stage of production process design in the automotive industry. The first standard proposing PFMEA in the automotive industry was the set of quality requirements – QS 9000, founded in 1994. for the automotive industry needs [55]. In the same year, Ford Motors, Chrysler and General Motors obligated their suppliers to change regulations used before with QS 9000 standard. In QS 9000 standard, PFMEA is mentioned in some clauses. With this standard, the usage of “Potential FMEA” manual proposed by AIAG, was demanded also. QS 9000 was changed for ISO/TS 16949 in 2006 [56]. ISO/TS 16949 (last version was ISO/TS 164949:2009) was changed for IATF 16949 (active version of this standard is IATF 16949:2016). One of the hard evidences of PFMEA relevance in the automotive industry is the fact that three international standards for the automotive industry have changed, but PFMEA still stayed the same till nowadays.

3.4.4.1 PFMEA and IATF 16949:2016

IATF 16949 is a new international automotive standard for quality management system, which recently replaced ISO/TS 16949 international automotive standard. Main goal of this international standard is to provide continuous improvement system in order to implement better preventive measures for failure or deviation reduction, as well as losses in general inside a supply chain [50].

The first version of ISO/TS 16949 is published in 1999 by International Automotive Task Force (IATF)[14]. The main goal for forming of this standard was harmonization of different principles and certified systems related to automotive industry all over the world. The second version of this standard was published in 2002, the third and the last one in 2009 [50].

In the IATF 16949 international automotive standard, PFMEA was mentioned 18 times, in opposite to the previous standards for the automotive industry (QS 9000 and ISO/TS 16949) where PFMEA was mentioned only in a few clauses. Clauses of the IATF 16949:2016 international automotive standard in which PFMEA was mentioned are [50]:

- 4.4.1.2 Product safety.
- 7.2.3 Internal auditor competency.
- 7.2.4 Second-party auditor competency.
- 7.5.3.2.2 Engineering specifications.
- 8.3.2.1 Design and development planning – supplemental.
- 8.3.3.3 Special characteristics.
- 8.3.5.2 Manufacturing process design output.
- 8.5.1.1 Control plan.
- 8.5.6.1.1 Temporary change of process controls.
- 8.7.1.4 Control of reworked product.
- 8.7.1.5 Control of repaired product.
- 9.1.1.1 Monitoring and measurement of manufacturing processes.
- 9.1.1.2 Identification of statistical tools.

[14] *IATF* is a group of automotive producers and their reputable selling associations formed in order to provide better product quality to the customers.

- 9.2.2.3 Manufacturing process audit.
- 9.3.2.1 Management review inputs – supplemental.
- 10.2.3 Problem solving.
- 10.2.4 Error-proofing.
- 10.3.1 Continual improvement – supplemental.

According to this, it is obvious that relevance of PFMEA analysis is increased in the automotive industry with regard to previous years and standards.

3.5 Chapter conclusion and future research

Opposite to the other types and applications FMEA in different fields, PFMEA framework for the automotive industry is proposed by standards and regulations for the automotive industry. Therefore, there are no much degrees of freedom for PFMEA structure and procedure changes in the outer look. PFMEA form has to be adopted to the AIAGs manual mostly because of external auditors. By the internal look PFMEA structure and procedure may be changed, but that changes have to be transformed later into traditional PFMEA form. This transformation usually may lead to the more time-consuming PFMEA conduction.

Anyway, traditional PFMEA form for the automotive industry contains many constraints. Therefore, it could be said there is a need for improvements on this analysis. Johnson and Khan [7] conducted survey on 150 suppliers from the automotive industry related to application of the PFMEA in the automotive industry. According to this survey, many constraints were identified and some directions for improvements were proposed. Study was conducted 15 years ago. From that time many improvements were proposed, but there is still many space for improvements.

RPN and S, O and D indices constraint are solved with many solutions proposed by different authors. For solving of this kind of FMEA constraints were used many MCDM methods, mathematical programming, artificial intelligence, integrated and hybrid approaches, pondering methods, and many other. One of the most efficient, but in the same time most used approaches in the literature is fuzzy. Fuzzy approach gives many advantages to FMEA improvement, but still has some disadvantages. One of the biggest is very hard (almost impossible) application in practice, because of the need for defuzzification of big amount of fuzzy rules. By the other side, setting of the priority criteria between S, O and D indices by pondering, proven to be very efficient. The most efficient and frequently applied pondering method is AHP. One of the problems for application of those methodologies may be coming out from the traditional PFMEA framework for the automotive industry.

According to the extensive literature review and many problems identified by different authors, some future trends for improvements of the PFMEA for the automotive industry are proposed:

- Separation of S, O and D indices too the lesser degrees in order to define them more detailed [8].
- S, O and D indices weighting and definition of the priority criteria [8].
- Usage of the hybrid approaches by combining two or more MCDM methods in order to define priority risks more detailed [8].
- Finding of the way to include costs into risk consideration [7].
- Finding of the way to describe safety more detailed during the severity ranking [7].
- Improvement of the PFMEA of the automotive industry procedure [43].
- Comprehensive databases [47].
- Software solutions [7, 49].

These before mentioned improvement proposals are mainly oriented to solving of the procedure and structural PFMEA shortcomings. Besides these improvements, human factor shortcoming should be considered as well. These issues are considering multidisciplinary approach, which can be constraint for engineers at start. Author which mostly addressed these problems in the literature is Stamatis [6]. Some of the future improvements may be:

- Inclusion of the time aspect as a risk factor into PFMEA for the automotive industry. Due to the lack of time to conduct PFMEA on appropriate way, many omissions may occur. This may lead to the critical failure mode appearance.
- Decision making simplification.
- Human resource management [6, 49].
- Training [6, 7, 49].

Improvement solutions will be presented in the next three chapters: Chapter 4, Chapter 5 and Chapter 6. In chapter 4 procedural shortcomings related to PFMEA for automotive industry will be addressed by integration of lean approach into traditional PFMEA procedure. Risk estimation and evaluation shortcomings will be addressed in Chapter 5 by usage of mathematical methods, with inclusion of costs and safety as additional severity factors. Last type of shortcomings related to human factor will be solved by putting all improvements related to procedure and risk estimation and evaluation of PFMEA for automotive industry into automatized software solution supported by comprehensive database.

4. INTEGRATED LEAN APPROACH TO PFMEA FOR AUTOMOTIVE INDSUTRY

Both, PFMEA and lean have the same main purpose – identification, prevention, and correction of failures during the production process. Besides PFMEA wide application in the automotive industry, lean finds it as well. Therefore, both PFMEA and lean are usually used for the same purpose in the automotive industry. PFMEA is obligated by standard for automotive industry IATF 16949 and lean become usual practice in the automotive industry. Also, lean contains failure under the one of the seven lean wastes. In nowadays, a wide application of lean can be found in automotive companies all over the world. From the case study carried out on 300 manufacturers, it is evident that 90% of them are applying lean [57]. Also, according to the recent research from 2015 published by Boston Consulting Group, 30% of the world's original equipment manufacturers use lean tools in their production systems [58]. With this data, the theory about wide application of lean approach in automotive industry is confirmed.

This is the new approach in science until now. Various authors conducted several researches on similar but reverse approach. They were using FMEA as a tool to improve lean system. Automotive company is the unique example, because FMEA is obligatory, while most of them using lean approach as well [43]. Shekari et al. (2007) [59] were using FMEA as a tool for failure detection to improve lean system. Sawhney et al. (2010) [60] presented modified FMEA approach for reliability improvements of lean system. Then, Shahrabi et al. (2014) [61] applied FMEA and AHP methods for improvements due to maintenance of lean system. These papers were related to the use of FMEA in order to improve lean systems. One example of using lean tools to improve FMEA. Puvanasvaran et al. (2014) [62, 63] used lean tool named *Poka-Yoke* to improve FMEA. However, this tool was used separately, not as a whole lean approach.

Since lot of automotive companies are using lean approach and PFMEA for prevention of failures, methodology for realization of PFMEA with integrated lean approach, will be presented in this chapter. A broader concept of lean with regard to lean approach and methods, tools and techniques will be given fist. Also, a case study in one specific automotive company will be given. In a Case study, results from reports of already realized traditional PFMEA and new PFMEA with integrated lean approach will be compared. At last, summary of the results will be presented with contribution of integration of lean into PFMEA for automotive industry.

4.1 Lean

Lean is American term to describe the Toyota Production System (TPS) [43]. The advent of TPS is related to period after World War II. This Company was in need of a great solution which will turn the company on and make it more competitive on the market. Popular mass production which was widely used all over the world was changed with "pull system" or production of the customer demanded products only [64]. Company focus was changed to continuous improvement and quality management in every step. TPS was not famous beside the Toyota Motor Corporation and its suppliers until 1943, when first oil crisis attacked the world. The most important fact is that the TPS led Toyota Motor Corporation to the first place on world's car manufacturers list. Lean became popular worldwide in the 1990s, when many companies started applying it [65, 66].

This term lean was first used by John Krafcik in 1988 and it was result of intensive research collaboration within the global automotive industry [59]. Firstly, lean was related to production only – lean production. Later, Womack and Jones [67] used term lean thinking to spread wider possibilities of lean application. Lean thinking describes what we today call lean management, or more simply lean. Lean thinking helped in spreading of lean besides automotive industry of many different fields and areas. Therefore in nowadays there are many of them with lean prefix: Lean enterprise, lean office, lean development, lean leadership, lean logistics, lean IT, lean safety, etc. [43, 66]. Beside this application of lean to other segments of industry, there are also popular applications of lean across other fields. Some of them are: Lean healthcare, lean justice, lean education, lean schools and universities, lean retail, etc. [66].

Increased application of lean concept all over the world in many different fields and for many different purposes made confusion in defining of lean approach. Main confusion is that lean is just a set of tools and techniques introduced by Toyota Motors Company [66]. Lean approach in this dissertation is a term used to describe using lean thinking, principles, methods, tools and techniques for solving PFMEA problems related to procedural shortcoming of the PFMEA for automotive industry. Lean principles can be understood best through 4 basic Toyota principles: *Genchi Genbutsu* (go and see by yourself), *Kaizen* (continuous improvement), team work and respect for people, and challenge. Based on this 4 principles, Liker [65] preformed his own 4 principles known as 4P: philosophy, process, people and partners, and problem solving. Lean approach could be applied to any other business aspect or in any business situation [65]. Lean approach in automotive industry is mostly used for production process improvements. For these improvements, various lean tools are commonly used in order to eliminate seven wastes: overproduction, unnecessary transportation, waiting, over processing, overstock, unnecessary motions, failures (defects), repair, non-value added work. These tools and techniques are: *Jidoka*, *Poka-Yoke*, *Kanban*, single minute exchange of die (SMED), *Kaizen*, Just in Time (JIT), 5S, standardized work, 5 why?, total productive maintenance (TPM), PDCA cycle (plan, do, check, act), etc.

4.2 Lean methods, tools and techniques integrated into PFMEA for automotive industry

There are various lean principles, methods, tools and techniques used in general in automotive industry. But for the purpose of integration of lean approach into PFMEA for automotive industry are used only specific ones. Lean tools and techniques used for this purpose are: Standardized work, *jidoka* and 5 why?. Besides tools and techniques, two lean principles was used as well: *Kaizen* and *Genchi Genbutsu*.

4.2.1 Standardized work

Standardized work usually associates on the steps made by rules shop floor workers should follow. In case of a lean, standardized work have a deeper sense. Imai [68] said it is impossible to improve any process until it is standardized. Standardized work is also a key facilitator of building in quality [65].

4.2.2 *Kaizen*

Kaizen is a method for continuous improvement first introduced by Imai [68]. Term *kaizen* is Japanese term based on two words: *kai* (isolate) and *zen* (improve). *Kaizen* is one of the key tools for business progress. Its application starts with identification of the problem. Problem is isolated and solutions are proposed. *Kaizen* finishes with standardization of the solution. There are five basic *Kaizen* types [68]:

1. Kaizen event
2. Gemba *Kaizen*

3. System *Kaizen*
4. Blitz *Kaizen*
5. Super blitz *Kaizen*

4.2.3 *Jidoka*

Jidoka is practically a synonym for source quality. Jidoka is automatized system in a machine which will automatically stop a machine when defective part occurs. This system is based on sensors specialized to detect a failure during the process. *Jidoka* system was founded by Sakichi Toyoda in order to suppress failure occurring at automatic loom [64]. This method is one of the pillars of the TPS and it is founded even before Toyota Motors. Implementation of this method leads to failure reduction and reliability increment.

4.2.4 "5 Why?"

5 why is one of the main tools for cause identification. This tool is not used to remove failure, but to identify its root cause. The most important thing is to define problem appropriately at the start. Wrong definition of the problem may lead cause identification in a wrong direction. This tool is functioning by asking a question "why?" five times in the row (can be more or less than five times). Therefore, tool is very simple for use, but in the same time very effective.

4.3 Integration of lean approach into PFMEA for automotive industry

The idea is to integrate lean approach into PFMEA procedure in order to overcome shortcomings related to the PFMEA procedure for automotive industry. For the other two group of shortcomings, various solutions have been already proposed. Especially for shortcomings related to risk estimation and evaluation PFMEA. For example, for RPN, costs, S, O, and D indices, etc. lot of solutions have been found. But, there is still a lot of space for improvements. Specified problems related to procedural PFMEA shortcoming are identified in literature. Problems can be fixed by integration of lean approach to PFMEA. These problems are presented in Table 4.1. These procedural shortcomings are defined by various authors and they are presented in the left column of the table. In the right column of the table, the lean approach solutions for fixing of specified shortcomings are presented. There both seven shortcomings and solutions presented.

Table 4.1. Proposed lean approach for fixing of the specific PFMEA shortcomings [43].

Shortcomings	**Lean approach for fixing the shortcomings**
Wrong approach to detecting failure root cause [7]	Root cause of failure can be identified with lean tool for identification of root cause – 5 why
Unutilized existing resources [7]	There are many resources unutilized in companies which can be used for improvements during PFMEA realization. One of the most unused resources are human resources in company. In lean systems, all employees should be involved in improvements – Lean approach
Problem during defining RPN actions [8]	Failures should be treated respectively with higher RPN. Surely, all failures should be solved or reduced due to the "zero failure" goal of lean approach. For this case should be used continuous improvement approach – *Kaizen*
Repeating of failures in next row [8]	Failures should be solved with solutions consequently standardized. Data base also needs to avoid failure repeating – standardized work
Traditional brainstorming is boring and time-consuming [69]	Failure identification should be done directly in shop floor and workers should be involved in analyzing process as well. For this case should be used lean principle – Genchi Genbutsu
It's impossible to use FMEA report again [25]	Use of software with tables in which revision can be done that imply a constant improvement – software solution and *Kaizen*
FMEA report fulfilment is very time-consuming [32, 70]	Lean should be accessed slowly and thoroughly, rather than fast and superficially. Standardization of PFMEA failures will mean less failures to improve in future. Therefore, PFMEA realization will go faster long termly - lean approach

For each of the problems mentioned in the Table 4.1, appropriate lean approach solution is proposed. The new procedural approach for PFMEA for automotive industry is proposed in algorithm form in Appendix F. Proposed algorithm is divided in four phases based on Deming's - plan, do, check, act (PDCA) cycle for problem solving. PDCA is a four-phase-cycle for problem solving which Deming proposed in 1950 [71]. Plan phase is the biggest phase adapted to detail analysis. Do phase is related to execution of the plan phase. Check phase is needed for checking of every progress. Act phase is related to recognized and standardized solution. PDCA cycle is the approach to problem solving frequently used in lean approach.

New PFMEA approach is starting with multidisciplinary team forming. When the team is confirmed, the identification of problems is next. Firstly, team has to go directly to the place where the process is going in *gemba*[15] to observe the process – *Genchi Genbutsu*. Also, it is

[15] *Gemba* is Japanese term to describe shop floor place where work is happening. This term was adopted by Taichi Ohno (Famous Toyota leader).

highly recommended to include shop floor workers in decision making process. Workers are directly in contact with the production process, and they usually know best what kind of problems may occur during the production process. When these terms are satisfied, the team is proposing production process flow chart. After flow chart definition, process and product characteristics are deeply analyzed. Identification of failures is one of the most important steps, because it directly depends on team members' opinion. There are two types of failures: standardized failures and failures that are occurring for the first time. Standardized failures are already familiar and they exist in data base (if there is any). Failures that are occurring for the first time have to be defined, solved and standardized. For these new failures, failure effects and causes are identified as well [43]. Team is often blending effects and causes which is a very big problem [7]. For all causes, one lean tool is specified for finding a root cause of the problem – 5 why. According to the current state, S, O, and D indices are defined. For O index, a special data base is needed. This data base should contain the amount of same or similar problem occurrence. D is another index with special issue, due to the lean approach purpose of producing quality, so quality have to be provided on source - *Jidoka* [43]. For the case of automotive industry, in detection table from fourth edition of reference manual guide for automotive industry, automatized control for first 5 indices, is predicted [21]. When value of D index is over 5, control is not automatized. Therefore, if D index exceeds value 5 then *Jidoka* or source quality, should be implemented. With all three indices defined, RPN can be calculated as the end of the plan phase [43].

After the plan phase, do phase or realization phase follow. For all defined RPN, corrective actions or *kaizen*, should be taken. Suggested improvements had to be set on a list of solutions, with exact deadlines and with responsible team members.

Third phase is a check phase where the action taken has to be checked with repeating of RPN calculation. If there is no progress, then *kaizen* should be performed again. This check phase have to be realized very carefully, because after this phase failure should be standardized.

Last phase is act phase. When the solution is finally found and the progress has been made, failure and elected solution have to be implemented and standardized.

4.4 A case study

The company elected for the case study is automotive company which produces electronic circuit boards and electronic cables for automobiles. Company is supplying automotive suppliers and corporations all over the world. This company applies lean approach in its production system for a long time and also uses PFMEA for prevention of failures and risks. The use of PFMEA in this company is obligatory according to the IATF 16949 standard.

PFMEA for product “MSM6BL” was already conducted on traditional way (see results in Appendix G). Results are presented in Table 4.2. Measured conditions taken for comparation are: number of team members, identification of failures, change of S, O and/or D indices and RPN values, reduced S, O and/or D indices, and RPN values after taken actions, RPN with value over 100, and S, O and/or D indices with value over 8. These conditions are measured in total amount for whole PFMEA. The goal was to compare them with the new approach and see the differences after its implementation. S, O and/or D indices and RPN value changes are also calculated in total change regardless if it is increased or reduced value.

Methodology set in algorithm form from Appendix F is used for realization of PFMEA. Realized PFMEA report is presented in Appendix H. The changes made after the new approach are painted in blue, yellow and orange. Blue paint is for changes, yellow is for new failures and orange is for failures with implemented lean approach. The data for a new state are also presented in Table 4.2. Comparison between the state after traditional approach to PFMEA realization and the new approach to PFMEA realization with integrated lean approach, was made. These results are also presented in Table 4.2.

From Table 4.2, it can be seen that almost all conditions are changed, except one - reduced S index value due to taken actions. Two conditions; the actions taken and identification of failures, are very important for analysis because they are related to the purpose of analysis to detect a failure and take action to improve it. *Genchi Genbutsu* has mostly contributed to these changes. Lean approach stimulated involvement of more employees in PFMEA conduction process. As it was predicted, workers contributed a lot to failure identification because they are directly involved in a production process. But *Genchi Genbutsu* stimulated PFMEA team to go directly in process and observe an actual status. Increased identification of failures and the taken action can avoid hidden failures reaching customer. Also, they affected the changes of O and D indices and RPN values. Moreover, during these changes, value of some S, O and D indices exceeded 8 and RPN values exceeded 100. The lack of situations when some of S, O and/or D indices and/or RPN exceed predicted values for improvements may cause serious problems if failures reach a customer. Only one condition which is not reduced is S index due to the actions taken, which is not a big issue due to the O and D indices reduction for that failures.

Table 4.2. Comparison of state before and after lean approach to PFMEA [43].

Measured conditions	**State after traditional approach**	**New state after lean approach**	**Improvements [%]**
Number of team members	2	9+6 workers	85
The actions taken	1	19	95
Identification of failures	18	27	33
Change of S value	155	227	32
Change of O value	64	105	39
Change of D value	85	161	47
Change of RPN value	1642	3720	56
Reduced RPN value	2602	3366	23
Reduced S value due to taken actions	226	226	/
Reduced O value due to taken actions	80	127	37
Reduced D value due to taken actions	121	139	13
RPN value over 100	/	16	100
S, O and D values over 8	/	3	100

Reduction of O and D indices was achieved due to the application of *Kaizen*. Also, some of D indices of different failures were reduced due to the application of *Jidoka*. Causes of failures were superficially defined and some resulted with mixing of causes and effects. With application of lean tool - 5 why?, root causes of failures were deeply analyzed. The actions taken were oriented on fixing root causes of failure, not effects. Another lean tool used in this case study, is standardized work. Some of failures were standardized. This means that in the next PFMEA for some of the new processes or products, standardized solution will be used. Standardized solutions saved a lot of time.

4.5 Chapter conclusion

Both lean and PFMEA have a long tradition in failure prevention during the production process in automotive industry. Here in this chapter is presented way of integration of lean approach (principles, thinking, methods, tools and techniques) into PFMEA procedure. Specific case is automotive industry because PFMEA is obligated by standards. On the other hand lean is an increasing trend in the world, currently used mostly in automotive industry. Possibilities of integration of lean approach into PFMEA procedure was approved by case study in one automotive company which uses IATF 16949 standard and lean as well. Lean approach was integrated true integration of specific methods, tools and techniques (standardized work, *Jidoka*, *Kaizen* and "5 why?") and principle *Genchi Genbutsu*. Whole process of PFMEA realization was conducted in four phases according to the Deming's PDCA cycle. The most important thing in this new approach was keeping the traditional PFMEA framework for automotive industry.

The integration of lean approach into PFMEA procedure provided many advantages especially related to procedure and realization steps. Some of these advantages are:

- Root cause of the failures was more deeply analyzed and some effects were switched with causes. This advantage was achieved by application of "5 why?" lean technique for finding of root cause of failure.
- More employees were included into PFMEA realization process (especially shop floor workers) which resulted by identifying of hidden and marginalized failures.
- Kaizen principle and method led to involvement of continuous improvement philosophy into process and failure improvement phase.
- Improved solutions were standardized which led to decrease of volume of repeatable failures.
- Due to the improvement of PFMEA by lean integration, more solutions were implemented and more hidden risks were addressed.

Some disadvantages were noticed as well. But in ideal case they can be neglected. These disadvantages are mainly related to the increase of time needed for PFMEA realization. Integration of lean approach can demand additional training and education, as well. These two problems are short-term problems. Long-termly every PFMEA demands time for realization and every employed person needs training and education for PFMEA.

5. USAGE OF MATHEMATICAL METHODOLOGY IN ORDER TO ACHIEVE BETTER RISK PRIORITIZATION AT PFMEA FOR AUTOMOTIVE INDUSTRY

Many authors addressed different risk estimation and evaluation shortcomings and many other authors have given different solutions in order to overcome mentioned shortcomings. The methods most frequently used to improve these shortcomings are: artificial intelligence based methods, MCDM, integrated approaches (or hybrid methods) and mathematical programming. These improvements are mostly addressing the problems related to S, O and D indices and RPN. The biggest problem of all these improvements is exceeding of traditional PFMEA framework for automotive industry. Lot of authors invented new ways for RPN calculation. Other authors switched traditional risk priority indices for other indices. This leads to change of the traditional structure of the PFMEA for automotive industry. All these before mentioned improvements are proposed in order to achieve better risk prioritization and to improve decision making. The biggest problem due to risk prioritization could be hidden risks. Severity of the failure effect is usually observed by quality aspect, but quality is not the only aspect which influences the risk prioritization.

The way of integration of two additional severity aspects (safety and cost) will be presented as follows. Afterwards, the way of ranking and prioritization for new severity indices will be presented. At last, case study is conducted in one automotive company and achieved results are presented.

5.1 Integration of additional risk aspects into severity index

Severity index for PFMEA for automotive industry is defined according to the severity table proposed by AIAG. First eight values for severity are related to quality aspect of risk, while last two values 9 and 10 are related to safety risk aspect. Cost risk aspect is not taken into account during the risk prioritization even if costs play very important role in nowadays automobile industry. There are more other aspects of risks which may influence on severity of failure effect like time and human factor aspect, but these aspects can be observed from the ideal case point of view or to be left to some other cognitive and human factor studies. Herein dissertation focus will be on more realistic and measurable aspects of severity of failure effects like safety and costs.

In next two chapters way to integrate safety and cost aspect into severity index will be proposed. One option is to sustain the traditional PFMEA framework, but to integrate costs and safety aspect into traditional PFMEA. Another way is to split risk factors on partial severity factors for each of aspects. These kinds of studies were mentioned as future research in a review study on FMEA conducted by Liu et al. [8]. Some authors have already done similar studies. Zammori and Gabbrielli (2012) [72] split the severity index into three risk factors: damage, production, and maintenance costs. Another study was conducted by Braglia (2000) [73], in which he included expected costs with other indices (severity, occurrence and detection). Both authors used MCDM as support for the weighing of risk factors, including the costs. The same problem is identified for safety. Therefore, there is a need for inclusion of safety index into severity evaluation process as well as for costs.

This paper will present the safety, quality and cost model of PFMEA for the automotive industry based on integration of additional risk factors (safety and cost) into an already existing model proposed by AIAG. Uncertainties are modeled by using the fuzzy sets theories, in order to keep the traditional PFMEA framework, but to achieve more precise results.

5.1.1 Safety aspect of severity index

Besides reliability and quality estimation, FMEA can be used for safety estimation as well. Rouvroye and Van Den Bliek [74] made comparison analysis of safety analysis methods, where FMEA was ranked as a very good qualitative analysis. Type of FMEA used for safety aspect is usually FMECA which have additional way for criticality aspect calculation.

Safety is already defined by crisp values 9 and 10 in severity table for PFMEA for automotive industry, but roughly. In Table 5.1 are presented 10 different scenarios of safety influence on severity of failure effect. Safety aspect of severity index is named safety severity index. These scenarios are adopted by expert opinion based on the risk scenarios defined in two basic risk estimation practical methods recommended by Macdonald [75]. One of these methods is the "PILZ system" method for risk estimation. This method is useful for a more deterministic mathematical definition of risks, but still contains some scenarios. Another one is suggested by "Guardmaster" (supplier from United Kingdom). It could be said that scenarios listed in Table 5.1 presents a combination and extension of two before mentioned risk estimation methods, adapted to the scale (1-10) in order to satisfy severity estimation principle at traditional PFMEA for automotive industry. As a difference to the quality severity index proposed in AIAGs manual, safety severity index may have more than one scenario. Therefore, these scenarios will be attached to crisp values which belong to the interval (1-10) as it is presented in Table 5.1.

Table 5.1. Scenario based table for safety severity index.

Safety severity index (S_S)	**Scenarios**
10	Multiple deaths
9	Death
8	Multiple very heavy persistent consequences/persistent disease
7	Very heavy persistent consequences/persistent disease (disability, etc.)
6	Multiple persistent consequences/persistent disease
5	Persistent consequences/persistent disease (loss of eye, finger, hand, etc.)
4	Bigger fractures/heavier disease (without permanent)
3	Easier fractures/respite disease (without permanent)
2	Cuts/lacerations (first aid)
1	Scratches/contusions (negligible)

5.1.2 Cost aspect of severity index

Cost aspect of the failure effect (named cost severity index) was highlighted as a problem almost immediately after introduction of AIAGs manual in 1993. This problem first was introduced by Gilchrist in 1993 [76]. Gilchrist proposed mathematical model for costs in FMEA based on probability. He proposed three different scenarios for this mathematical model, also. In Gilchrists model some constraints were presented. These constraints were solved by Ben-Daya and Raouf (1996) [77]. Braglia (2000) [73] included expected cost into risk prioritization and used AHP to rank weight of each index including the cost index. Kmenta and Ishii (2004) [78] proposed scenario-based FMEA based on cost of failure during the whole life cycle. Rhee and Ishii (2003) [44] proposed *Life cost-based* FMEA with few constraints and a year later they upgraded proposed constraints. They used empirical data and *Monte Carlo* simulation to improve reliability and serviceability at FMEA. Tarum (2001) [79] proposed in construction of possible costs related to automotive industry, but only for decision making. He did not include costs into traditional RPN. D'Urso et al. (2005) [80] proposed new risk priority indices with time and cost included. Dong (2007) [33] used fuzzy utility theory for cost estimation. He also modified Gilchrists mathematical model. In his new calculation the expected cost is in increase when probability that failure will occur is in increase and probability that failure will be detected decreases. Chin (2008) [30] developed expert system based on fuzzy FMEA. He included cost into decision making, also. Von Ahsen (2008) [81] criticized Gilchrist model that it is impossible to include it into traditional RPN. She proposed a new mathematical model for cost estimation for FMEA. Hassan et Al. (2009 & 2010) [82, 83] proposed *activity-based costing* method for cost identification at cost-based FMEA. In later work, they added QFD method, also. Carmignani (2009) [84] proposed a new mathematical model for cost estimation. He changed traditional risk indices by new one, with new calculation formulas. He pondered these three indices by subjective opinion. Carmignani first proposed a mathematical model for improvement estimation and available budget for improvements. Vintr and Vintr (2009) [85] proposed an approach for warranty cost assessment at FMEA. This study continued Dong's previous work. Unlike Dong, they use available budget for improvements as Carmignani. Popović et al. (2010) [86] included costs for decision making during the FMEA fulfilment related to traffic. Abdelgawad and Fayek (2010) [87] used quality, cost and time instead of S index. They used fuzzy and AHP for pondering and decision making, also. Zammori and Gabbrielli (2012) [72] integrated costs into S index using AHP and ANP. Lillie et al. (2015) [88] used chart with scale from 1 to 5 to integrate cost in severity. They included implementation costs as well as return of the investment. Rezaee et al. (2016) [89] used costs for decision making separately from RPN, for processing industry purpose. Tazi et al. (2017) [90] used hybrid cost-FMEA approach for wind turbine reliability analysis. Banduka et al. (2017) [91] extended traditional RPN pattern with two additional coefficient. One based on cost priority and another on product priority. This research was extended research on previous work from 2016 where product priority coefficient was originally founded [92]. Guinot et al. (2017) [93] developed a ranking scale in order to relate S and O rank to cost consequence. They also used *Monte Carlo* simulations to determine the cost of external failures that resulted as the cost factor at each severity level and the number of instances at each level of occurrence varied.

Most of the proposed research replaces traditional RPN with a new RPN index. Some of them replace S, O and D indices with other indices, as well. Therefore, it could be said that this research leaves traditional PFMEA framework for the automotive industry.

PFMEA is preventive method for failure detection and prevention, but it is a living document as well. Therefore, cost influence can be observed during the both preventive and corrective phase.

5.1.2.1 Preventive phase

There are two ways for definition of the cost aspect of severity index. The first one is based on different scenarios. The second one is more of a traditional type, based on Gilchrist's cost model from 1993.

First way for definition of cost severity index of failure effects is proposed by special table with 10 different scenarios (see Table 5.2).

Table 5.2. Scenario based table for cost severity index.

Cost severity index (S_C)	**Scenarios**
10	Cost from lawsuit due to physical injuries/disability/death of employees, customers or consumers due to failure mode
9	Cost from lawsuit because of delivery of defective (dysfunctional) products/cost from lawsuit because of damage to equipment, products, infrastructure of the customer
8	Costs due to loss of profit if customer does not want to take or buy reproduced products/costs of declining reputation/costs of declining number of clients
7	Warranty costs (reproduction, transport, administration, etc.)
6	Costs of line/production stop of customers production
5	Costs of line/production stop of own production
4	Costs of backup on previous state of production (labor, material, time, equipment availability, etc.)/costs of replacement of defected products with new one/additional costs to suppliers and additional costs of transport
3	Costs of scrap and reproduction
2	Costs of rework
1	No costs/negligible

Table is adapted according to the traditional table for definition of severity index for PFMEA for automotive industry proposed by AIAG. Cost scenarios are defined according to the usual costs appearing in the industry from the production process to the delivery of the products to the customers, but also based on literature review related to costs-based FMEAs. The first five scenarios are determining costs related to the failure occurrence before defective product passes the production process. These costs may be defined as internal costs. Internal costs are cost usually appeared due to: rework, scrap, reproduction, costs of resetting of the production line on previous state for reproduction (like labor, loss of time, material, etc.), etc. Scenarios from 5 to 10 are related to scenario when product/s pass a production process in company and arrive to the customer/consumer. These costs may be defined as external cost. External costs appear due to: warranty, lawsuits, loss of profit, loss of market, loss of customer, etc. As in case for safety severity index, cost severity index can have more than one scenario as well.

Another way of cost aspect calculation is more traditional and it is based on cost priority according to the cost caused by failure appearance multiplied by probability that failure will occur. It is very hard (almost impossible) to define costs accurately in the production pre-phase, because they depends on the probability that failure will occur (p_F). Therefore, only expected costs of failure (EC_F) can be defined. In an ideal case, EC_F can be defined by multiplying all costs related to failure (C_F) with p_F (see Equation 2). Costs are defined as the sum of all internal costs (C_{FI}) and external costs (C_{FE}) of failure (see Equation 3).

$$EC_F = C_F * p_F \tag{2}$$

$$C_F = \sum_{i=1}^{n} C_{FIi} + \sum_{i=1}^{n} C_{FEi} \tag{3}$$

Gilchrist [76] also included in this pattern for costs the probability of failure detection (p_D). Gilchrist's pattern was later modified by Dong in 2007 [33]. Dong pointed out that EC_F increases when failure occurs more frequently and is less possible to be detected. This claim is true, but there is a problem in pattern for definition of costs, because if p_D is equal to 1, than the expected costs would be 0, which is incorrect. It is correct for C_{FE} because failure will not affect a customer, but failure still occurs and C_{FI} are present. In any case, p_D should be important only because of C_{FE}. Ideally, if p_D is on 100%, C_{FE} will not occur, because failure will not pass out of the production process. But there is still the possibility that C_{FI} will occur. Therefore, two different scenarios can appear:

1. The scenario in which D≤5 (from the table defined by AIAG in 2008 [21]). From 1 to 5, the values of the D index defined by AIAG, the likelihood of detection, are defined by automatized control, which means that failure will not pass to the customer. Therefore, only C_{FI} should be included in this pattern (see Equation 4).
2. The scenario when D>5 (from the table defined by AIAG in 2008 [21]). From 5 to 10, the values of D index as defined by AIAG, the likelihood of detection is defined by non-automatized methods, usually by the operator using visual/audible/tactile means,

attribute gauging, variable gauging, and the like, which means that failure may pass to the customer. As such, both C_{FI} and C_{FE} should be included in this pattern (see Equation 5).

$$EC_F = \sum_{i=1}^{n} C_{FIi} * p_F \tag{4}$$

$$EC_F = \sum_{i=1}^{n} (C_{FIi} + C_{FEi}) * p_F \tag{5}$$

Therefore, by these two scenarios, p_D can be excluded from the pattern. p_D is hard to define as there is no proper measure to define it.

Another problem is p_F. This variable is relative and cannot be precisely defined. It can be predicted approximately according to the historical data of similar failures or by expert opinion, for example. p_F can be defined in both preventive and corrective phase.

During the preventive phase before production starts, failures are defined by qualitative assessment (based on expert opinions, historical data, other products, etc.). According to this, it can be concluded that EC_F can be predicted only in the preventive phase. Costs measured during the corrective phase are real and can be precisely defined, but it is still difficult to predict them. The preventive phase is the more important, while the corrective phase is for alternative measuring of costs and failures.

After the definition of EC_F, C_{IS} still has to be defined. The implementation of solutions can be observed by two aspects:

1. From the aspect in which the S and O indices will decrease, and D index will stay the same.
2. From the aspect in which the D index will decrease, while the S and O indices will stay the same.

The purpose of the solution implementation is to protect a customer from a defective product. The first aspect is better and more profitable for the company but is usually more complicated and expensive. The second aspect is also reliable but failure may still occur and the basic problem is not solved. For the implementation of some solutions, C_{IS} should first be identified. After that, it is important to see if that solution is profitable. The profitability of solution (P_S) is defined as a divergence between EC_F and C_{IS} (see Equation 6). If EC_F is less then $C_{IS,}$ than a solution does not need to be implemented and vice versa. P_S cannot be defined precisely because it is dependent of $EC_{F,}$ which is hard to predict, while C_{IS} is easy to define. P_S can be precisely defined at the end of the production of a specific product to which failure is related.

$$P_S = EC_F - C_{IS} \quad (6)$$

The implementation of solutions and profitability of solutions was first introduced by Carmignani [76]. He also included an available budget for the implementation of solutions. This is not necessary because the solution is implemented if it is profitable or if it is important for company. As such, a minimal budget per failure should be equal to P_S value to implement solution. This budget constraint cannot be applied for all products. There are products in a company which are more important strategically to the company or simply more profitable compared to other products. The division of products can be done by using a Pareto analysis (principle 80/20) [83, 84]. For application of Pareto analysis on products, database with all products is needed. If a product belongs to a small group of products which gives the biggest part of the profit to the company, then the available budget should not be counted. Implementation must be conducted anyway. If the product belongs to a bigger group of products that gives a smaller part of profit to the company, then the solution implementation availability (I_A) should be checked as a divergence of available budget (B) with C_{IS} (see Equation 7). The availability of implementation may have two different scenarios:

1. If I_A is less than 1, then solution should not be implemented
2. If I_A is more than 1, then solution should be implemented

$$I_A = B - C_{IS} \quad (6)$$

The cases with budget should be practiced only when the company has a budget constraint. In the ideal case, all profitable solutions should be implemented immediately.

5.1.2.2 Corrective phase

The corrective phase is the phase of production process in which failures can be monitored and measured all the time. This way to define p_F is quantitative and is based on real data. In the corrective phase, costs of failure can be measured during the time (see Equation 7). Sum of costs related to one failure (C_F) is equal to sum of all internal and external costs related to failure (C_{Fi}) multiplied by amount of failures occurred during the production process (A_F). The importance of prediction for costs and failures decreases when time increases, or when production goes on. This case can be applied for the profitability of solution during the time (P_S), as well (see Equation 8). Time factor is realistic and measurable. It can be defined as a divergence between total amount of products to be produced with the number of currently produced products. This factor is just used to highlight number of product still to be produced in order to make decisions better.

$$\sum C_F = \sum_{i=1}^{n} C_{Fi} * A_F \tag{7}$$

$$P_S = C_F - C_{IS} \tag{8}$$

In the corrective phase implementation of solutions as well as profitability depends on time factor. When more products are produced it is bigger chance that implementation of solution will not be profitable for a company. Recommendation is to implement solution as soon as it is possible. The ideal case is to implement solution before production starts or after first failure appearance.

5.2 Mathematical modelling of the relative importance between new severity indices

Respecting to results of a good practice, each business process, but especially a production process has predispositions for occurrence of one or more failures during the time. Generally, identified failures may be presented by the set of indices *I*={1, …, i, …, I} where *I* presents the total number identified failures, and the index of each failure is denoted as i, *i*=1, …, *I*. It may be comprehended that the realization of each failure *i*, *i*=1, …, I could lead to the occurrence of one or more failure effects that may be generally presented with the set of indices J_i={1 …, j_i, … J_i} where J_i presents the total number of failure effects occurring during the failure mode *i*, and the index of each identified effect is j_i. Generally, failure effects for each failure i, i=1,…, I, are determined according to evidence data and the results of the best practice.

The failure effects of identified failures have different degrees of seriousness and heaviness. In traditional PFMEA, assessment of severity of failure effect is considered with respects to quality and partially safety. It can be assumed that severity influence factors (safety, quality and cost) are not with the same relative importance. Also, they can be considered as unchangeable at the level of automotive industry. Generally, the relative importance of severity indices should be defined at the level of each failure effect and each failure. Some authors are suggesting that is more precise and more suitable to human decision-making nature to consider each of the severity indices separately during the relative importance estimation between indices. In conventional AHP [94], decision makers map estimations to precise numbers. Using the common measurement scale is simple and easy, but it is not sufficient to take into account the uncertainty associated with the mapping of one's perception to a number [95].

In this subchapter, a fuzzy PFMEA approach with respect to safety, quality and cost, is presented. The modification is performed into:

1. Severity index is determined with respect safety severity index, quality severity index and cost severity index.
2. Each failure can occur to one or more failure effects under each severity index.
3. These indices have a different relative importance and they are modelled by using the fuzzy set theory [96, 97].

By applying fuzzy sets theory, uncertainties may be described very well. Many authors suggest triangular fuzzy numbers (TFNs) for modelling uncertainties [98, 99]. Therefore, TFNs offer a good compromise between descriptive power and computational simplicity. Existing uncertainties are modelled by using TFNs.

Decision makers express their judgments far better by using linguistic terms precise numbers. The number of linguistic expressions is determined by decision makers with respects to kind and size of considered problem. Five pre-defined linguistic expressions which are modelled by TFNs are used:

- Very low importance (VLW) – (1, 1, 3.5)
- Low importance (LW) – (1, 2, 5)
- Medium importance (MW) – (1, 3, 5)
- High importance (HW) - (1, 4, 5)
- Very high importance (VHW)– (2, 5, 5)

The domains of these TFNs are defined into the common measurement scale (1-5) [96, 97]. The value 1 i.e. the value 5 denotes that relative importance of severity index k according to severity index k' , k,k'={1, …, K} is the lowest, i.e. the highest, respectively. It should be noted that big matches of defined TFNs implying the decision makers do not have enough data or knowledge and experience about severity index. One of the reasons may be the fact that safety aspect of severity index is not well explained in traditional severity table of PFMEA for the automotive industry.

According to above introduced assumptions, the relative importance of severity indices is stated by the fuzzy pair-wise comparison matrix. It is assumed that decision makers made decision by consensus. The elements of constructed matrix are denoted in Equation 9 *with* the lower and upper bounds $l_{kk'}, u_{kk'}$ and modal value $m_{kk'}$, respectively.

$$\tilde{W}_{kk'} = \left(l_{kk'},\ m_{kk'},\ u_{kk'} \right) \tag{9}$$

If high relative importance of severity index k' holds, then the pair-wise comparison scale can be represented by the TFNs (see Equation 10).

$$\left(\tilde{W}_{kk'} \right)^{-1} = \left(\frac{1}{u_{kk'}}, \frac{1}{m_{kk'}}, \frac{1}{l_{kk'}} \right) \tag{10}$$

As decision makers may make errors in judgments. Therefore, it is important to be tested, how many occurred errors influence on estimation accuracy. In other words, to check if mentioned errors are acceptable or not. This decision is based on respecting of the value of consistency coefficient (C.I.). If C.I. is equal or less than 0.1 it can be assumed that errors assessment is acceptable. Therefore, determining of the weights vectors of severity indices should be based on the stated fuzzy pair-wise comparison matrix.

5.3 mathematical approach to risk prioritization

In this subchapter, new mathematical approach to risk prioritization by combining Fuzzy AHP (Chong's) with Order Weighted Aggregation (OWA) operator is presented. Basics of Fuzzy AHP and OWA will be introduced first. Then, in order to achieve better risk prioritization, the combination of both will be presented.

5.3.1 Fuzzy AHP

Fuzzy AHP was first introduced by Laarhoven and Pedrycz in 1983. Need for this hybrid method has appeared due to need to overcome constraints of AHP related to impression and subjectivity in the pair-wise comparison process. Fuzzy AHP does not use crisp values. It uses a range of values in order to incorporate the decision maker's uncertainty. There are four prominent Fuzzy AHP approaches [100]: firstly introduced Van Laarhoven and Pedrycz's approach, Buckley's fuzzy AHP approach, Chang's extent fuzzy AHP approach (used in this chapter), and Fuzzy AHP with entropy values. Detailed calculation process for mentioned Fuzzy AHP's, literature [100] should be checked.

5.3.2 Order Weighted Aggregation (OWA)

OWA was first introduced by Yager in 1988. Purpose of OWA is to aggregate multicriteria form to the form of overall decision function. Primary function of OWA is to determine relationship between involved criteria. There are usual two situations to be satisfied. One is when all criteria should be satisfied and another is when any of criteria should be satisfied. In both situations are used operators such as “and” and “or” in order to combine criteria functions. Formulation of the aggregation may be more detailed in literature overview [101].

5.3.3 Combination of Fuzzy AHP and OWA for better risk prioritization

RPN definition by using the new mathematical approach which is proposed in this subchapter can be realized through the seven following steps (see Figure 5.1)

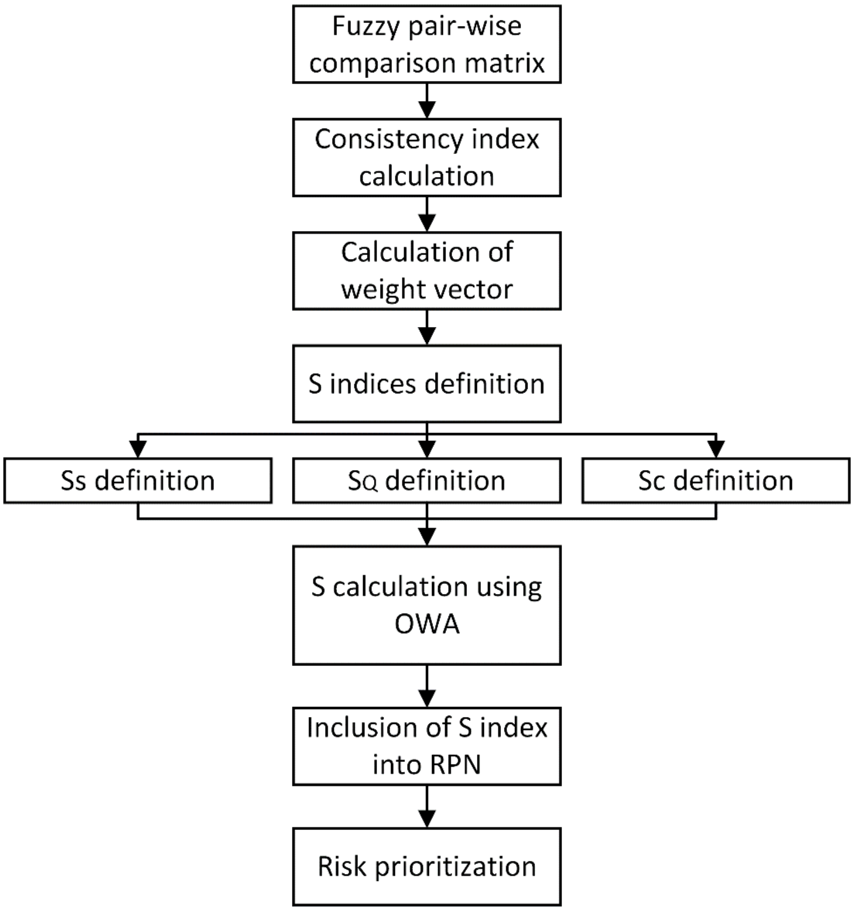

Figure 5.1 Flow chart of the steps taken for risk priority definition.

Step 1. The fuzzy pair-wise comparison matrix of the relative importance of severity indices is constructed (see Equation 11).

$$\left[\tilde{W}_{kk'}\right]_{3x3},\ k,k'=1,...,K;k\neq k \qquad (11)$$

Step 2. The fuzzy pair-wise comparison matrix is mapped into the pairwise comparison matrix and the coefficient consistency is calculated by using the *eigenvalue* method.

Step 3. The weights vector is calculated by using extent analysis (see Equation 12) [102].

$$[w_k]_{1xK},\ k = 1,..,K \tag{12}$$

Therefore, the elements of weights vector are crisp.

Step 4. The severity indices definition for all failure effects occurring during failure mode *i, i=1,..,I* . It can be assumed that each severity index should be assigned value of the worst scenarios (see Equation 13).

$$S_{ik} = \max_{j=1,..,J_i} S_{ijk} \tag{13}$$

Step 5. Calculate the severity index by using (Order Weighted Aggregation) OWA operator [101] (see Equation 14):

$$S_i = \sum_{k=1}^{K} w_k \cdot S_{ik} \tag{14}$$

Step 6. Determine value of RPN for failure modes *i, i=1,…I* (by analogy traditional PFMEA) (see Equation 15):

$$RPN_i = S_i \cdot O_i \cdot D_i \tag{15}$$

Step 7. Failure priorities should be set according to the highest RPN value.

5.4 A case study

A case study is realized in order to test new approach. For this purpose, one automotive company has been chosen—a company producing leather upholstery for automobiles. Company is located in the Central Europe region in republic of Serbia. Company is suited by appropriate international standard for automotive industry – IATF 16949. Company uses PFMEA in order to determine risks on failure occurrence and improve reliability of the product during the production process. PFMEA is realized by using reference manual proposed by AIAG.

This case study was conducted according to the flow chart from Figure 5.2. A multi-disciplinary team from different sectors was formed first. Decision makers make decisions by consensus. For realization of this case study, it is very important that team decision makers stay the same for both (traditional and new approach) PFMEA trials, with possibility for inclusion of additional team members if some more information is needed. Traditional PFMEA for specific product is realized on traditional way. For PFMEA conduction ten failures are selected (see Appendix I). Seven failures (i=1, i=2, i=3, i=4, i=6, i=7, i=8) are standard failures occurring during production process, while other three failures (i=5, i=9 and i=10) contain a criticality aspect caused by possibility to lead to critical consequences with endangered safety. Achieved data from PFMEA realization are presented in Appendix I.

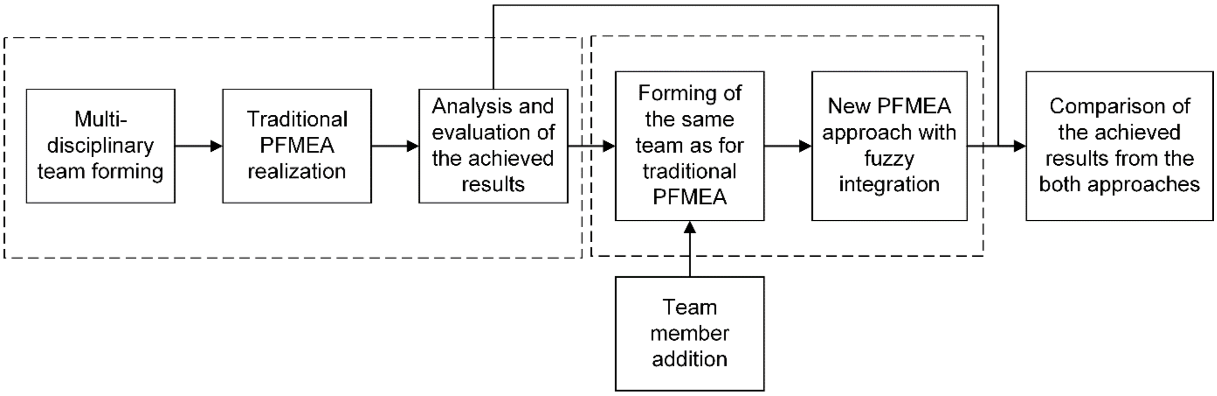

Figure 5.2. Flow chart for a case study.

According to the before proposed Algorithm (Figure 5.1), (Step 1) the fuzzy pair-wise comparison matrix is constructed (see Equation 16).

$$\begin{bmatrix} \tilde{1} & 1/LW & MW \\ & \tilde{1} & HW \\ & & \tilde{1} \end{bmatrix} \tag{16}$$

Consistency check for the stated fuzzy matrix and determination of weights vector is given by using the procedure (Step 2 to Step 3 of the proposed Algorithm) (see Equation 17):

$$\begin{bmatrix} 1 & 0.37 & 5 \\ & 1 & 6.67 \\ & & 1 \end{bmatrix}, \text{C.I.}= 0.003 \tag{17}$$

The weights vector is (respectively for S_S, S_Q and S_C): $[0.59, \quad 0.30, \quad 0.11]$

It is assumed that failure mode *i*, i=1, …, I leads to the appearance of one or more safety-based scenarios and cost-based scenarios. Determination safety severity index and cost severity index is based on procedure (Step 4 to Step 5 of the proposed Algorithm). The proposed procedure is illustrated by example of failure (*i*=5). According to opinions of decision makers, failure mode (*i*=5) leads to the appearance of from the second of the tenth safety-based scenarios and from sixth to tenth cost-based scenarios denoted.

The severity index of failure effect (i=5) is given by OWA operator (Step 6 of the proposed Algorithm) (see Equation 18):

$$S_5 = 0.34 \cdot 2 + 0.39 \cdot 5.95 + 0.27 \cdot 7.95 = 5.147 \quad (18)$$

Other chosen failures are calculated on similar way as for severity index.

RPN for each of the failures *i*, i=1, …, I is calculated by applying procedure which is developed in traditional PFMEA (Step 7 of the proposed Algorithm). For failure (*i*=5), RPN is (see Equation 19):

$$RPN_5 = 5.147 \cdot 2 \cdot 2 = 20.588 \quad (19)$$

It should be noted that quality severity index is determined according to the severity table for automotive industry [21].

According to these results the rank of identified failures is determined. At the first place in the rank, there is failure with the highest value of RPN. Similarity, failure with the lowest value of RPN is placed in the last place in the rank. The obtained results by using traditional PFMEA and the new approach are presented in Table 5.3.

Table 5.3. Range of the failures on both; "traditional" and "new approach" ways of conduction.

Failures	RPN obtained by traditional way	Traditional PFMEA rank	RPN obtained by using the new approach	New approach rank
i=1	36	7-9	13.44	9
i=2	36	7-9	14.10	8
i=3	108	1	42.30	3
i=4	105	2	39.75	4
i=5	36	7-9	37.64	5
i=6	42	6	15.24	7
i=7	28	10	9.72	10
i=8	54	5	19.17	6
i=9	60	3-4	60.00	1
i=10	60	3-4	58.68	2

Obtained results are addressing few differences between Traditional PFMEA for automotive industry and new approach:

1. The first important difference is in the ranking of failures. With traditional approach failures (i=1; i=2 and i=5) and failures (i=9 and i=10) have the same rank, which can be very problematic for decision making. While with new approach was no matching.

2. The second thing is that hidden criticality risks noticed at failures (i=5; i=9 and i=10) boosted priority in ranking. The most critical failures (i=9 and i=10) moved on the first and second place, while the failure (i=5) decreased from (7-9th) on 5th place. Therefore, it could be said that new approach is better to deal with failures with hidden risks.
3. The third noticed thing is that RPN obtained by new approach was significantly reduced, compared with traditional approach, so it can be a problem for decision makers. Recommendation by AIAG is that failures should be always controlled and reduced, but especially when RPN exceeds value 100 [21]. Users in automotive industry often consider that failure is not critical if some of the S, O and/or D indices exceed value 8 or RPN value 100, which can be a big problem because of hidden risks. Therefore, it can be concluded that AIAGs recommendation that risk has to be reduced when RPN exceeds value 100 is not relevant and it just make confusion to users.

5.5 Chapter conclusion

In this chapter a new approach which present extension (in the matter of safety and cost) of the PFMEA for automotive industry proposed by AIAG, is presented. By using the new approach, RPN index of each identified failure and priorities of failures can be determined. Based on the obtained results, management team may define appropriate activities that should lead to a decrease of risk during the production processes which is further propagated to the long term sustainability.

The fuzzy assessment of the relative importance of the severity indices and their values is performed by the management team. The assessments of decision makers are presented by linguistic expressions in a more precise way, rather than by precise numbers. These linguistic expressions are modelled as triangular fuzzy numbers. The proposed model was tested in one automotive company.

Comparing to analyzed papers, models, the new approach has important following advantages. Calculation of severity index depends on three indices safety, quality and cost which have a different the relative importance. The relative importance is stated by the fuzzy pair-wise comparison matrix. The weights of severity indices are calculated by extant analysis. Respecting to knowledge and results of the best practice for the automotive industry, new safety-based scenarios and cost-based scenarios are proposed. Each scenario is assigned with crisp values. At the same time, the proposed model in this paper enables ranking of failures in automotive company (which gives support in selecting of appropriate management actions).

This new proposed model mostly contributes in decision making during the risk selection, but it is very complex and practically hard to apply without some automatized or software solution.

The main contributions of the proposed model are:

- New tables (related to cost and safety) adapted to traditional severity table for automotive safety are invented.
- Three new severity indices are invented (safety severity index; quality severity index and cost severity index).
- The relative importance of defined severity indices is given by using the Fuzzy AHP.
- The severity index weight is aggregated by using the OWA operator.
- The considered problem may be described by formal language that enables the calculating of RPN by an exact method.
- All the changes, as with the changes in the number of failures can be easily incorporated into the model.

The general limitations related to the new approach can be sorted in two groups:

1. Limitations of the new approach.
    - New approach is complex and time-consuming as well as other models which combine fuzzy sets theory and FMEA. This constraint is recognized in the literature as well. Therefore, some automatized solution is needed in order to overcome this problem.
    - Fuzzy rating of the relative importance of severity indices depends on knowledge and experience of decision makers.
    - Sometimes failure effect does not have safety consequence, but this factor is still taken into consideration during the risk evaluation.
    - Main severity index obtained by combining other three new severity indices do not have the same weight as O and D indices. But in this model, as well in the case study is taken into account that these three main S, O and D indices have the same value of importance.
    - Hidden risks of S, O and D indices are highlighted even in RPN which is given by using the new approach.

- Time is not taken as a risk factor in severity index and it would be very hard to find a way to define it.

2. Limitations caused by following of AIAGs traditional framework for PFMEA for automotive industry:
   - Risks obtained by new approach have low values, which can confuse users because border line when risk must be reduced is when RPN have value more than 100. This model is making prioritization of the risks, but it must be counted that all risks must be reduced.
   - Quality severity index is based on severity index proposed by AIAG. This table for severity contains two scenarios of safety aspect in severity values 9 and 10. This is not necessary because specialized index for safety severity is invented. But modification of quality severity index will cause exceeding of the traditional PFMEA framework for automotive industry.

In general, this new approach presents important ground work for quantitative approaches in measurement and ranking of failures in the automotive industry. The further research should include:

- Finding a way to adapt the proposed model in other industries and areas.
- From the traditional PFMEA severity table, safety aspects should be excluded and new quality severity table should be invented.

6. COMPREHENSIVE SOFTWARE SOLUTION FOR PFMEA IN AUTOMOTIVE INDUSTRY

Software and automatized solutions for FMEA were popular in the past, as well as nowadays and according to the some authors will be very popular in the future. Industrial concepts of the future like Industry 4.0 are based on digitalization and connection of everything in industry. Therefore, it could be said that software solutions for FMEAs are future toward industry 4.0 and other world popular industrial concepts of the future.

According to the fact that FMEA is time-consuming and robust for conduction, many authors are proposing comprehensiveness as a solution. FMEA software may be comprehensive solution to simplify FMEA and to integrate risk estimation and evaluation and procedural improvements proposed by many different authors. FMEA software can integrate and comprehend all improvement solutions, decrease level of time-consuming during the FMEA report fulfillment, decrease complexity during the decision making, increase data accuracy, etc.

The newest review study comprehended software patents and solutions which are increasing [57]. 109 patents were overviewed, where 23 of them are coming from academia and other 86 from industry. In review study software and automatized solutions proposed by many authors during the period from 1993 until 2012, were presented (see Table 6.1) [8].

Table 6.1. Review on software and automatized FMEA solutions.

Authors	Methodology	Year
Hunt et al. [103]	Functional modelling system	1993.
Russomanno et al. [104]	Artificial intelligence	1994.
Hunt et al. [105]	Automatized FMEA and functional modelling	1995.
Wirth et al. [106]	Knowledge-based system	1996.
Price et al. [107]	Diagnostic system	1997.
Hawkins i Woollons [108]	Functional modelling system	1998.
Huang and Mak [109]	Internet	2000.
Price i Taylor [110]	Automatized FMEA	2002.
Teoh and Case [111]	Knowledge-based system	2004.
Teoh and Case [25]	Automatized FMEA	2005.
Chin [30]	EPSD-1	2005.
Kurtoglu and Tumer [112]	FFIP	2008.
Li et al. [113]	Knowledge-based system	2009.
Ebrahimipour et al. [114]	Oncology based system	2010.
Noh et al. [115]	MFP	2011.
Gan et al. [116]	Automatized FMEA	2012.

Hunt et al. (1993) [103] has presented a program for automatized prediction of failure effects which appear at automobile electronic system for automobiles. This solution contains 5 possible ways for problem solving and data library. They are both integrated into architecture of distribute reasoning. Russomanno et al. (1994) [104] connected FMEA procedure with different artificial intelligence methods, which makes computer process simulations much easier. Hunt et al. (1995) [105] has developed FMEA software prototype with option of functional system modelling based on results achieved from basic structural simulator. Wirth et al. (1996) [106] proposed WIFA project based on knowledge and knowledge-based FMEA for presentation of knowledge related to functional standard and system at FMEA. Price et al. (1997) [107] has connected functional reasoning with structural reasoning in order to conduct safety analysis for electrical design. For this purpose, automatized FMEA system has been developed. Hawkins and Woollons (1998) [108] has developed graphical model method for quantitative reasoning about behavior of changes at FMEA. Huang and Mak (2003) [109] proposed FMEA approach based on Web used to collect FMEA data on internet for FMEA information in distributive conditions. Unlike, FMEA approach based on Web may give better support for FMEA conduction. This approach may be used for involvement of customers/consumers into FMEA conduction as well. Price and Taylor (2002) [110] have used approximate component failure rate in order to identify the most frequent failure combinations for automatized search with the use of simulations. They discovered that important information may be automatically identified from results report. Moreover, it allows easier overview and search for the user. Teoh and Case (2004) [111] give approach of knowledge representation in order to make FMEA model. Also, they included technique for functional reasoning to allow automatic generation FMEA with past data. Year later, Teoh and Case (2005) [25] proposed FMEA generation method known as Failure Mode Analysis Generation for generic application by using minimal amount of information during the conceptual design phase. For this purpose, software prototype is founded in order to manage knowledge and generate reports of FMEA much easier. Chin (2005) [30] developed software prototype ”EPDS-1” which can help inexperienced users with quality and reliability improvement. This software model includes certain costs, unlike previous. Kurtoglu and Tumer (2008) [112] proposed analytical framework for spreading errors and functional determination - Functional-failure identification and propagation. This FMEA approach is based on graphical modelling which causing internal and external interactions between modules in order to identify bigger amount of failures. Li et al. (2009) [113] have presented a formal model of knowledge presentation about failures in order to make FMEA modelling and reasoning much easier. Modeling methodology contained polychromatic sets for failure representation, as well as their causes and effects. In combination with reasoning matrix, this model may be a base for automatization process for failure effect analysis. Ebrahimipour et al. (2010) [114] developed oncology approach for management of FMEA information. Noh et al. (2011) [115] developed model with mode formal functions with failure spreading included. This model is based on modules and they named it Module-based failure propagation. This model is developed in order to solve constraints of previous FMEA approaches It is based on functional decomposition of three model, graphical model of flow configuration, functional rules and failure rules. Gan et al. (2012) [116] have presented a computer integrated FMEA approach for improvement of FMEA for supply chain management needs with automatic processing by using fuzzy approach and computer integrated interfaces (with internet support). This system can help a lot in failure prevention during the design phase, process phase, etc.

The need for software solution for PFMEA in automotive industry was first noticed in research study conducted by Johnson and Khan [7]. They highlighted that there is a space for development of software solutions, especially knowledge based solution. Software solution for automotive industry should be very specifically based. This solution has to satisfy traditional PFMEA framework for automotive industry. Software should contain integrated comprehensive database as well as possibility to integrate some improvements related to PFMEA risk estimation and evaluation and procedural shortcomings.

In this Chapter, a comprehensive database solution adjusted for integration into software solution will be presented. Than comprehensive software solution adopted to automotive industry framework and needs will be shown. This solution will contain a way for integration of procedural and risk estimation and evaluation PFMEA improvements presented in chapter 4 and 5. As completion, chapter conclusion will be given.

6.1 Comprehensive database

The newest research have highlighted the increase of the need of FMEAs specialized database acquisition [50]. Comprehensive database considers database which is modeled to contain all necessary data related to failures. Under these data, the data about product, process, failures, failure causes, failure effects, implemented solutions, etc. are considered. Besides these basic characteristic related to failure, database should be adapted to follow failure occurrence level during the certain process. Nowadays, modern industries contain Enterprise Resource Planning (ERP) systems. This system usually contains failure occurrence. Therefore, FMEA database could be connected with ERP system in order to adapt information about failure appearance during the production process. If there is no ERP system, there is possibility to adapt this data from process manually. This can help a lot to FMEA team during the decision making process related to O index definition.

Block diagram for comprehensive database is presented in Appendix J. This block diagram is also called entity relations (ER) diagram. It is based on 9 entities: failure, requirement, effect, cause, prevention process, detection process, recommended action, process and product. Entities are defined according to basic data from traditional PFMEA procedure for automotive industry. Each entity contains "primary key". Primary key is unique key with each record contains. Entities also contain entity attributes which are painted in grey color. Entities failure and recommended action contains more than one attributes. Entity failure contains: classification, failure mode, severity, occurrence, detection, rpn, standard and genchi genbutsu attributes. These attributes are related to failure. Attributes related to recommended action entity are more related to improvements and failure correction or detection. These attributes are: name, solution, deadline, team member responsibilities, and kaizen. The cause is a specific entity and contains attribute why which belongs to each name attribute of this entity. All entities are connected with main entity with many-to-many relation. This connection is presented by cross foot notation. All data inputted into true software interfaces are gathered in proposed comprehensive database

6.2 Comprehensive software solution

Proposed improvement solutions for PFMEA for automotive industry from chapter 4 and chapter 5, significantly improve certain procedural and risk estimation and evaluation shortcomings of PFMEA for automotive industry. Problem is that these improvements stimulate complexity increase. Additional complexity may lead to the increase of time-consumingness and to appearance of negative consequences in real conditions. In order to overcome complexity and time-consumingness of new improved PFMEA, comprehensive software solution is proposed. Besides database, improvements from chapter 4 and chapter

5 are integrated into software solution as well. Conduction procedure is almost the same as the procedure proposed in chapter 4 – lean approach to PFMEA. Difference is in additional procedure for definition of S index proposed in chapter 5 (see Appendix K).

Software contains main interface with four main options (see Figure 6.1): overview (option for searching of any data collected in integrated database), add failure, add product, and add process.

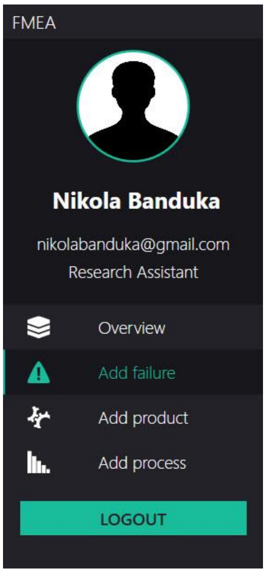

Figure 6.1. Main Software interface.

Option overview (see Figure 6.2) can be used to overview certain information or to check relations between new and existing product, process or failure.

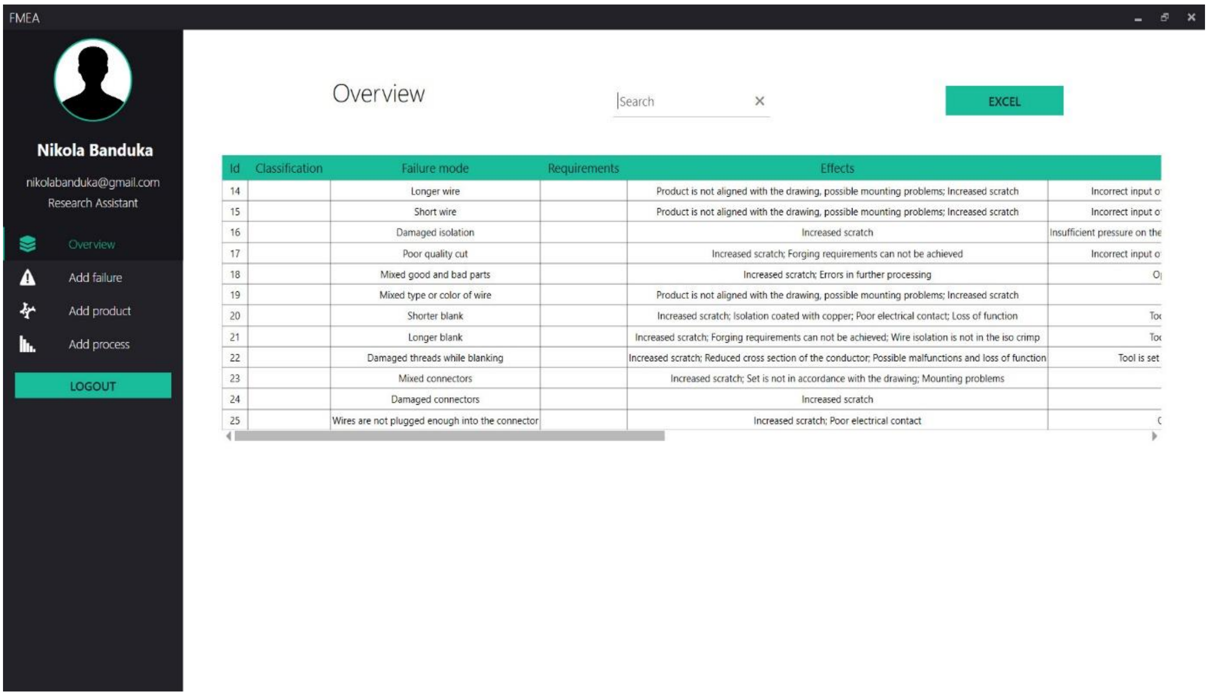

Figure 6.2. Interface related to software option - overview.

According to proposed procedure mentioned in Appendix K, product and process characteristics and relations should be entered. After this basic data about product and process, data about failure are next. This sub interface related to failure (see Figure 6.3) contains all basic data related to failure based on traditional PFMEA form for automotive industry.

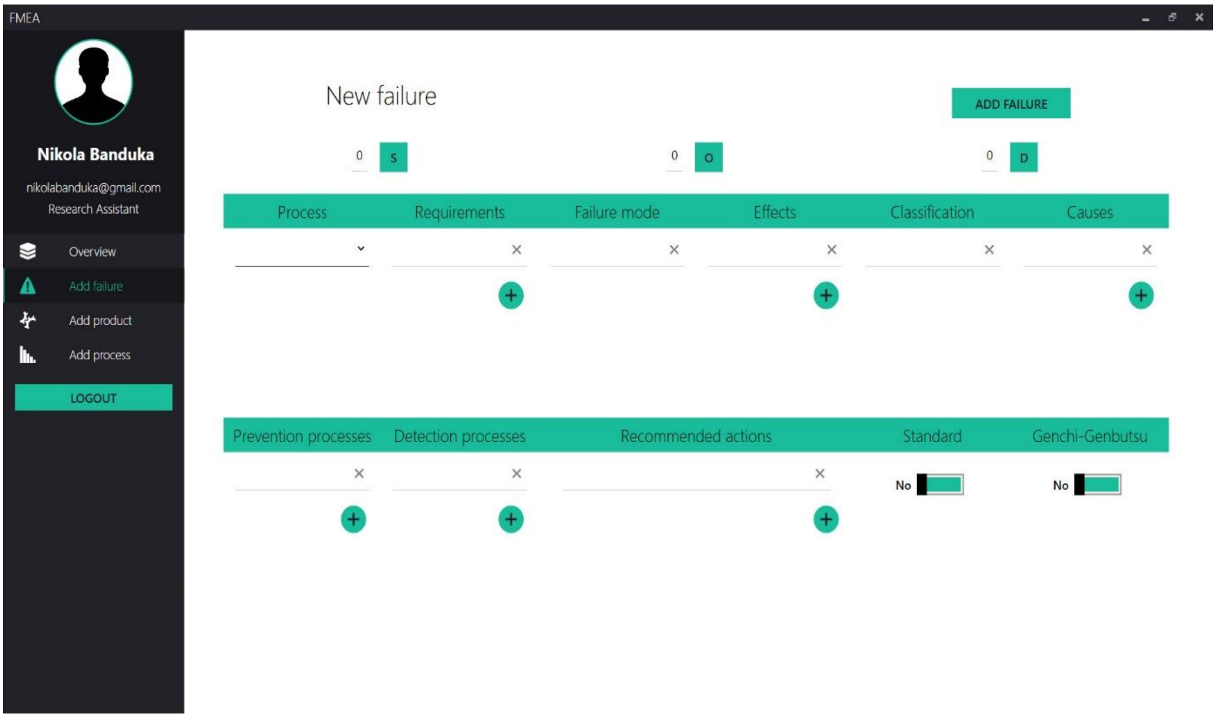

Figure 6.3. Interface related to software option “add failure”.

These data are: Process, Requirements, Failure mode, Effects, Classification, Causes, Prevention process, Detection process, and Recommended actions. In addition to these traditional elements, there are few lean elements added as well. Opening of field Recommended actions redirect user to new sub interface to describe recommended actions related to failure prevention or correction (see Figure 6.4).

After failure definition, definition of S, O and D indices are next. S index definition is improved. Therefore, a special attention will be given to this index in one of the following subchapters. O index is defined according to the table proposed by AIAG (See Figure 6.5). One more characteristic thing for O index is the connection with database. By updating data from process, O index is changing. This keeps PFMEA up to date. This database advantage can be used for decision making, as well. Especially, when new product is presented or when new failure appears.

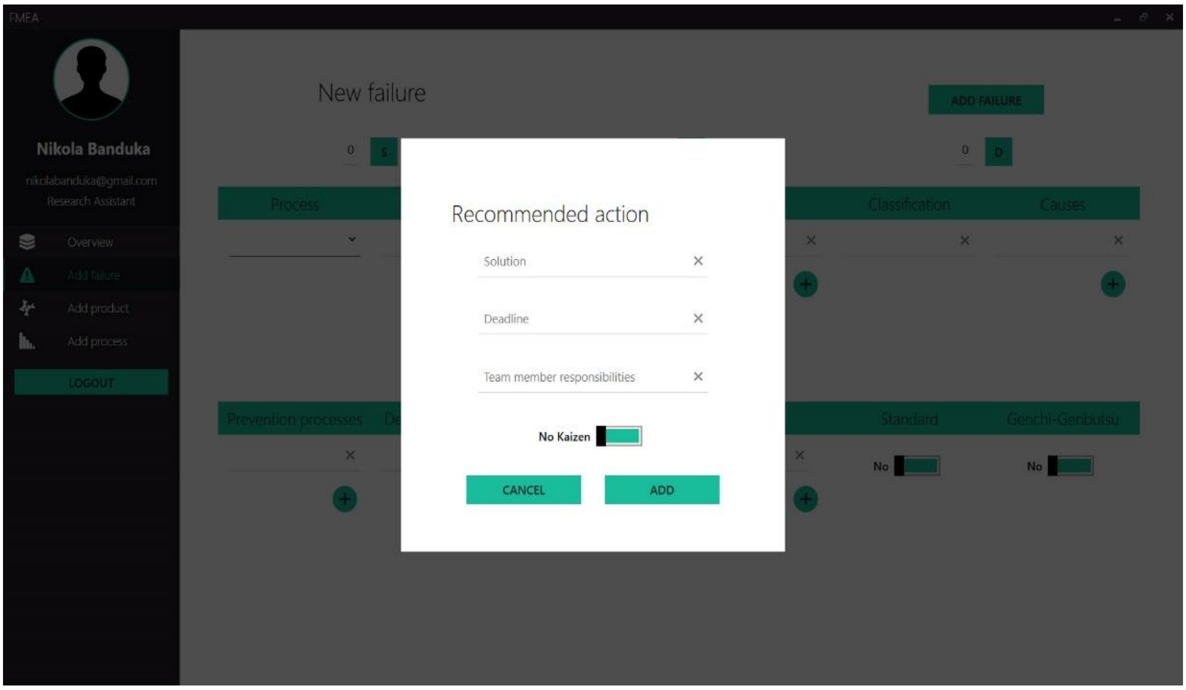

Figure 6.4. Sub interface related to field recommended action.

Figure 6.5. O index interface.

D index is defined in the same way as O index (see Figure 6.6) according to the table proposed by AIAG. D index has an additional protection option related to lean, which will be presented in one of the following subchapters. More or less, lean integrated approach to PFMEA is an extension of traditional PFMEA for automotive industry. Therefore, main focus will be on the innovations in this software solution.

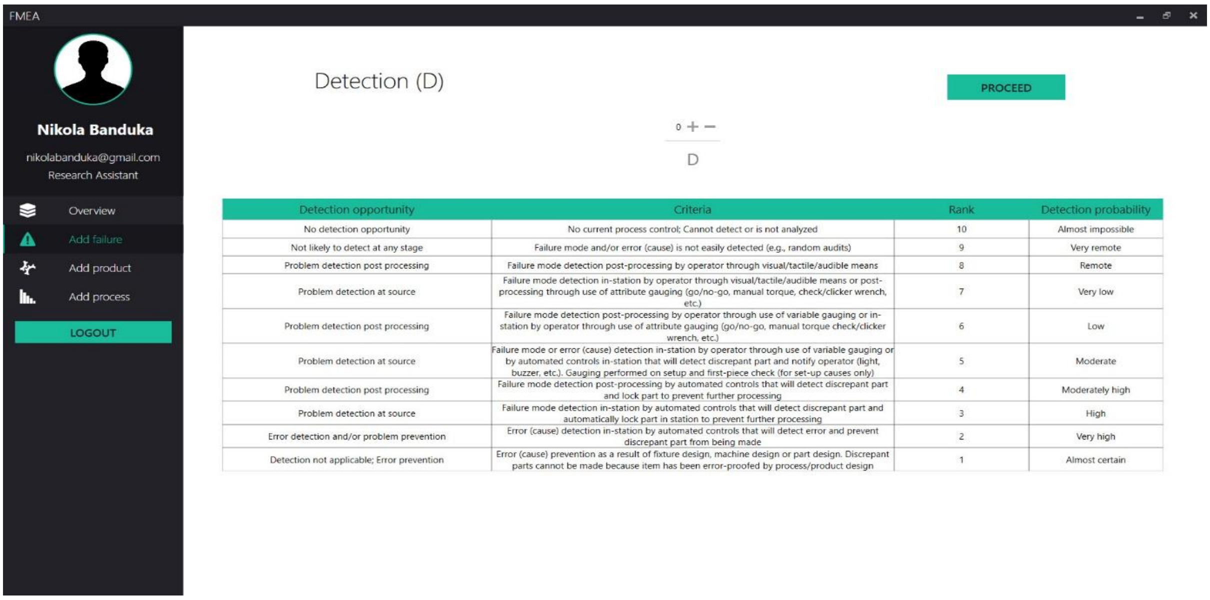

Figure 6.6. D index interface.

6.2.1 Integration of PFMEA with integrated lean approach into software solution

This integration is based on integration of algorithm proposed in Appendix F into software solution in order to make PFMEA with integrated lean approach more user-friendly. Integration of this new approach into software solution decrease robustness of PFMEA procedure and report. It makes standardization much easier, as well. There are few lean elements integrated into software solution: *Genchi Genbutsu,* standardized work, "5 why?" technique, *Jidoka*, and *Kaizen*.

- In Figure 6.3 *Genchi Genbutsu* switch can be noticed, which shows if PFMEA is conducted on the place where process will be done (or is done), or in the office (or some other place). This option is connected with database as well, in order to collect data for statistical analysis.
- Standardized work or, in this case standardized failure is based on the same principle as *Genchi Genbutsu* lean element (see Figure 6.3). If new failure is at some point related to standardized failures, than is not necessary to duplicate failures. This also saves a considerable amount of time for PFMEA team.
- "5 why?" technique is integrated in the field causes. There are lot sub tabs available for input data related to field cause (see Figure 6.3). Therefore, identification of the root causes can be done by statistical analysis of existing data. Cause contains specialized sub interface with 5 why options (see Figure 6.7)

- *Jidoka* is integrated in part of software solution related to D index definition. According to the table proposed by AIAG, if D index value passes 5, then D index is not prevented by automatized solution. This solution is integrated in D index definition and it is not visible on software interface as before mentioned solutions. It is visible like a pop-up[16] (see Figure 6.8).
- *Kaizen* is proposed as a switch option in filed Recommended action (see Figure 6.4). There is a way to do traditional failure prevention or correction and kaizen way. Main difference is that kaizen workshops lead failures to standardized solutions.

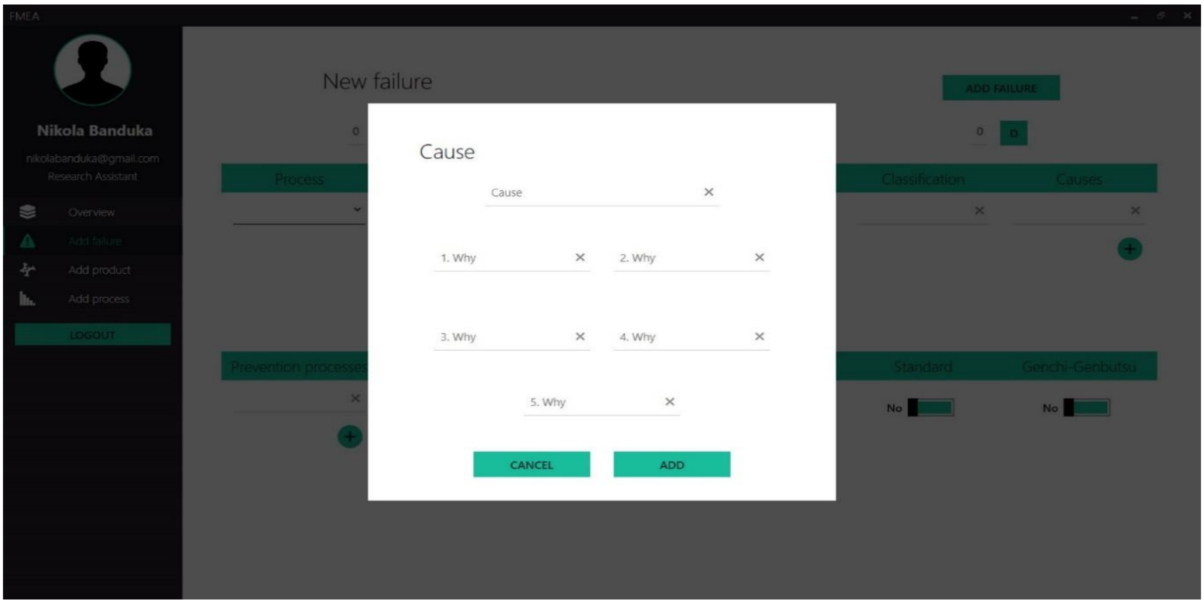

Figure 6.7. Sub interface related to cause – 5 why.

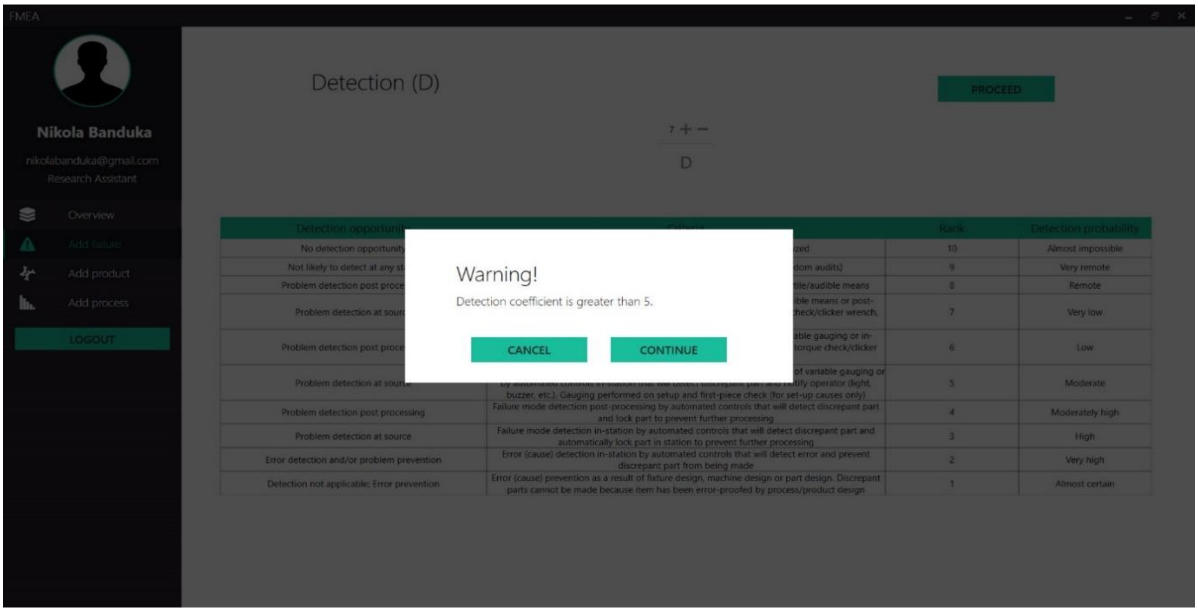

Figure 6.8. Pop-up window in detection sub interface to warn when D pass value 5.

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[16] *Pop-up* is popping up window as the term describes it. This term is mostly used on *World Wide Web* for reclaims or warnings.

6.2.2 Integration of risk estimation and evaluation improvements into PFMEA software solution

Improvements on FMEA based on fuzzy are very efficient, but at the same time, very complex for practical use [8]. Therefore, integration of risk estimation and evaluation improvements presented in chapter 5 will be much easier for use. A user just needs to make decision and bring input data into certain fields and software will do the calculation and results. This is possible because all proposed mathematics is integrated into software which provides precise calculation (See Figure 5.1).

Mathematics is integrated in software solution. The interfaces are only visible thing related to new S indices definition. S index has constraint for definition, because data for S index definition are dragged by other three S indices (S_S, S_Q and S_C) definition. S_S and S_C are based on new tables invented in chapter 5. Both are adapted to traditional PFMEA for automotive industry (See Figure 6.9 and Figure 6.10).

Table for S_Q is adapted to traditional table proposed by AIAG (see Figure 6.11). By keeping this table for S index, PFMEA stays in traditional framework proposed by AIAG. After definition of all three mentioned S indices, S index is automatically defined by mathematical calculation integrated in software. All three indices are connected with comprehensive database, also. Therefore, all data can be followed and searched at any time.

Figure 6.9. S_S definition interface.

Figure 6.10. S_C definition interface.

Figure 6.11. S_Q definition interface.

6.3 Chapter conclusion

Software solutions and database have been a trend in FMEAs for a long time. Many authors proposed various software solutions from both industry and academy. Academy sector is mostly based on FMEA improvements related to procedural and risk estimation and evaluation shortcomings. Most of these various solutions usually make usage of FMEA more complex and time-consuming.

In this chapter, a comprehensive software solution for PFMEA for automotive industry is presented. The comprehensiveness of this solution is in possibility to integrate all improvements related to procedural and risk estimation and evaluation shortcomings proposed in chapter 4 and chapter 5. Besides this, comprehensive database solution is also integrated into software solution in order to comprehend all data on the one place. The advantages of software solution mostly influenced on shortcomings related to human factor. Both advantages, achieved by database and software solution, are presented as follows.

Advantages of comprehensive database integrated in software for PFMEA in automotive industry are:

- Make decision making process much easier.
- Comprehend all data on one place.
- Easier searching of any data related to any failure.
- Possibility to connect similar processes, products or failures in order to achieve more realistic view during the definition of new failures.
- Make failure standardization process much easier.
- Makes failure prioritization process much easier and more transparent.
- Follow and update data automatically.

Advantages of comprehensive software solution for PFMEA in automotive industry are:

- PFMEA is more simplified and user-friendly with software solution.
- Robust mathematical calculations are simplified for usage.
- It is much easier to manipulate with data.
- Decision-making is simplified.

Potential shortcomings software solutions are:

- Additional professional training is required.
- New specialized workplace is needed.

7. Conclusion

PFMEA is in use in automotive industry for a long time. This analysis contains many shortcomings which are set in three groups (respectively from the most important): shortcomings related to human factor, risk estimation and evaluation shortcomings and procedural shortcomings. Also, certain PFMEA framework for automotive industry proposed by AIAG should be satisfied during PFMEA report fulfillment. Main goal of this dissertation was to overcome these shortcomings in order to improve product reliability during the production process. Therefore two hypotheses (see subchapter 1.3) were set. In order to approve both hypotheses different methodology is proposed. For both hypotheses case studies were conducted in automotive industry with state of PFMEA before implementation of solutions and after implementation of solutions.

In order to approve the first hypothesis, lean approach is integrated into traditional PFMEA for automotive industry. This integration is related to procedural manner. Traditional PFMEA procedure for automotive industry is extended with lean approach. This extended (or modified) PFMEA with lean approach is tested in one automotive company which is producing electronics and cables for automobiles. Obtained results are much better than the results of PFMEA conducted before implementation of lean approach (comparison of results is presented in Table 4.1, subchapter 4.4). Besides improved reliability, procedural constraints were solved as well by integration of lean approach to PFMEA. Original scientific contribution is in the integration of lean approach into PFMEA for automotive industry. Until now, a reverse approach was used in literature, while FMEA was used in order to improve reliability of lean systems. Both, product and production process have become more reliable after the integration of lean approach into PFMEA.

The second hypothesis (see subchapter 1.3) is related to risk estimation and evaluation problems at PFMEA for automotive industry. During the risk estimation and evaluation quality is considered (and partially safety) as a risk factor in severity table for automotive industry. Safety and costs have risk influence as well, but they are not considered during the both risk estimation and evaluation process. In order to improve this constraint, new tables for safety and cost severity are invented. Both severity and cost aspect were integrated into severity index and weighting was done as well. For this purpose Fuzzy AHP mathematical approach was used, combined with OWA for better aggregation. In order to approve proposed methodology, case study was implemented in one automotive company which producing leather upholstery. This company is producing leather upholstery for air bags as well. This was one of the reasons to choose this company, because safety aspect can be tested as well. Achieved results are presented in Table 5.3, subchapter 5.4. By implementation of mentioned mathematical methodology, more accurate and more precise results were obtained. Original scientific contribution is in combination of mathematical methodology used for solving of this problem. Also, new tables for new severity risk factors (safety and cost) are invented. These tables are inevitable element for application of proposed methodology.

With proposed methodology some of procedural and risk estimation and evaluation problems have been solved, but problems related to human factor increased. Used methodology made PFMEA more complex and time-consuming. This leads to additional complications for practical usage of PFMEA. Therefore, need for better decision making and improved solutions simplification appeared. In order to overcome this problem software solution with integrated database is proposed. Advantages of software solutions helped to overcome increased problems related to human factor. These advantages mostly refer to simplification of use of proposed methodologies, improvement of decision making automatized data control and collection. Proposed comprehensive software solution for PFMEA enabled practical application of proposed methodology.

Partial advantages and constraints are presented in subchapter 4.5 (for lean integration into PFMEA); subchapter 5,5 (for risk estimation and evaluation) and subchapter 6.3 (for constraints related to human factor). Advantages of comprehensive solution (which considers Software with integrate database and integrated solutions proposed in chapter 4 and chapter 5) are:

- Better product reliability (during production process) is achieved.
- More reliable risk estimation and evaluation is achieved.
- Costs are included into risk analysis.
- Safety is more precisely defined in risk estimation process.
- Traditional PFMEA framework for automotive industry is kept.
- PFMEA conduction is simplified.
- Improved decision making.
- Better cause identification is achieved.

- All data are centralized and data search is much easier.
- It is much easier to do statistical analysis.
- Practical use of PFMEA for automotive industry is enabled.
- Complexity improvement methods are overcrowded.
- Time-consumingness is decreased by automatization and data centralization.
- Failure and recommended action standardization is enabled.
- Similar products, processes and failures are connected in order for better decision making according to statistics
- Following and updating of failure occurrence during the time.

Some constraints of the proposed comprehensive approach are identified as well:

- S, O and D indices have the same weight and there is no known mathematical solution to weight them but to keep traditional PFMEA framework for automotive industry.
- O index is hard to define precisely during the preventive phase.
- Need for additional education about implemented modifications.
- Additional specialized workplace may be necessary for PFMEA conduction.

Besides constraints of proposed comprehensive solution and always present constraint of human factor, there are constraints of traditional PFMEA framework as well. Some of them are overcrowded by proposed solutions, while some of them are still present:

- Traditional S table (which is taken as table for quality severity index) still contains safety aspect under values 9 and 10. This is not necessary because new severity safety index (S_S) adapted to traditional S index estimation (1-10) is invented. S index values 9 and 10 should be adapted to quality issues.
- Recommended boarder line for implementation of solutions is 100. There is no explanation why it is 100. By integration of lean into PFMEA this becomes meaningless, because one of the main principles of lean approach is failure free product and/or process.
- RPN equation is questionable for risk estimation.

Therefore, traditional PFMEA framework for automotive industry proposed by AIAG (last in 2008) should be updated and upgraded according to the FMEA improvements and concepts of the future (like Industry 4.0 or lean).

Some of the future researches can be:

- Finding a way to predict failure occurrence more accurately. Because of the cost involvement (which is directly connected with failure occurrence) the need for more accurate failure occurrence increased.
- Making a failure cause construction by finding a root cause of the failures using some techniques like “5 why?”. This will enable PFMEA user to identify percentage of failures caused by human factor, equipment, external factors, etc. By this identification, researchers will be able to focus on the future improvements.
- Weighting of RPN indices (S, O and D) while keeping traditional PFMEA framework for automotive industry.

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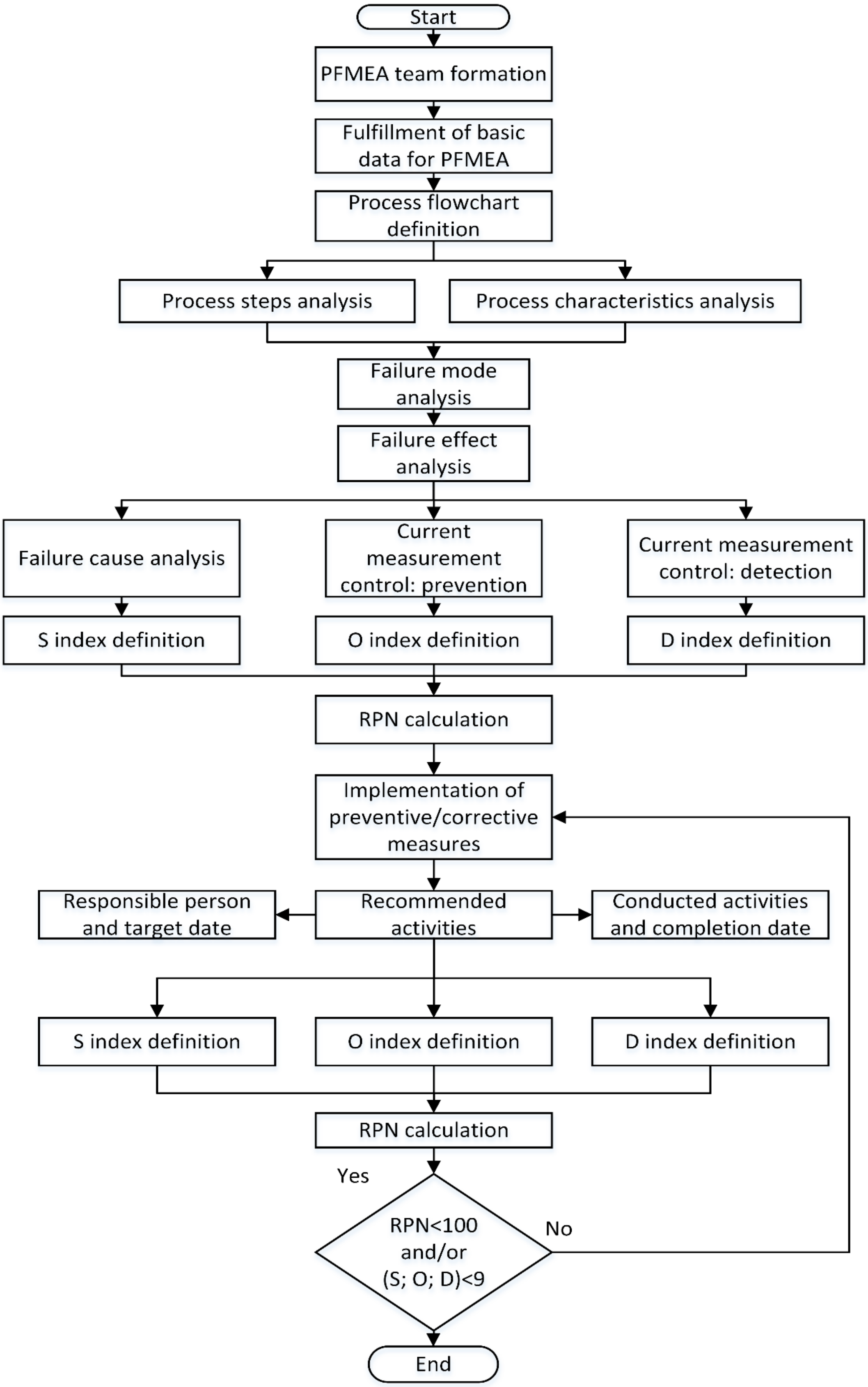
APENDICES

A Algorithm for traditional PFMEA procedure



B Traditional PFMEA form

PFMEA REPORT

PFMEA number:______________________________

Pages: ____________________________________

Item: ____ Process responsibility:__________________________________ Powered by: ________________________________

Model/Year program:____ Key date:____ PFMEA date::________________________________

Core team:____

Process step or function	Requirements	Failure mode	Failure effect	Severity (S)	Classification	Failure mode cause	Occurrence (O)	Current process control: detection	Current process control: detection	Detection (D)	RPN	Recommended actions	Responsible person and target date	Conducted activities and competition date.	Severity (S)	Occurrence (O)	Detection (D)	RPN

C Severity table proposed by AIAG

Effects	Criteria: Severity of Effect on Product (Customer Effect)	Rank	Effects	Criteria: Severity of Effect on Product (Manufacturing/Assembly Effect)
Failure to Meet Safety and/or Regulatory Requirements	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning.	10	**Failure to Meet Safety and/or Regulatory Requirements**	May endanger operator (machine or assembly) without warning.
	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning.	9		May endanger operator (machine or assembly) with warning.
Loss or Degradation of Primary Function	Loss of primary function (vehicle inoperable, does not affect safe vehicle operation)	8	**Major Disruption**	100% of product may have to be scrapped. Line shutdown or stop ship.
	Degradation of primary function (vehicle operable, but at reduced level of performance)	7	**Significant Disruption**	A portion of the run may have to be scrapped. Deviation from primary process including decreased line speed or added manpower.
Loss or Degradation of Secondary Function	Loss of secondary function (vehicle operable, but comfort / convenience function inoperable)	6	**Moderate Disruption**	100% of production run may have to be reworked off line and accepted
	Degradation of primary function (vehicle operable, but comfort / convenience function at reduced level of performance)	5		A portion of the production run may have to be reworked off line and accepted
Annoyance	Appearance of Audible Noise, vehicle operable, item does not conform and noticed by most customers (<75%)	4	**Moderate Disruption**	100% of production run may have to be reworked in station before it is processed
	Appearance of Audible Noise, vehicle operable, item does not conform and noticed by many customers (<50%)	3		A portion of the production run may have to be reworked in station before it is processed
	Appearance of Audible Noise, vehicle operable, item does not conform and noticed by discriminating customers (<25%)	2	**Minor Disruption**	Slight inconvenience to process, operation or operator
No Effect	No discernible effect	1	**No Effect**	No discernible effect

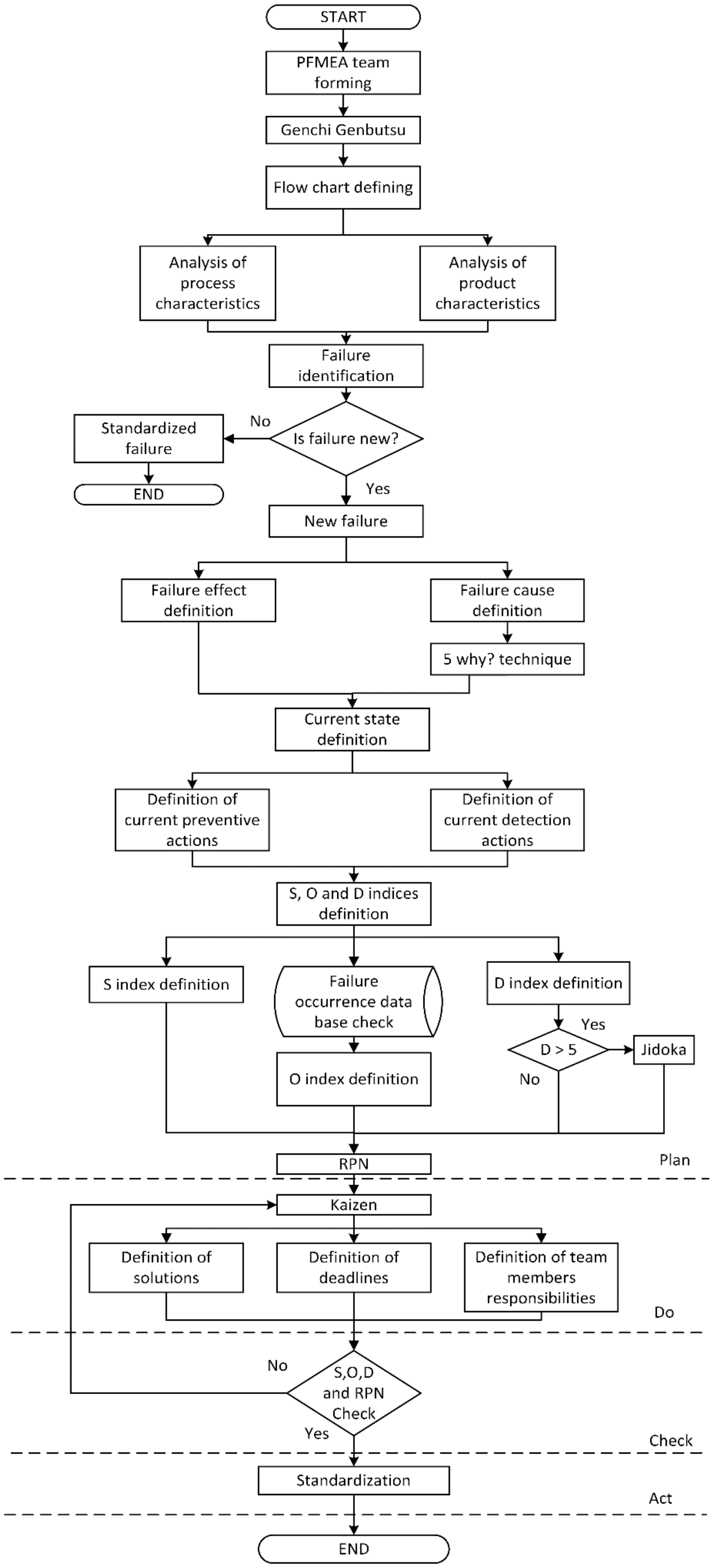
D Occurrence table proposed by AIAG

Likelihood of Failure	Criteria: Occurrence of Cause – PFMEA (Incidents per items/vehicles)	Rank
Very High	≥100 per thousand ≥ 1 in 10	10
High	50 per thousand 1 in 20	9
	20 per thousand 1 in 50	8
	10 per thousand 1 in 100	7
Moderate	2 per thousand 1 in 500	6
	0.5 per thousand 1 in 2,000	5
	0.1 per thousand 1 in 10,000	4
Low	0.01 per thousand 1 in 100,000	3
	≤ 0.001 per thousand 1 in 1,000,000	2
Very Low	Failure is eliminated through preventive control	1

E Detection table proposed by AIAG

Opportunity for Detection	Criteria: Likelihood of Detection by Process Control	Rank	Likelihood of Detection
No detection opportunity	No current process control, Cannot detect or is not analyzed.	10	Almost Impossible
Not likely to detect at any stage	Failure Mode and/or Error (Cause) is not easily detected (e.g., random audits).	9	Very Remote
Problem Detection Post Processing	Failure Mode detection post-processing by operator through visual/tactile/audible means.	8	Remote
Problem Detection at Source	Failure Mode detection in-station by operator through visual/tactile/audible means or post-processing through use of attribute gauging (go/no-go, manual torque check/clicker wrench, etc.).	7	Very Low
Problem Detection Post Processing	Failure Mode detection post-processing by operator through use of variable gauging or in-station by operator through use of attribute gauging (go/no-go, manual torque check/clicker wrench, etc.).	6	Low
Problem Detection at Source	Failure Mode and/or Error (Cause) detection in-station by operator through use of variable gauging or by automated controls in-station that will detect discrepant part and notify operator (light, buzzer, etc.). Gauging performed on setup and first-piece check (for set-up causes only).	5	Moderate
Problem Detection Post Processing	Failure Mode detection post-processing by automated controls that will detect discrepant part and automatically lock part in station to prevent further processing.	4	Moderately High
Problem Detection at Source	Failure Mode detection in-station by automated controls that will detect discrepant part and automatically lock part in station to prevent further processing.	3	High
Error Detection and/or Problem Prevention	Error (Cause) detection in-station by automated controls that will detect error and prevent discrepant part from being made.	2	Very High
Detection not applicable, Error Prevention	Error (Cause) prevention as a result of fixture design, machine design or part design. Discrepant parts cannot be made because item been error-proofed by process/product design	1	Almost Certain

F Algorithm for lean integrated approach to PFMEA



G Results for PFMEA realized on tradtional way

FMEA Number	Part Name/Part No		Project Manager
51	**BSH MSM6BL**	**E index: A1**	
FMEA Date (Orig)	FMEA Revision Date		Prepared by
20.4.2015	20.04.2015. Rev.00		Project Leader
FMEA Team			
Project leader x2			

Process No./Function		**Requirements**	**Potential Failure Mode**	**Potenial Effect(s) of Failure**	**Severity**	**Classification**	**Potential Cause(s) of Failure**	**Occurrence**	**Current Process Controls: Prevention**	**Current Process Controls: Detection**	**Detection**	**RPN**	**Recomended Action(s)**	**Responsibillity**	**Target Completetion Date**	Action Results					
																Actions Taken	**Effective Date**	**Occurrence**	**Severity**	**Detection**	**RPN**
E110	Insertion axial		Component failed	PCB with failed function; No function	8		No components in magazin	2	Intern schooling, working instruction	Process approved	6	96	No								0
E110	Insertion axial		Component with false value	Badly equipped PCB; PCB with failed function; No function	8		Wrong components in magazin	2	Intern schooling, working instruction	Process approved	6	96	No								0
E110	Insertion axial		Wrong orientation of component	Incorect or no function	7		Machine failure	2	Intern schooling, working instruction	Process approved	6	84	No								0
E412	Manual inserting		Mechanical damaged component	Trouble in process	7		Inattention	4	Intern schooling, working instruction	Visual control; Process approved	3	84	No								0
E412	Manual inserting		Wrong component	PCB with false components	8		Inattention	2	Intern schooling, working instruction	Process approved	3	48	No								0
E412	Manual inserting		Contact badly placed	Trouble in process	7		Inattention	2	Intern schooling, working instruction	Visual control; Process approved	3	42	No								0

E412	Manual inserting		Component failed on PCB	PCB with failed function, no function	8		Inattention	3	Visual inspection before use	Visual inspection by end inspection	4	96	No							0
E500	Wave Soldering		Use of false temperature profil	Bad or not soldered joints between pads and component contacts	8	§	Inattention, false setting of machine parameters	4	Intern schooling, working instruction	Visual inspection	3	96	Check the temperature profile	Technologists	1 x monthly	Record checking temperature profile	1 x monthly	4	8	2	64
E500	Wave Soldering		Too much solder on solder joint	Short circuit on PCB	7		False setting the process parameter – speed of soldering line is wrong	3	Intern schooling, working instruction	Visual inspection, check the parameter before use	4	84	No							0
E500	Wave Soldering		Uncorect solder joint	Unreliable joint - unreliable function	7		False setting the process parameter –	4	Intern schooling, working instruction	Visual inspection, check the parameter before use	3	84	No							0
E500	Wave Soldering		Not enough solder on solder joint	Bad solder joint	7		False setting the process parameter	3	Intern schooling, working instruction	Visual inspection - check the parameter before use	4	84	No							0
E500	Wave Soldering		Cold contact	Bad solder joint	7		False setting the process parameter	2	Intern schooling, working instruction	Visual inspection, check the parameter before use	3	42	No							0
E650	Function test		Skipped the final control	Bad parts can be sent to the customer	8		Inattention	4	Intern schooling, working instruction	Process approved	3	96	No							0
E521	Rework; visual inspection		Not sensed missing element	PCB with false function	8		Inttenation	4	Intern schooling, working instruction, changing workers	Visual inspection	2	64	No							0
E521	Rework; visual inspection		Not sensed wrong orientated element	PCB with false function	7		Inttenation	3	Intern schooling, working instruction, changing workers	Visual inspection; Function test	4	84	No							0

E521	Rework; visual inspection		Not sensed shoort circuit	No function	7		Inttenation	3	Intern schooling, working instruction, changing workers	Visual inspection; Function test	4	84	No								0
E521	Rework; visual inspection		Not sensed broken connections	No function	8		Inttenation	2	Intern schooling, working instruction, changing workers	Visual inspection; Function test	4	64	No								0
E521	Rework; visual inspection		Not sensed mechanical damages	No function	8		Inttenation	2	Intern schooling, working instruction	Visual inspection	4	64	No								0
E710	Marking		No data about the product	Bad tracking of product, tracking unpossible	5		Inattention	4	Intern schooling, working instruction	Visual inspection	3	60	No								0
E710	Marking		In the wrong place labeled product	Unwilling customer, customer reclamation	5		Inattention	4	Intern schooling, working instruction	Visual inspection	3	60	No								0
E710	Marking		Wrong data on product	Bad tracking of product, tracking unpossible	5		Inattention	4	Intern schooling, working instruction	Visual inspection	4	80	No								0
E531	Separation PCB		Damage the PCB, outline is not clear	Trouble by assembling in houssing	6		Innatenation, damaged tooling	2	Intern schooling, working instruction	Visual inspection	5	60	No								0
E531	Separation PCB		Break the PCB	Useless of PCB	8			3	Intern schooling, working instruction	Visual inspection	2	48	No								0
E900	Final control and packing		Wrong products in the box	Unwilling customer, customer reclamation	8		Operator error, mess at the working place	3	Intern schooling	Visual inspection	4	96	No								0
E900	Final control and packing		Mixed products in the box	Unwilling customer, customer reclamation	8		Operator error, mess at the working place	3	Intern schooling	Visual final inspection	4	96	No								0

E900	Final control and packing		Quantity is false	Unwilling customer, customer reclamation	7		Inattention	3	Intern schooling	Visual final inspection	4	84	No								0
E900	Final control and packing		VDA label is uncorect fullfield	Identification, tracebility is not assure	6		Mistake in system, not enough datas	2	Intern schooling	Visual final inspection	5	60	No								0

H Results achieved after lean integration into PFMEA

FMEA Number	Part Name/Part No		Realized by:
51	**BSH MSM6BL**	**E index: A1**	Project manager
FMEA Date (Orig)	FMEA Revision Date		Prepared by:
20.4.2015	20.04.2015. Rev.01		Project Leader
FMEA Team			
Project Leader x2, Project manager, Quality manager, Logistics manager, Procurement manager, R&Dx2, Maintanance manager **+ 6 workers**			

Process No./Function		Requirements	Potential Failure Mode	Potenial Effect(s) of Failure	Severity	Classification	Potential Cause(s) of Failure	Occurrence	Current Process Controls: Prevention	Current Process Controls: Detaction	Detection	RPN	Recomended Action(s)	Responsibility	Target Completetion Date	Action Results: Actions Taken	Effective Date	Occurrence	Severity	Detection	RPN
E110	Axial insertion		Component failed	PCB with failed function; No function	6		No components in magazin	2	Intern schooling, working instruction	Process approved	6	72	No								0
E110	Axial insertion		Component with false value	Badly equipped PCB; PCB with failed function; No function	6		Wrong components in magazin	2	Intern schooling, working instruction	Process approved	6	72	No								0
E110	Axial insertion		Wrong orientation of component	Incorect or no function	6		Machine failure	2	Intern schooling, working instruction	Process approved	6	72	No								0
E412	Manual inserting		Mechanical damaged component	Trouble in process	5		Inattention	4	Intern schooling, working instruction	Visual control; Process approved	6	120	Increase workers precaution	Project manager		Work instructions		5	1	6	30
E412	Manual inserting		Component failed on PCB	PCB with failed function, no function	5		Inattention	5	Visual inspection before use	Visual inspection by end inspection	5	125	Poka yoke	Project manager		Aditional tool for chack out of components no.		5	1	6	30
E412	Manual inserting		Wrong component	PCB with false components	7		Inattention	4	Intern schooling, working instruction	Process approved	8	224	kaizen workshop	Project manager		Process improvement + check out after component election		7	1	8	56

E412	Manual inserting		Contact badly placed	Trouble in process	8		Inattention	4	Intern schooling, working instruction	Visual control; Process approved	8	256	Kaizen + poka yoke	Project manager		Process improvement + tool for contact set up		8	1	8	64
E500	Wave Soldering		Too much solder on solder joint	Short circuit on PCB	7		False setting the process parameter – speed of soldering line is wrong	4	Intern schooling, working instruction	Visual inspection, check the parameter before use	5	140	Preventive machine maintanance	Maintanance manager		Check out of parameters before start of machine		7	1	4	28
E500	Wave Soldering		Use of false temperature profil	Bad or not soldered joints between pads and component contacts	8	§	Inattention, false setting of machine parameters	5	Intern schooling, working instruction	Visual inspection	5	200	Preventive machine maintanance	Maintanance manager		Check out of parameters before start of machine		8	1	6	48
E500	Wave Soldering		Uncorect solder joint	Unreliable joint - unreliable function	8		False setting the process parameter –	5	Intern schooling, working instruction	Visual inspection, check the parameter before use	5	200	Preventive machine maintanance	Maintanance manager		Check out of parameters before start of machine		8	1	6	48
E500	Wave Soldering		Not enough solder on solder joint	Bad solder joint	8		False setting the process parameter	4	Intern schooling, working instruction	Visual inspection - check the parameter before use	5	160	Preventive machine maintanance	Maintanance manager		Check out of parameters before start of machine		8	1	5	40
E500	Wave Soldering		Cold contact	Bad solder joint	7		False setting the process parameter	4	Intern schooling, working instruction	Visual inspection, check the parameter before use	5	140	Preventive machine maintanance	Maintanance manager		Check out of parameters before start of machine		7	1	5	35
E650	Function test		Skipped the final control	Bad parts can be sent to the customer	8		Inattention	3	Intern schooling, working instruction	Process approved	8	192	One piece flow	Worker		Work instructions		7	1	5	35
E521	Rework; visual inspection		Not sensed missing element	PCB with false function	7		Inttenation	3	Intern schooling, working instruction, changing workers	Visual inspection	5	105	Kaizen + poka yoke	Project manager		Process improvement + tool for contact set up		7	1	4	28

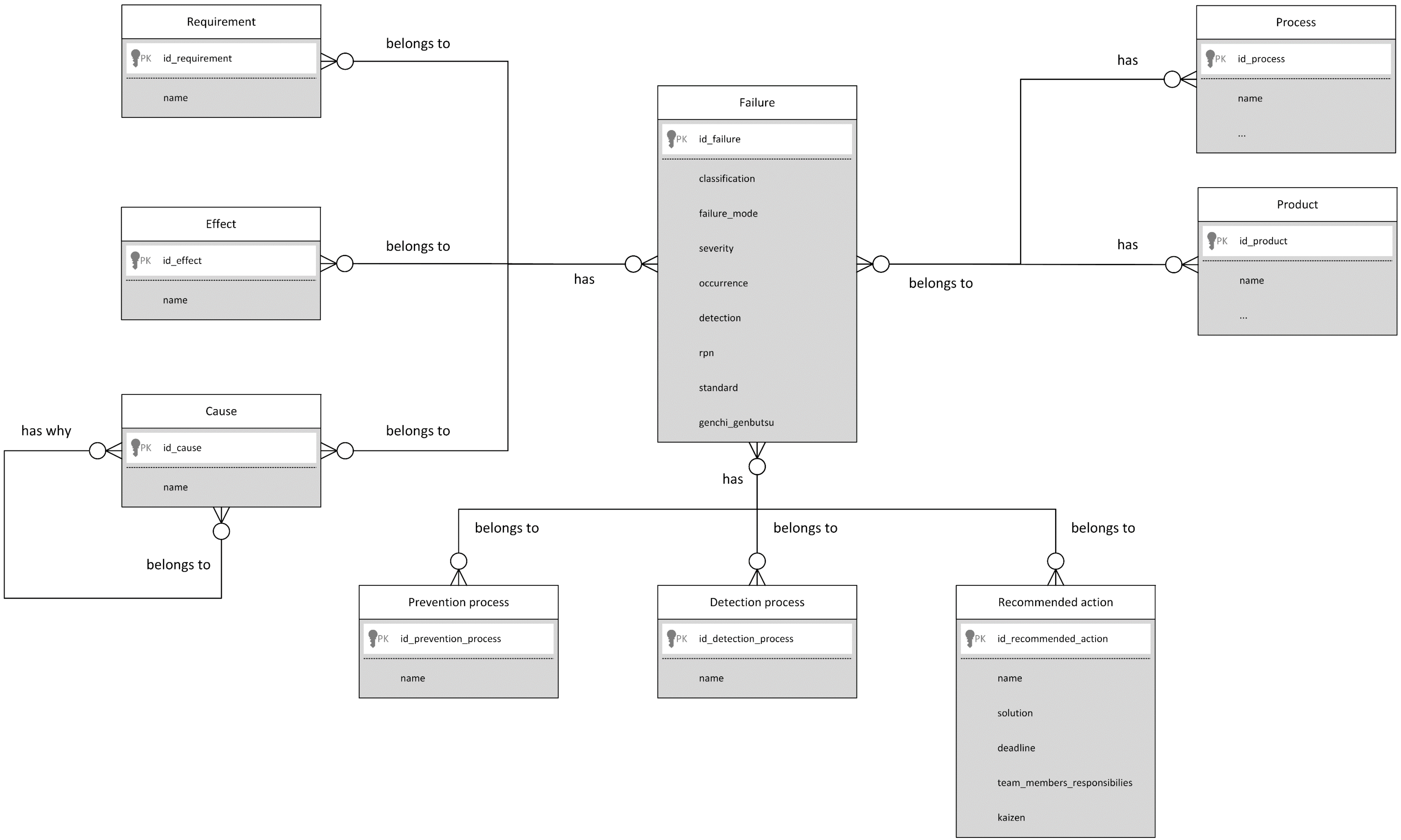
E521	Rework; visual inspection		Not sensed wrong orientated element	PCB with false function	7		Inttenation	2	Intern schooling, working instruction, changing workers	Visual inspection; Function test	5	70	No								0
E521	Rework; visual inspection		Not sensed mechanical damages	No function	6		Inttenation	2	Intern schooling, working instruction	Visual inspection	5	60	No								0
E521	Rework; visual inspection		Not sensed shoort circuit	No function	8		Inttenation	3	Intern schooling, working instruction, changing workers	Visual inspection; Function test	6	144	Jidoka	Project manager		Implement testing of current flow		8	1	4	32
E521	Rework; visual inspection		Not sensed broken connections	No function	8		Inttenation	3	Intern schooling, working instruction, changing workers	Visual inspection; Function test	6	144	Isolation of part for special inspection	QS		Rework after check		8	1	8	64
E710	Marking		No data about the product	Bad tracking of product, tracking unpossible	4		Inattention	2	Intern schooling, working instruction	Visual inspection	5	40	No								0
E710	Marking		In the wrong place labeled product	Unwilling customer, customer reclamation	4		Inattention	2	Intern schooling, working instruction	Visual inspection	5	40	No								0
E710	Marking		Wrong data on product	Bad tracking of product, tracking unpossible	4		Inattention	2	Intern schooling, working instruction	Visual inspection	5	40	No								0
E531	PCB separation		Damage the PCB, outline is not clear	Trouble by assembling in houssing	6		Innatenation damaged tooling	6	Intern schooling, working instruction	Visual inspection	5	180	Jidoka	Project manager + workers		Kvalitet na izvorištu		6	1	8	48
E531	PCB separation		Break the PCB	Useless of PCB	8			3	Intern schooling, working instruction	Visual inspection	5	120	kaizen workshop	Project manager + R&D		Made tools for automatic removing of excess		8	1	2	16

E900	Final control and packing		Mixed products in the box	Unwilling customer, customer reclamation	2		Operator error, mess at the working place	2	Intern schooling	Visual final inspection	9	36	5S + Work instructions	Project manager + workers		organisation of work place + aditional worker education		2	2	8	32
E900	Final control and packing		Quantity is false	Unwilling customer, customer reclamation	2		Inattention	2	Intern schooling	Visual final inspection	9	36	5S + Work instructions	Project manager + workers		organisation of work place + aditional worker education		2	2	8	32
E900	Final control and packing		VDA label is uncorect full-field	Identification, tracebility is not assure	2		Mistake in system, not enough datas	2	Intern schooling	Visual final inspection	9	36	Kaizen	Project manager + workers		System for VDA markers chose		2	1	1	2
E900	Final control and packing		Wrong products in the box	Unwilling customer, customer reclamation	8		Operator error, mess at the working place	2	Intern schooling	Visual inspection	8	128	Jidoka	Project manager + workers		Kvalitet na izvorištu		8	1	8	64

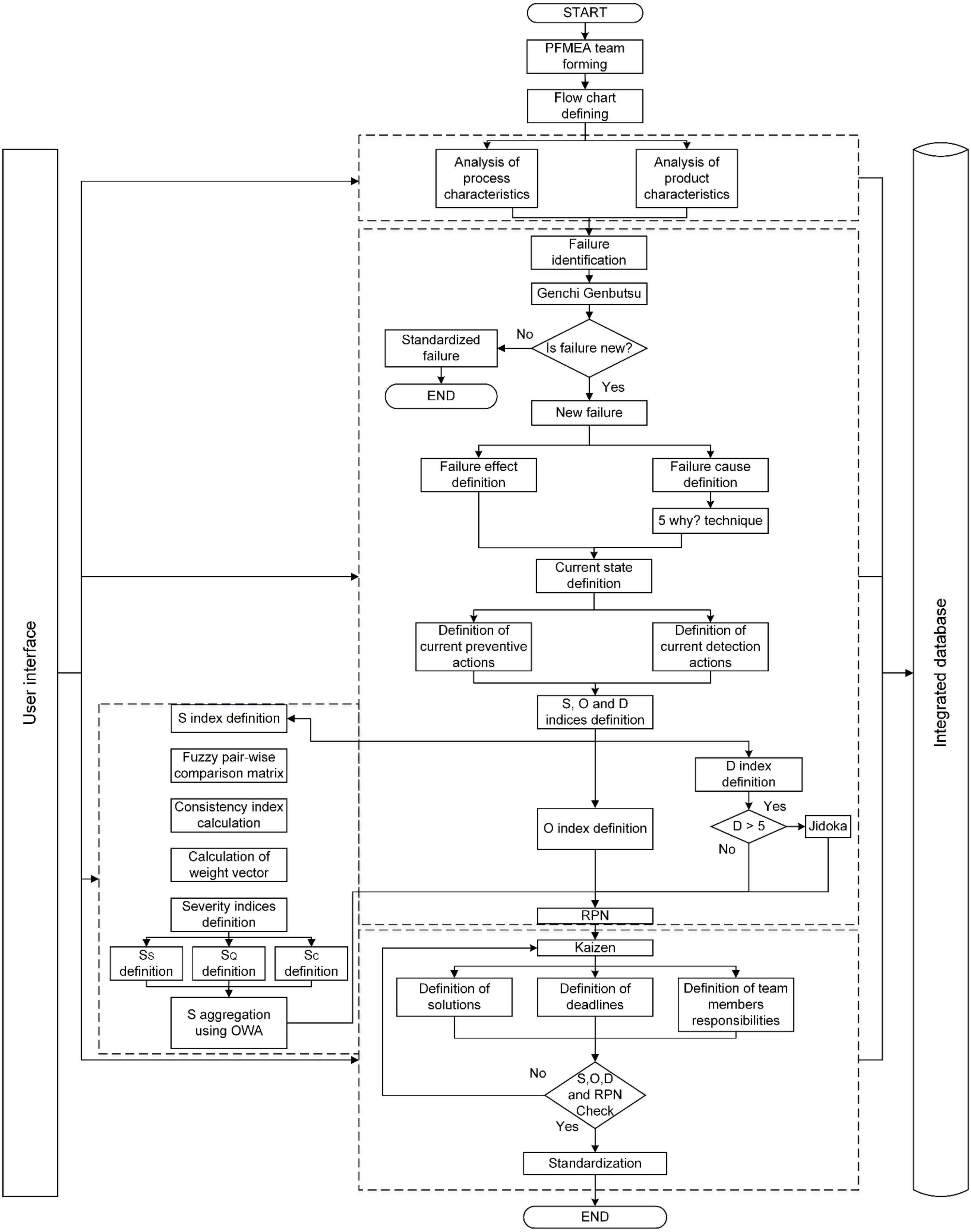
I Results for case study achieved on traditional way

No.	Process	Failure	Failure Effect	Severity (S)	Failure cause	Classification	Occurrence (O)	Current control method	Phase of failure detection	Detection (D)	RPN
1	Measuring of leather thickness	Leather thickness is not according to specification	Final product not in compliance with customer's requirements	6	Supplier factor	HI	2	Measuring with thickness meter	Marking, Cutting, Lamination, Overlock, Separation, Sewing	3	36
2	Cutting of leather	Wrong or incomplete file inserted to the cutting machines	Final product not in compliance with customer's requirements	6	Mistake in program preparation	HI	3	1. Visual control 2. Master sample	Cutting, Lamination, Overlock, Separation, Sewing	2	36
3	Measuring of cut leather parts	Defective parts left cutting process	Final product not in compliance with customer's requirements	6	Sampling frequency is too low	HI	6	Measuring with ruler and comparison with patterns	Cutting, Lamination, Overlock, Separation, Sewing	3	108
4	Cutting of soft materials	Wrong parameter of Orox and Gerber GT cutter	Final product not in compliance with customer's requirements	7	Wrong parameters of machine (speed, vacuum, head speed, number of layers, pressure)	HI	5	Visual control	Cutting, Separation, Sewing	3	105
5	Measuring of AB straps	Defective parts left cutting process	Final product not in compliance with customer's requirements; potential problem with AB deployment	9	/	CC	2	Measurement with ruler and comparison with GO-NOGO jigs	Cutting Separation, Sewing	2	36
6	Perforation of leather cut parts	Wrong angle of perforation	Product not according to drawing specifications	7	Positioning of parts is not according to drawing specifications	HI	3	Visual control	Lamination , Sewing, Quality control	2	42
7	Cutting of profiles	Wrong length/type	Irregular installation	7	Wrong set-up of limiter for cutting profiles	HI	2	1. Measuring tool 2. Visual control	Cutting of profiles, Sewing, Quality control	2	28
8	Cutting of leather part from foam	Damaged part with scissors	Final product not in compliance with customer's requirements	6	Human factor	HI	3	Visual control and comparison with drawings	Lamination, Overlock, Separation, Sewing	3	54
9	Sewing of air bag (AB) straps	Incorrect length of AB strap (if given in technical drawing)	Improper installation of AB	10	Human factor	CC	3	Visual control X-R Chart WI 80.11	1. Sewing phase 2. Quality control	2	60
10	Sewing of AB clips	Wrong position of AB clips (if given in technical drawing)	Improper installation of AB	10	Human factor	CC	3	Visual control SPC QA 80.5	1. Sewing phase 2. Quality control	2	60

J ER diagram for comprehensive database



K Algorithm for comprehensive software solution

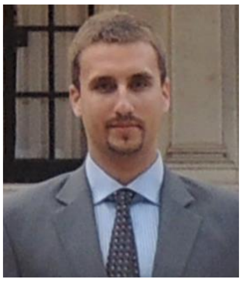


BIOGRAPHY

Nikola Banduka was born on the 26th of May, 1990 in Belgrade, Serbia. The most of his time he spent in the city of Kragujevac (Serbia) where he lived and finished electro-technical high school in 2009. In the same year he started his bachelor studies at the Faculty of Engineering, University of Kragujevac. Bachelor thesis he defended in 2012 was "*Concept of lean production*". After finishing bachelor studies, he enrolled master studies at the same faculty and university. During the second year of master studies he spent one month on internship at the Faculty of Mechanical Engineering, University of Ljubljana (Ljubljana, Slovenia). This internship was conducted at the Department for production engineering. His main occupation during this internship was programing of AAB welding robot. He finished Master studies in September 2014 on the thesis "*Display of advanced measurement system for testing and analysing of ergonomic factors which influence on workers mental workload at workplace in industry*". Later in November 2014, he was hired by the Slovenian automotive company with branch in Serbia – *Grah Automotive*. He was working in this company as a project leader until June 2015 and one of his main occupations was PFMEA analysis. While working at the company he enrolled doctoral studies at the Faculty of Engineering, University of Kragujevac in December, 2014. Later on in June 2015 he got ERASMUS MUNDUS scholarship and paid mobility in duration of 34 months to realize it at FESB, University of Split. During the studies at the University of Split he joined two scientific projects. The first one is INSENT 1353 (Innovative smart enterprise) founded by Croatian Ministry of science and another one is Network innovative learning factories (NIL) founded by German Academic Exchange Service (DAAD). During his academic studies he published 13 scientific papers, 4 in journals and 9 at scientific conferences.

CURRICULUM VITAE

PERSONAL INFORMATION Nikola Banduka



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Date of birth 26 May 1990

WORK EXPERIENCE

12/11/2014–01/06/2015

Production and operations department manager in manufacturing (Project leader)

Grah automotive d.o.o, Kragujevac (Serbia)

- Leading of the existing and new projects
- Forming and maintaining Process Failure Mode and Effect Analysis (PFMEA)
- Using lean approach to improve process reliability

07/2015–Present

Research assistant (participant on a project)

Croatian ministry project INSENT (Innovative smart enterprise) 1353, Split (Croatia)

- Projecting of digital twins and factory layout optimization using software tool visTABLE
- Projecting and optimization of production processes using Siemens Tecnomatix
- Forming of the Croatian production system model based on lean approach, tools, methods and techniques

EDUCATION AND TRAINING

07/2009–10/2012

Bachelor studies in Mechanical Engineering, Industrial engineering

EQF level 6

University of Kragujevac, Faculty of Engineering, Kragujevac (Serbia)

Thesis: Basics of the lean concept of production

09/09/2013–04/10/2013

Mobility Internship

University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana (Slovenia)

Licence No.: EI 2013/1

Lecturer: Prof. Dr Mirko Soković

Course title: Master's Practicum in the field of Production Engineering

No. of hours: 150

Grade: 9 (B)

10/2012–09/2014

Master studies in Mechanical Engineering, Industrial Engineering

EQF level 7

University of Kragujevac, Faculty of Engineering, Kragujevac (Serbia)

Thesis: Display of advanced measurement system for testing and analysing of ergonomic factors which influence on workers mental workload at workplace in industry

12/2014–Present

Doctoral studies in Mechanical Engineering, Industrial Engineering

EQF level 8

University of Kragujevac, Faculty of Engineering, Kragujevac (Serbia)

Thesis: Improvement of product reliability during the production process in the automotive industry using improved FMEA analysis

Planned completion date: 06/2018

18/10/2015–25/10/2015

International doctoral school

DAAAM International Vienna, Zadar (Croatia)

Doctoral school was founded by FESTO company

12/2015–12/2015

Training in Learning factories

ESB business school, Reutlingen (Germany)

This training mobility was fully supported by Network innovative learning factories (NIL) project founded by "German Academic Exchange Service" (DAAD)

09/2016–09/2016

Training in Learning factories

Fraunhofer IWU, Augsburg (Germany)

This training mobility was fully supported by Network innovative learning factories (NIL) project founded by "German Academic Exchange Service" (DAAD)

23/10/2016–30/10/2016

International doctoral school

DAAAM International Vienna, Mostar (Bosnia and Herzegovina)

This doctoral school was founded by FESTO company

09/2015–Present

Doctoral studies in Mechanical Engineering, Industrial Engineering

EQF level 8

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture (FESB), Kragujevac (Serbia)

Foundation: This second doctorate was founded by project: Erasmus Mundus Green-Tech-WB: Smart and Green technologies for innovative and sustainable societies in Western Balkans; Erasmus Mundus Action 2: 551984-EM-1-2014-1-ES-ERA MUNDUS-EMA21

Thesis: Improvement of product reliability during the production process in the automotive industry using improved FMEA analysis

Planned completion date: 06/2018

PERSONAL SKILLS

Mother tongue(s): Serbian

Other language(s)

	UNDERSTANDING		SPEAKING		WRITING
	Listening	Reading	Spoken interaction	Spoken production	
English	B2	B2	B2	B2	B2
Spanish	A1	A1	A1	A1	A1

Levels: A1 and A2: Basic user - B1 and B2: Independent user - C1 and C2: Proficient user
Common European Framework of Reference for Languages

ADDITIONAL INFORMATION

Publications

Journals:

1. Banduka, N., Veza, I., & Bilic, B. (2016). An integrated lean approach to Process Failure Mode and Effect Analysis (PFMEA): A case study from automotive industry. *Advances in Production Engineering & Management*, *11*(4), 355.

2. Banduka, N., Mladineo, M., & Eric, M. (2017). DESIGNING A LAYOUT USING SCHMIGALLA METHOD COMBINED WITH SOFTWARE TOOL VISTABLE. *International journal of simulation modelling*, *16*(3), 375.

3. Crnjac, M., Veža, I., & Banduka, N. (2017). From Concept to the Introduction of Industry 4.0. *International Journal of Industrial Engineering and Management*, *8*, 21.

4. Babić, Z. B., Veža, I., & Banduka, N. (2017). ASSESSMENT OF INDUSTRIAL MATURITY LEVEL BY MULTICRITERIAL ANALYSIS. *International Journal ''Advanced Quality''*, *45*(4), 13-16.

Conferences:

1. Banduka, N. & Đurić, S. INFLUENCE OF MICROCLIMATE PARAMETERS ON THE INDIVIDUAL FEELING OF STUDENT THERMAL COMFORT. *SRMA 2014*, 56-61.

2. Banduka, N. DISPLAY OF PROGRESSIVE METERING SYSTEM FOR ERGONOMIC TESTING WHICH INFLUENCING ON MENTAL WORKLOAD OF WORKERS. *SRMA 2014*, 62-68.

3. Banduka, N., Veža, I., & Gjeldum, N. (2016, January). Supply chain model based on management principles of supply chain key elements and on Lean principles. In *International conference "Mechanical Technologies and Structural Materials" 2016*.

4. Banduka, N., Mačužić, I., Stojkić, Ž., Bošnjak, I., & Peronja, I. (2016). USING 80/20 PRINCIPLE TO IMPROVE DECISION MAKING AT PFMEA. *Annals of DAAAM & Proceedings*, *27*.

5. Banduka, N., Peko, I., Crnjac, M., Bošnjak, I., & Đurić, S. (2017, February). Linear layout design using a software tool visTABLE. In *15th Annual Industrial Simulation Conference*.

6. Mladineo, M., Banduka, N., & Peko, I. (2017, January). Using Cyber-Physical System and Virtual Reality for improvement of Factory Layout. In *CCGIDIS 2017*.

7. Babić, Z., Veža, I., & Banduka, N. (2017, January). ASSESSMENT OF INDUSTRIAL MATURITY LEVEL BY MULTI-CRITERIAL ANALYSIS. In *Total Quality Management-Advanced an Intelligent Approaches*.

8. Nikezić, S., Dželetović, M. & Banduka, N. (2017, September). Evaluation of the current state of an automotive factory in the Republic of Serbia in the course of the reengineering process. In *RaDMI-2017.*

9. Banduka, N., Veža, I., Bilić, B., Mačužić, I. & Radojičić, M. (2017). Using cost-based mathematical model and principle 80/20 to improve decision making for risk priority at FMEA. In IS'17.

Projects

Mobility projects:

- Improvement of students' internship in Serbia. Internship in Slovenia, Ljubljana in 2013, duration 1 month. (2014-2018)
- Erasmus Mundus Green-Tech-WB: Smart and Green technologies for innovative and sustainable societies in Western Balkans; Erasmus Mundus Action 2: 551984-EM-1-2014-1-ES-ERA MUNDUS-EMA21, Doctorate in Croatia, Split, duration 34 months. (2015 - 2018)

Research projects:

- Network of Innovative Learning-Factories (NIL) is project founded by German Academic Exchange Service (DAAD) and the Federal Ministry of Education and Research (BMBF). Trainings in learning factories in Germany, Reutlingen and Augsburg, Duration for a week both times. (2014 - 2016)
- Innovative smart enterprise (INSENT) 1353 project supported by Croatian ministry of science. From 2015-ongoing (2014-2018)