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Enhancement of the Selected Management and Planning Quality Control Tools

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Declaration

I declare that this thesis entitled “Enhancement of the selected management and planning quality control tools” is the result of my own research except as cited in references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Date ………………… Signature………………………

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ABSTRACT

A detailed analysis of three management and planning quality control tools – affinity diagram, arrow diagram and process decision program chart – was performed. Then fuzzy logic was used for increase the yield of information of these tools. All three tools shown up to be flexible for fuzzy approach application.

As the first, an application of an arrow diagram with a support of fuzzy logic to solution of mobile phone functionality problem at a service center for repair of mobile phones is presented. For the smooth course of negotiation between a client and the mobile phone reparation service there is a need to estimate the time of the problem solution as precisely as possible. Fuzzy logic as a supporter for an arrow diagram was used in order to determine the time interval of mobile reparation process more accurately in comparison with a standard approach. Better estimation of the time of a step "Diagnostics with the goal to find a cause of a problem" using the fuzzy logic is demonstrated.

Then, an affinity diagram formed for a process of adhesive assembly of electronic components on the printed circuit board was constructed. Fuzzy approach showed the degree of an influence of the failures in some operations of the process to the failures in the following operations of this process. Non-obvious failures that could be met during a testing step were estimated and their significance was calculated.

Process decision program chart (PDPC) created for assembly of electronic components on a printed circuit board based on wave soldering was also presented. The process decision program chart was constructed to identify risks and develop counter-measures (preventive actions). Volume of information, which should be involved into such the diagram, is very high. Fuzzy approach was used to find information of lower importance, which can occur, and thereby reduce the amount of entering information for processing of the PDPC diagram.

The use of fuzzy logic is, with respect to the range of the thesis, documented on selected steps used in the processing of selected managerial quality control tools. The approach is generic and can be used for any technological or other type of an operation or a process to obtain deeper insight into the problem and better estimation of the course of an event under analysis.

ABSTRAKT

Je provedena podrobná analýza s následnou fuzzifikací tří nástrojů řízení jakosti – afinity diagramu, síťového grafu a PDPS diagramu. Ukázalo se, že všechny uvedené nástroje mohou být vylepšeny použitím fuzzy analýzy.

První uvedený případ poukazuje na použití fuzzy logiky pro řešení odhadu doby opravy mobilního telefonu v servisním centru na základě sít'ového grafu. S ohledem na zákazníka je třeba odhadnout dobu opravy s co nejvyšší přesností. Fuzzy logika umožnila zpřesnění odhadu doby opravy telefonu v porovnání s klasickým přístupem. Proces opravy sestává ze čtyř kroků. Je demonstrováno užití této metody pro odhad doby kroku „Diagnostika s cílem nalézt příčinu problémy".

Dále byl aplikován pristup na zaklade fuzzy logiky na adhezní montáž elektronických součástek na desku plošného spoje. Pomoci afinitniho diagramu byl studován vliv chyb v dané operaci montáže na chyby vyskytující se v následujícím kroku procesu, kterým bylo testování. Byl hodnocen význam nové chyby, vyskytující se při testování, v závislosti na významu chyb vyskytujících se v předchozích operacícn.

Na závěr byl zpracován PDPC diagram pro montáž elektronickich součástek na desku plošného spoje pájení vlnou. PDPC diagram byl vytvořen s cílem identifikaci rizik a definování preventivních akci. Objem informací, které mohou být zahrnuty do tohoto diagramu, je velmi vysoký. Fuzzy přístup byl použít k nalezení informací menší důležitosti, které mohou být zanedbané, a tím k redukci objemu vstupních informací pro zpracování PDPC diagramu.

Použití fuzzy logiky je vždy prezentováno pro jeden krok či operaci procesu. Uvedený přístup může být použit pro libovolný proces, operaci či krok s cílem získat hlubší poznání problému a lepší odhad průběhu analyzované události.

1 Introduction

In 1965, a work of Zadeh [1] under the name of Fuzzy Sets, was published in the journal *Information and control*. The aim of ideas and views of Zadeh fuzzy set theory was to describe phenomena and concepts that are inaccurate and have more meanings, which are fuzzy. Known mathematical techniques use classical set theory and two-valued logic that do not allow solving problems of this type. Fuzzy logic theory and its applications are covered in various books and monographs in different languages [2] – [12]. This notion will be described more detailed in the chapter *Basics of Fuzzy Theory*.

Fuzzy logic was widely used in the area of management of production quality. Such methods as 6 sigma, histograms, failure mode and effect analysis, fault tree diagram, control charts and others tools were combined with the fuzzy approach for obtaining of more powerful impact of such tools application and achieving of additional and more effective results [13] – [22]. This will be discussed in details in the chapter *Contemporary Fuzzy Approach to Quality Control*.

In this thesis, the application of fuzzy logic to selected management and planning quality control tools is presented. The approach finds its application when discords occur during discussion of the problems in the brainstorming group. For example, in the case when determining the timing of an action, each member of brainstorming group can have his own opinion. To combine the views obtained without losing any minor information the method of fuzzy logic was applied. The use of fuzzy logic makes acceptance of all ideas possible with a possibility to take into account a relative weight of each member of brainstorming group.

Application of fuzzy approach to the brainstorming analysis gives huge opportunity to increase quality of whole process by minimization of the impact issues related to the incorrect incoming analysis or low qualification of the members of brainstorming team. Goal of this work is to enhance standard quality control tools by an application of the fuzzy approach wherever brainstorming analysis takes place. This work presents improvement of timing analysis, possibility of a failure occurrence and severity of a failures, that occur in a process.

1.1 Goals of Thesis

There is many tools used for quality assessment. Among them are seven new management and planning tools: affinity diagrams, arrow diagrams, matrix data analysis, matrix diagrams, process decision program charts, relations diagrams and tree diagrams.

A team from the Union of Japanese Scientists and Engineers (JUSE) first collected these tools in 1976 with the aim to develop more quality control techniques with design approach. Those methods provide organization of verbal data diagrammatically, generating ideas, improving planning, eliminating errors, explaining problems intelligibly, persuading powerfully, and securing full cooperation. Some of the tools were not necessarily new, but their grouping and promotion were.

GOALS:

a) Present using of fuzzy approach to contemporary used quality control tools.
b) Apply the fuzzy approach to affinity diagram and compare the results with a standard affinity diagram approach.
c) Apply the fuzzy approach to process desision program chart and compare the results with a standard process desision program chart approach.
d) Apply the fuzzy approach to arrow diagram and compare the results with a standard arrow diagram approach.
e) Estimate an overall impact of the fuzzy logic to the selected management and planning tool.

2 State of the Art

2.1 Basics of Fuzzy Theory

2.1.1 Basic Characteristics of Fuzzy Logic

Fuzzy logic can be presented as a generalization of a classical logic. Fuzzy logic was developed in 1965, by Lotfi A. Zadeh, professor for computer science at the University of California in Berkeley. It was made to solve problems associated with imprecise data and where derivation rules are formulated in a very uncertain way [23].

Basis for development of fuzzy logic is that components of human thinking are not numbers. It is rather, linguistic terms that are not precisely defined. Linguistic terms also can also be called fuzzy sets [24]. It cannot be always referred one or another object to a particular group or class. There are a lot of objects related to the several groups simultaneously. It depends on criteria of a group. Criteria of one or another class should be defined precisely. Some objects cannot be defined using classical logic. For example, *big house*, *beautiful woman* or *loud music* cannot constitute clear group or its class. It is not always possible to certainly refer a particular object to a particular group; the data vary according to the expert opinion. Such cases are under observation of fuzzy logic [25].

Classical logical systems are usually based on Boolean two-valued logic. Any proffer can be either true or false. We can assume that it has its disadvantages during analysis of such *imprecise* meanings as *poor*, *tall* or *loud*.

Area of application of fuzzy logic is very wide. The paper *Application of fuzzy logic in the management of food industry enterprises* presents an analysis of the software of financial management in the enterprise, where the appropriate option for the enterprise is selected and the optimal price of the food product using fuzzy sets based on the Mathsad 14 program is calculated [26]. The article *Development of fuzzy logic for stock management in the repair of machine tools* describes the fundamentals of the method of fuzzy logic to control inventory in the repair of machine tools. An example of determining the optimal inventory units by fuzzy logic is introduced [27]. In the article *Quantitative assessment of image quality with the use of fuzzy logic methods*, approach to image quality measurement and image improvement and image quality is described. The proposed approach uses fuzzy logic techniques, especially the method of object edge detection [28]. The article *The development of a model system of decision support for railway transport* examines possibilities of creation on the railway transport of the adequate decision-making support system based on the fundamentals of the fuzzy sets and fuzzy logic theories [29]. The article *The application of fuzzy logic in humanitarian research* makes an attempt to prove that strictly formalized quantitative analysis has its limits, beyond which the quality, depth and completeness of the comprehension of reality can be lost. Therefore, in humanitarian studies, it is necessary to use "flexible" methods, one of which is fuzzy logic [30].

The research *The use of fuzzy logic tools in assessing the quality of customs services* studies the process of building a fuzzy model of the customs services quality evaluation. MatLab's Fuzzy Logic Toolbox was used and referred to separate customs services to illustrate how the proposed approach can be implemented. Fuzzy Logic Toolbox helped assess the quality of the services and provided an illustrative presentation of the findings. Considering limited and fuzzy information on the customs' performance, the fuzzy logic methodology constitutes the main tool to evaluate the quality of customs services [31].
Fuzzy analysis is applied in the areas described above, and in many other areas. Quality Management is a area of studies that contributes to all other areas and therefore research in this direction is made in the thesis.

The fuzzy logic is the rule-based system for making a right decision. It is a kind of multi-valued logic derived from fuzzy set theory to handle with approximate reasoning rather than with accurate. Fuzzy set theory specifies fuzzy operators on fuzzy sets. IF-THEN rules are usually used in fuzzy logic [32].

Fuzzy Logic arises as an advantageous tool for the controlling and handling of systems and complex industrial processes, as well as for household and entertainment electronics or for other expert systems and applications [33].

2.1.2 Fuzzyfication

The fuzzy set theory states that a fuzzy set A is a special fuzzy subset of real numbers. Its membership function μ_A (x), is a continuous mapping on an interval [0, 1].

Fuzzyfication is a process that converts crisp values into linguistic terms (linguistic variables), which are later quantified by fuzzy membership function using fuzzy sets (Fig. 1). Linguistic variables are the input or output variables of the system whose values are words or sentences from a natural language, instead of numerical values. Each fuzzy set expresses particular linguistic term. Fuzzyfication is the process of changing a real scalar value into a fuzzy value, this translates accurate crisp input values into linguistic variables.

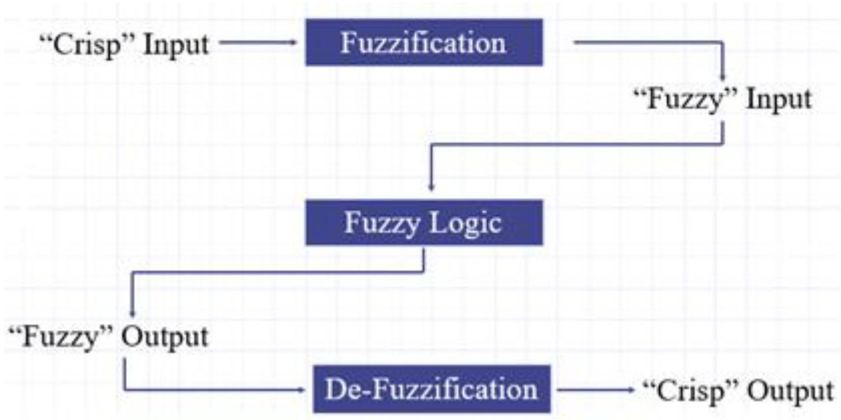

Figure 1. Fuzzy logic process

Many types of membership functions (μ) can be used. There are generally several types of membership functions, which are used for the fuzzyfication process: the Gaussian membership function (fig 2), a singleton membership function (fig 3). A fuzzy singleton includes only one element. Once the element x is defined, the corresponding fuzzy set is accordingly defined [34]. Trapezoidal or triangular membership functions are shown in fig. 4 and fig. 5. They are the most $\mu(x)$commonly used.

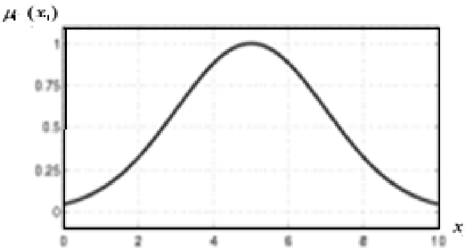

Figure 2. Gaussian membership function

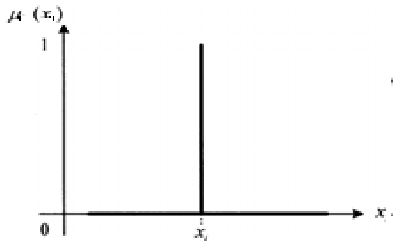

Figure 3. Singleton membership function

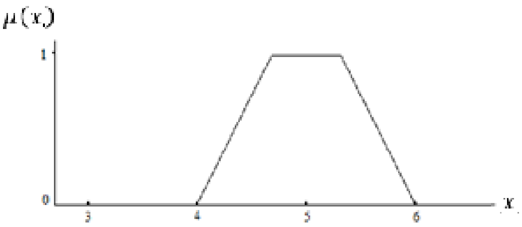

Figure 4. Trapezoidal membership function

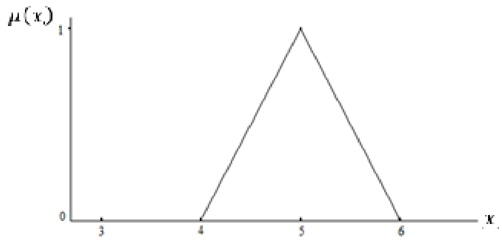

Figure 5. Triangular membership function

Shapes named as S function, P function and Z function. (Fig. 6) Three related membership functions are the Z, S, and Pi curves, all named because of their shape. The function Z is the asymmetrical polynomial curve open to the left, S is the mirror-image function that opens to the right, and P is zero on both extremes with a rise in the middle.

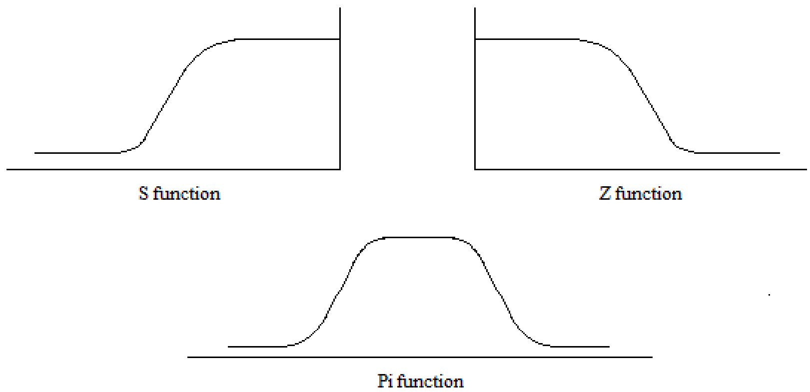

Figure 6. Graphs of the S function, the Z function and P function

The fuzzyfier decides how the crisp input will be converted into a fuzzy input. The singleton fuzzyfier simplifies the computation involved in any fuzzy inference engine. The Gaussian and triangular fuzzyfiers also simplify the computation in the fuzzy inference engine with Gaussian and triangular membership functions. They can suppress noise in the input, but singleton fuzzyfier cannot.

As trapezoidal and triangular shapes of membership functions are used in the thesis, they are examined more detailed. Membership function of triangular structure (Fig. 7) can be defined as follows (1) [35]:

$$\mu(x;m_1,m_2,m_3)=\begin{cases}0, & x\le m_1\\ \dfrac{x-m_1}{m_2-m_1} & m_1\le x\le m_2\\ \dfrac{m_3-x}{m_3-m_2} & m_2\le x\le m_3\\ 0, & x\ge m_3\end{cases} \tag{1}$$

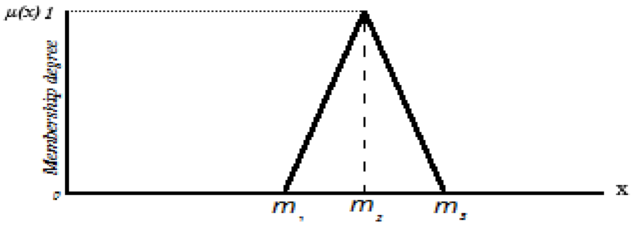

Figure 7. Triangular structure of membership function

A triangular fuzzy set is just a special case of a generalized trapezoidal fuzzy set. In fact, $(m_1, m_2, m_3) = (m_1, m_2, m_2, m_3)$, where $\mu(x)$ is a membership degree and x is an element of fuzzy set.

[36]. Trapezoidal fuzzy set is called a generalized fuzzy set and will be denoted by A (m_1, m_2, c, m_3, m_4) and has membership function (Fig.8) defined as follows (2):

$$\mu(x;m_1,m_2,m_3,m_4)=\begin{cases}0, & x\le m_1, x\ge m_4\\ \dfrac{c(x-m_1)}{m_2-m_1}, & m_1\le x< m_2\\ c, & m_2\le x< m_3\\ \dfrac{c(m_4-x)}{m_4-m_3}, & m_3\le x< m_4\end{cases} \tag{2}$$

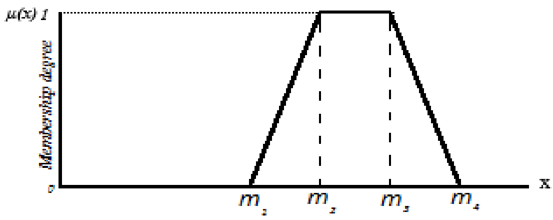

Figure 8. Trapezoidal structure of membership function

Number of membership functions depends on a number of input data (linguistic variables). Triangular and trapezoidal membership functions are encountered more often in practice e.g. [18-20, 37, 38] etc. As was specified, basis for development of fuzzy logic is that components of human thinking are linguistic terms or linguistic variables. And linguistic terms can be represented as fuzzy sets.

In practice, triangular or trapezoidal membership functions used to specify type of uncertainties: "approximately equal", "mean", "located in the interval", "similar to the object", etc. Z-shaped membership functions used to specify uncertainties of type: "small quantity", "small value", "insignificant value", "low level" and opposite S-shaped membership functions used to specify uncertainties of type: "large number", "large value", "significant value", "high level". Difference in Z- or S-shaped membership functions that they have either high or low degree of occurrence of a particular qualitative or quantitative trait [39].

2.1.3 Defuzzification

In fuzzification process, the crisp numbers are converted into fuzzy numbers, however in several applications as well as most of actions or decisions implemented by human or machines are binary or crisp in nature. So it is necessary after all to defuzzify the fuzzy results that have been made through fuzzy analysis. The process of converting the fuzzy output to a crisp value is said to be defuzzification.

A process of defuzzification that produces crisp value from fuzzy value is described in terms of membership in fuzzy sets. In other words, this is an integration of the membership degrees of the fuzzy sets into a specific decision or real value. There are a number of defuzzification methods, including center of gravity, center-of-area and mean of maximums, smallest of maximum and largest of maximum. The input for the defuzzification process is the aggregate set and the output is a single number. Center of gravity is frequently used in control engineering and process modeling. The rest represents discontinuous methods, which are mainly used in decision making and pattern recognition applications for selecting the alternative [40].

Figure 9 demonstrate how values for each method are found on membership function [41].

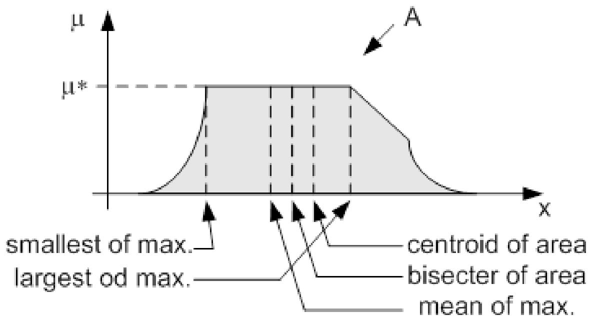

Figure 9. Graphical demonstration of results of defuzzification methods

Centroid defuzzification is the most commonly used method, as it is very accurate. This method is also known as center of gravity or center of area defuzzification. This technique was developed by Sugeno in 1985. This is the most commonly used technique. The only disadvantage of this method is that it is computationally difficult for complex membership functions. As a result the method provides center of the area under the curve of membership function. It can be expressed by the following formula 3:

$$x^* = \frac{\int \mu_i(x)x\,dx}{\int \mu_i(x)\,dx} \tag{3}$$

where x^* is defuzzified output (crisp value), μ_i is a membership degree and x is an element of fuzzy set.

Bisector defuzzification uses vertical line that divides area under the curve into two equal areas and can be represented by formula 4:

$$\int_{\alpha}^{z} \mu_A(x)\,dx = \int_{z}^{\beta} \mu_A(x)\,dx \tag{4}$$

Mean of maximum defuzzification method uses the average value of the aggregated membership function outputs, can be defined by formula 5: (Fig. 10)

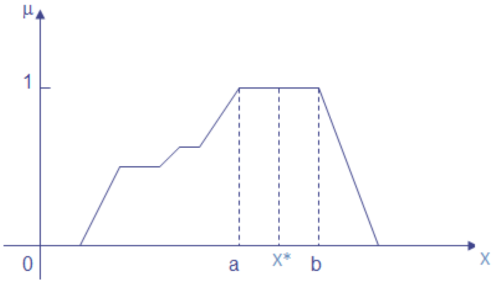

Figure 10. Graphical demonstration of *mean of maximum* defuzzification method

$$x^* = (a+b)/2 \tag{5}$$

Smallest of maximum defuzzification method uses the minimum value of the aggregated membership function outputs, and defined by formula 6:

$$x^* \in \left\{ x \middle| \mu(x) = \min_{\omega} \mu(\omega) \right\} \tag{6}$$

Largest of maximum defuzzification method uses the maximum value of the aggregated membership function outputs, and defined by formula 7:

$$x^* \in \left\{ x \middle| \mu(x) = \max_{\omega} \mu(\omega) \right\} \tag{7}$$

Weighted average defuzzification method, based on peak value of each fuzzy sets, calculates weighted sum of these peak values. According to these weight values and the degree of membership for fuzzy output, the crisp value of output is determined by the following formula 8:

$$x^* = \frac{\sum \mu(\mathrm{x})_\mathrm{i} \times \mathrm{W}_\mathrm{i}}{\sum \mu(\mathrm{x})_\mathrm{i}} \tag{8}$$

where μ_i is the degree of membership in output singleton *i*, W_i and is the fuzzy output weight value for the output singleton *i* [42].

2.2 Brainstorming

Brainstorming is a form of creative, collaborative searching for solutions to the problems. This method is widely used in various fields. Brainstorming combines options of teamwork where new ideas are created or the known facts are being associated.

Common situations for a brainstorming are to generate different ideas in a short period, to develop unconventional ideas, to look for solutions in a situation where a decision cannot be obtained logically. To systematize information when it is messy and distributed among several sources.

The most effective brainstorming works only in the groups with active teamwork, as in this case the effect of the interaction occurs. Group size is important because if the group is too small, some interactions may be lost. If the group is too large, discussion can turn to chaos.

Brainstorming includes the following steps:

1. Define the problem to solve. The problem should be stated clearly, precisely and avoid ambiguity.

2. Assign (determine) a curator of a brainstorming session. Only person with special skills of teamwork organization can be chosen for this role. In addition, the person has to have clear understanding of the problem and to be the leader of the group that performs brainstorming. If necessary, separate person for records keeping in the session can be assigned (or curator can do the records).

3. Form a group of between 5 to 8 people interested in solving the problem. Experts in various fields should be selected for the group. It would be advised to avoid including people with mutual negative attitude towards each other into either team. This is because they will interfere with the team's ability to create new ideas in the processes.

4. The team members are arranged so that they are all looking in the same direction - on the flip chart or a whiteboard. A problem to solve is written on the whiteboard. Thus, team members will look at the problem and not on each other. This will create a more comfortable atmosphere for psychological work and effective for brainstorming.

5. During the session, the curator of the group must ensure that members of the group abide by the four main rules of brainstorming.

These rules help to manage work groups:

- No criticism or discussion during the generation of ideas. No negative comments about the proposed solutions. Participants should focus on the problem, rather than on criticism of the proposed solutions. Assessment of proposed solutions run after ideas "generation" process.
- There are no restrictions. Welcome any, even the most absurd ideas;
- Quantity is more important than quality. The more ideas will come up, the higher the chances of a successful solution to the problem;
- Combining and improving. In order to get new ideas all offers should be combined and modified. Allowed even the minor changes and incorrect interpretation of the presented ideas.

Curator must support psychologically comfortable environment while brainstorming. His responsibilities include following to the rule of "no criticism", as well as prevention of situations that can block the ideas' statements. Also, to avoid interruptions during the work running, as they interfere with the free generating new ideas.

6. Perform teamwork, during which the team members offer their solutions to the problem. The curator must ensure that all members of the group were involved in brainstorming. For this example, the word can be given to one-by-one. Then, when all are concerned, the word can be given randomly. Team members must submit one idea at a time and avoid a return to the ideas already announced.

7. While ideas will be offered responsible person for the records must register each of them on the board or flip chart, so that all team members can see them. Brainstorming should always be accompanied by recordings.

8. When the number of new ideas will start to decrease, attempt to stimulate the flow of ideas.

Actions to proceed may include:

- each member of the group may create own list of ideas in advance and present them when run out of ideas created collectively;
- at the time to stop and conduct a review of previously proposed ideas. Search possibilities of combining and changing the ideas presented;

- to take a break. Allow team members to relax, escape from the problem being solved. You can even postpone brainstorm for a few days. This will allow people to add new ideas that came to mind during this period;
- hold a session of "crazy ideas" when the goal is to create the most absurd ideas;
- improve the most promising ideas through discussion;
- use a combination of the above action options.
- after completion of the ideas' generation, discuss the solutions, in order to select the best. These ideas need to be analyzed taking into account possible limitations, such as time and cost.
- if the team cannot agree on the choice of the best ideas or if the team members are not ready to give preference, the ideas used for the selection of the consensus method (voting system).
- Once the best ideas will be selected curator will have to confirm that this decision is a collective and all team members agree with this decision. At this level brainstorming can be considered as completed.

Brainstorm has several advantages in comparison with other methods of teamwork. In particular, for the creation of new ideas do not need to attract highly qualified specialists or experts, the method is simple to understand and requires no special training participants, allows you to quickly generate new ideas, provides opportunity for professionals of different fields to participate in the searching of problems solutions.

Disadvantages of the brainstorming method associate with the organization of the working process. If the curator cannot manage and control team, then the team will deviate from established rules and work process can be a long and useless. Another disadvantage may be generating ideas that would either difficult or impossible to implement [43].

Nowadays many quality control methods use brainstorming. The essence of this work is to propose the use of fuzzy logic to the management and planning tools through brainstorming. Fuzzy logic is able to present the results of brainstorming numerically, be counted and the result then transformed (defuzzified) back into a "crisp" result. Thus, the result of applying the method of quality control will be much more accurate.

3 Contemporary Fuzzy Approach to Quality Control

Quality control and risk analysis became an essential part of the success of each company. However, with ever increasing frequency companies have to make decisions under conditions of uncertainty, which may lead to unintended consequences and, therefore, adverse outcomes and losses. Especially serious consequences may be the wrong decision for long-term periods that are usually implied in the evaluation of projects. Therefore, the identification in time, as well as adequate and the most accurate risk and quality assessment is one of the most vital problems of modern quality management and risk analysis.

Unfortunately, the risk analysis and quality management techniques existing nowadays are not devoid of subjectivity and substantial assumptions, which lead to incorrect results during the risk analysis and quality estimation processes. The theory of fuzzy logic is a new, dynamic approach to risk and quality assessment. In recent years, fuzzy modeling is one of the most active and promising areas of applied science in the field of management of production quality.

Contemporary fuzzy approach to quality control is presented in presented in this chapter, such as, fuzzy failure mode and effect analysis, fuzzy fault tree analysis method, fuzzy histograms, fuzzy control. Definitions of the methods as well as principles of fuzzy logic are mentioned in previous chapters. At the moment it is necessary to focus on existing advantages and disadvantages of the fuzzy logic approach. The use of fuzzy logic has several advantages. It allows you to:

- include qualitative variables into analysis,
- handle fuzzy input data,
- operate on linguistic criteria,
- simulate complex dynamic systems and compare them with a predetermined degree of accuracy in short period of time,
- overcome the shortcomings and limitations of existing methods for assessing project risks and solving production quality issues.

Disadvantages of the method:

- subjectivity in the choice of membership functions and establishing of fuzzy rules shaping the input,
- lack of awareness about the method, as well as little attention to the use of the method by professional institutions,
- need in special software, as well as professionals who are able to work with it.

Despite the shortcomings and limitations of the theory, the method of fuzzy sets has been recognized as a promising and giving accurate results by some of the largest international companies (Motorola, General Electric, Otis Elevator, Pacific Gas & Electric, Ford). Risk analysis based on statistical methods for most of the newly formed company is not applicable, since there is no accumulation of statistical information for objective assessments [18, 44-47].

Thus, the method of fuzzy sets does not preclude the application of statistical methods, but becomes an instrument when other approaches to risk assessment are not applicable.

3.1 Contemporary Fuzzy Approach to Failure Mode and Effect Analysis

3.1.1 Failure Mode and Effect Analysis

FMEA is an inductive approach, which consist of steps for identifying the potential failure modes of its components, their causes and their effects in a system, process or in one of its sub-action.

Failure mode (FM) refers to the way or mode in which something might fail and includes potential errors that may occur. Failures are any errors or defects, especially ones that affect the customer, and can be potential or actual.

Effect analysis (EA) involves discovering of the consequences of those failures by making sure that all errors can be detected, establishing how frequently a failure might occur and prioritizing potential failures. Analysts in different areas typically use FMEA to assist them in the completion of the analysis. They might perform an FMEA when a product or service is being designed or fixed or an existing product is under modification and going to be used in a different way.

Failures are prioritized according to how serious their consequences are (Severity), how frequently they occur (Occurrence) and how easily they can be detected (Detectability). The purpose of the FMEA is to take actions to eliminate or reduce failures, starting with the highest-priority ones [48].

There are several types of FMEAs (some are used much more often than others):

- System – adjusted for global system functions
- Design - adjusted for components and subsystems
- Process - adjusted for manufacturing and assembly processes
- Service - adjusted for service functions
- Software - adjusted for software functions

Generally, there are few main points of FMEA method:

It is inductive, bottom-up analysis method directed at analyzing the effects of single component or function failures on equipment or subsystems;

It is good at exhaustively cataloging initiating faults, and identifying their local effects;

It is not good at observation of multiple failures or their effects at a process level;

It does not consider external events.

The benefits of the process FMEA are:

- Identifies process deficiencies and offers a corrective action plan.
- Identifies the critical or significant characteristics and helps in developing control plans.
- Establishes a priority of corrective actions.
- Assists in the analysis of the manufacturing or assembly process.
- Documents the rationale for changes.

It can also be used before developing control plans for a new process or following a quality function deployment. Typically, FMEA often combined with different quality management tools to increase the usability and preciseness with following increasing of the final product quality, for example, lean production methodology uses an FMEA periodically throughout the life cycle of a product or service [49].

3.1.2 Fuzzy Approach to Failure Mode and Effect Analysis

The reason of attempt to make FMEA fuzzy is that the crisp RPN has a range of disadvantages which are mentioned in the following articles: *An assessment of RPN prioritization in a failure mode effects and criticality analysis* [50], *A revised failure mode and effects analysis model* [51]. However, major disadvantage of the traditional FMEA is that it doesn't take into account the relative importance of the risk factors and treats them equally. For example, two different events with the values of 4, 3, 1 and 2, 1, 6 for O (Occurrence), S (Severity) and D (Delectability), respectively, have the same RPN, value of 12. These three risk factors are considered to be the same degree of importance. Therefore, it does not give objective empirical result. The possible way to overcome this drawback is to join the risk factors with the relative importance. This issue is solved in the article *Risk evaluation in failure mode and effect analysis using fuzzy weighted geometric mean* [22].

Other case of the usage of fuzzy FMEA is shown in the article *Development of a fuzzy FMEA based product design system*. The applicability of fuzzy logic and knowledge-based approach with the FMEA methodology to today's competitive product design and development is explored in the paper. A framework of a fuzzy FMEA-based evaluation system for new product concepts is proposed. A prototype fuzzy knowledge-based system named EPDS-1, which can assist inexperienced users to perform the FMEA analysis for quality and reliability improvement, alternative design evaluation, materials selection, and cost assessment, which could help to enhance robustness of new products at the conceptual design stage is developed, based on the proposed approach and methodologies [49].

In the paper *Failure mode and effects analysis using fuzzy evidential reasoning approach and grey theory*, the two issues of FMEA are being solved. The first, the acquirement of FMEA team members' diversity opinions and, the second, the determination of risk priorities of the failure modes that have been identified. In this paper, an FMEA using the fuzzy evidential reasoning (FER) approach and grey theory to solve the two problems and improve the effectiveness of the traditional FMEA is presented. As a result, it is illustrated by the numerical example, that the proposed FMEA can well capture FMEA team members' diversity opinions and prioritize failure modes under different types of uncertainties [52].

The aim of the next research under the name *Modified failure mode and effects analysis using approximate reasoning* is to develop a method that does not require to define the probability of occurrence, severity and detectability considered for the analysis and to avoid the use of the traditional RPN. Information gathered from experts and integrating them in a formal way to reflect a subjective method of ranking risk to achieve this goal [48].

3.2 Contemporary Fuzzy Approach to Fault Tree Analysis

3.2.1 Fault Tree Anaylsis

Fault Tree Analysis (FTA) is another technique for reliability and safety analysis. The concept was developed in Bell Telephone Laboratories in 1962 for the US Air Force. It was later adopted and extensively applied by the Boeing Company. FTA is a very powerful systematic way which is used widely for estimation of process quality. The tool helps to define areas of concern for new product design or for improvement of existing products. It also helps to define corrective actions to fix or decrease a number of issues. FTA is useful both in new products designing and in continuation of identified problems solving which belonged to existing products/services. As the great part of process quality improvement, the FTA can be used to optimize goals and process features and at the same time to design for critical factors and human error.

Fault tree analysis is a top-down approach to failure analysis. Starting from the top event, the fault-tree method uses a Boolean algebra and logical modeling to graphically represent the relations among various failure events at different levels of the process. The analysis proceeds by identification how the top-event (fault) can be caused by individual or combined lower level failures or events. The causes of the top-event are *connected* through logic gates as shown on figure 11 [53].

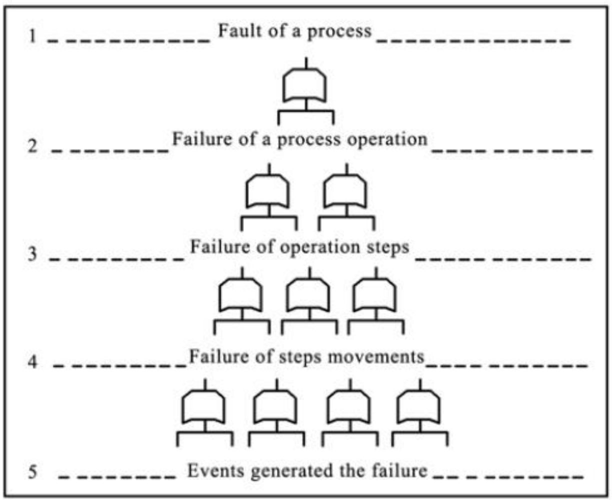

Figure 11. Typical Fault Tree

In this technique, the deductive logic is used. It gives possibility to find the root causes of failure events of a process. This type of logic helps to establish a clear and detailed scheme of relationships between steps or events of the process that can affect their quality.

The contribution of the fault tree is as follows:

- Understand the logic leading to the undesired state (top-event).
- Clearly shows weak parts of the process.
- A graphical representation of the results is common for analysts what facilitate the execution of the final task.
- Allows seeing in details potentially failure parts of the process.
- Helps identify failures deductively.
- Gives a possibility to do a qualitative or quantitative analysis of the process.
- Assist in designing a system.
- Method allows focusing on the different parts of the process, and extracting specific failures.
- Minimize and optimize resources
- Clearly represents the behavior of the process.
- Helps to understand the idea of the system or process behavior deeply with consequent penetration into its functionality.
- Functioning as a diagnostic tool to identify and correct causes of the top-event. It can help with the creation of diagnostic manuals / processes.
- Highly facilitate the reliability analysis of complex systems or processes.

The main advantage of the fault tree, in comparison with other methods, is that the analysis is limited by identification of those events of the process only which lead to a specific process failure.

Disadvantages of a fault tree are as follows:

- Implementation of the method requires serious expenses and time consumption, because increase of the process details leads to geometric increase of analyzed area and the number of influencing events grows correspondingly.
- Fault tree represents a boolean logic diagram, which shows only two states: working and failed.
- Requires reliability specialists having deep knowledge of a process.
- It is difficult to estimate the state of partial failure of the process parts, because using the method generally believes that the process is either in a good condition, or in a faulty state [54].

3.2.2 Fuzzy Approach to Fault Tree Analysis

A definition of a fault tree analysis method was given in a previous chapter. The latest experience of application of fuzzy logic approach to FTA is presented.

As the first example, the research under a name *Fuzzy set theoretic approach to fault tree analysis* will be considered [46]. This work is based mainly on failure probability of basic events, which uses classical probability distribution. He substituted probabilistic consideration of basic events with possibilities, consequently arriving to fuzzy fault tree analysis. The author made an attempt to create an algorithm to find a single fuzzy number for every single basic event, wherein more than one fuzzy number is assigned to that particular event. As each basic event play different role in the occurrence of top event correspondingly having different importance, author arrived to the conclusion that a critical analysis of the importance of different basic events may help in making a proper sequence of their importance. On improving the reliability of the event having greater importance, one can improve the reliability of the system. As an example of application, the author chose *Nuclear power plant* with a *Radiation release* as a top event. On replacing the Boolean operators with fuzzy logic operators FNOT, ORF and ANF, we get the possibility of the top event in form of a fuzzy number. It is also assumed that each basic event is fuzzified by assigning three fuzzy numbers to each basic event following the decision of three experts. The fuzzy importance of each basic event can be obtained in the form of fuzzy importance index (FII) for all basic events. This approach can be widely used to improve the reliability and to reduce the operating cost of a system.

The paper *Fuzzy fault tree analysis for fault diagnosis of cannula fault in power transformer* presents an intelligent fault diagnosis method of power transformer using fuzzy fault tree analysis (FTA) and beta distribution for failure possibility estimation [45]. This is highly important to ensure an uninterrupted power supply. Author used a row of possible issues (information transmission mistakes as well as arisen errors while processing data in surveying and monitoring state information of transformer, uncertain and incomplete information may be produced) to analyze. By using the technique, he proposed herein, the continuous attribute values are transformed into the fuzzy numbers to give a realistic estimate of failure possibility of a basic event in FTA. Further, it explains a new approach based on Euclidean distance between fuzzy numbers, to rank the basic events in accordance with their *Fuzzy importance index*.

Another application of fuzzy approach to FTA is the research *An application fuzzy fault tree analysis to uncontained events of an aero-engine rotors* [55]. Chinese authors used descending method to determine the minimal cut sets. Furthermore, the interval representation and calculation strategy is presented to describe the failure probability, and the resulting fault tree is analyzed quantitatively in a case study.

3.3 Contemporary Fuzzy Approach to Histograms

3.3.1 Histograms

Histogram - a tool to visually assess the distribution of statistical data, grouped by frequency of occurrence data in a certain (predetermined) interval. A histogram is a graphical method for displaying the shape of a distribution. It is particularly useful when there are a large number of observations. It is built using rectangles, their area is proportional to the frequency of finding of a given value in the interval on which this rectangle is built.

Histogram example is presented in figure 12.

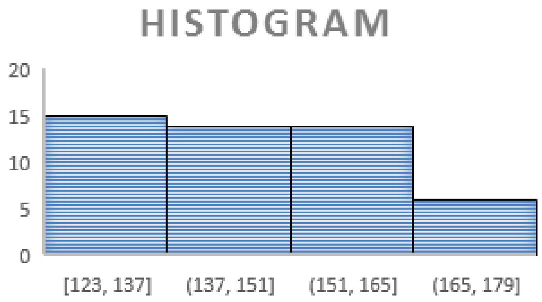

Figure 12. Example of a histogram

Steps to create a histogram:

1. On the vertical axis, place frequencies. Label this axis *Frequency*.
2. On the horizontal axis, place the lower value of each interval. Label this axis with the type of data shown.
3. Draw a bar extending from the lower value of each interval to the lower value of the next interval. The height of each bar should be equal to the frequency of its corresponding interval.

3.3.2 Fuzzy Approach to Histograms

In the paper *Fuzzy histograms: a statistical analysis* is declared, that Fuzzy histogram is a fuzzy generalization of ordinary crisp histogram. Fuzzy histograms statistically and compared with other nonparametric density estimators were analyzed in the paper. And at the end it turns out that fuzzy histograms can be used to combine a high level of statistical efficiency with a high level of computational efficiency [14].

In the paper *Fuzzy histograms and density estimation* was noticed that the popularity of the histogram technique is not only due to its simplicity (no particular skills are needed to manipulate this tool) but also to the fact, that the piece of information provided by a histogram is more than a rough representation of the density underlying the data. It was denoted that a histogram displays the number of data (or observations) of a finite data set that belong to a given class i.e. in complete agreement with the concept summarized by the label associated with each bin of the partition thanks to the quantity. Also, it was pointed out that the histogram density estimator has some weaknesses. The choice of both reference interval and number of cells (i.e. bin width) have quite an effect on the estimated density. The apriorism needed to set those values makes it a tool whose robustness and reliability are too low to be used for statistical estimation. It was investigated that during the last five years, it has been suggested by some authors that replacing the binary partition by a fuzzy partition will reduce the effect of arbitrariness of partitioning. This solution has been studied as a practical tool for Chi-squared tests estimation of conditional probabilities in a learning context or estimation of percentiles and modes [56-59]. Recently, some authors have proposed to explore the universal approximation properties of fuzzy systems to solve system of equations. In a first part of this paper it was formally presented the fuzzy partition as proposed in [59]. Then, a histogram based upon this previous notion was defined, that was called a fuzzy histogram. In a last section, some estimators of probability density functions are shown. At the end, density estimators based upon a fuzzy histogram were presented. This latter being nothing else but a generalization of the popular crisp histogram, when replacing the crisp partition by a fuzzy partition. Those proposed density estimators consist in interpolations of the node values of the density obtained in the usual way.

3.4 Contemporary Fuzzy Approach to Control Charts

3.4.1 Control Charts

The control chart is a graph used to study how a process changes over the time. Data are plotted in time order. A control chart always has a central line for the average, an upper line for the upper control limit and a lower line for the lower control limit. These lines are determined from historical data.

Control chart basic steps:

1. Choose the appropriate control chart for your data.
2. Determine the appropriate period for collecting and plotting data.
3. Collect data, construct your chart and analyze the data.
4. Look for “out-of-control signals” on the control chart.
5. When one is found, mark it on the chart and search for the cause. Make a report how you investigated, what you learned, the cause and how it was corrected. (Fig.13)

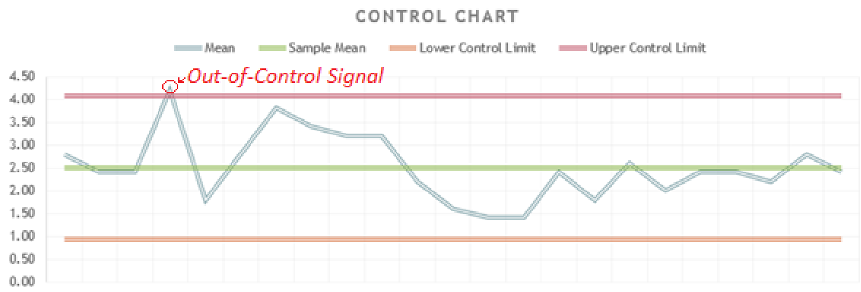

Figure 13. Example of a control chart built in Excel

3.4.2 Fuzzy Approach to Control Charts

Statistical control charts are useful tools in monitoring the state of a manufacturing process. Control charts are used to plot process data and compare it to the limits set for the process. Points plotting outside these limits indicate an out-of-control condition. D. J. Fonseca1 from the University of Alabama, USA in his paper *Fuzzy short-run control charts* [60] arrived to the conclusion that standard control charting procedures are limited as they cannot take into account the case when data is of a fuzzy nature. Another limitation of standard charting methods is when the data produced by the process is short-run data. Often, the situation where the data is short-run occurs in conjunction with data that is considered fuzzy. This paper discusses the development of a fuzzy control charting technique, called short-Run α-cut p control chart, to account for fuzzy data in a short-run situation. The developed chart parameters accounted for the fuzzy nature of the data in a short-run situation. The parameters were validated by comparing the false alarm rates for various combinations of subgroup numbers (m) and subgroup sizes (n). It was shown that for every combination of m and n, the short-run α-cut p control chart limits produced a lower false alarm rate than that of the standard fuzzy α-cut control chart.

The objective of this research was to modify the α-cut procedure for fraction nonconforming control charts to account for the case when data collected from the process is of a short-run nature. The results of the study included algorithms for all chart parameters involving the center line, plot values, and upper and lower control limits.

The short-run α-cut p control chart parameters were validated and verified, and have been proven successful in producing results that exceed that of the standard α-cut p control chart by Gulbay et al. [61]. The objective of this research was to modify the α-cut procedure for fraction nonconforming control charts to account for the case when data collected from the process is of a short-run nature. The results of the study included algorithms for all chart parameters involving the centerline, plot values, and upper and lower control limits. The short-run α-cut p control chart parameters were validated and verified, and have been proven successful in producing results that exceed that of the standard α-cut p control chart by Gulbay et al.

In the article *Fuzzy control chart A better alternative for Shewhart average chart* was declared that a real illustrative example and a power test that designing a fuzzy control chart for process average of a continuous (variable) quality characteristic with a warning line is a better alternative to Shewhart. $\bar{X}$ chart in many respects, like providing better neural view to inspectors, offering different strategic options for company to choose, detecting the desire shifts more quickly, and more sensibility to small shifts without any complexity augmentation to the chart [62].

In [62] it is introduced a fuzzy chart for controlling the process mean. Also she classified the observations in the rational groups and that helps to the inspector that has a neural view of the shifts in the process mean and also can control the dispersion by this classification. Also as many inspectors want to control the process in a specific level of shifts in the process mean, so she designed a fuzzy chart that has a warning line besides upper control limit. The control limit, UCL, controls the process in all. The warning line is designed for detecting desired shift in the process that is important to the company.

As mentioned in [63], that is not possible to forget that the importance of a process shift depends on the process capability. If a process is very capable, small process shifts hardly influence the amount of nonconforming items. If we a plan for these very capable processes has to be chosen, the one able to quickly detect large process shifts should be selected. On the other hand, for a process of small capability even a small shift can produce a large amount of nonconforming items. Therefore, these small shifts should be quickly detected. Thus, shift sizes which are “important” for control purposes needed to be clarified.

Also the false alarm rates and warning lines besides average run length values were calculated. The best value of ARL for detecting the specified shift is shown by this fuzzy chart. Also comparison between fuzzy chart and Shewhart chart is made. And the fact that this new method has better power to detect shifts is shown in this paper.

One year later one more paper of the same author was published in the journal *Fuzzy Sets and Systems* with a name *An application of fuzzy random variables to control charts*. The author declared that the two most significant sources of uncertainty are randomness and incomplete information. Her paper aims to construct a fuzzy statistical control chart that can explain existing fuzziness in data while considering the essential variability between observations. The proposed control chart is an extension of Shewhart $\bar{X}- S^2$ control charts in fuzzy space. The proposed control chart avoids defuzzification methods such as fuzzy mean, fuzzy mode, fuzzy midrange, and fuzzy median. The out-of-control states are determined based on a fuzzy in-control region and a simple and precise graded exclusion measure that determines the degree to which fuzzy subgroups are excluded from the fuzzy in-control region. The proposed chart is illustrated with a numerical example in this paper [64].

After analysis of fuzzy process control literature, the author arrived to the conclusion that some existing control charts use various representative values, such as fuzzy mean, fuzzy mode, fuzzy midrange, and fuzzy median to control the fuzzy processes. It is mentioned, there is no theoretical basis supporting any one specific methodology, and selection should be based mainly on the ease of computation or the user's preference [65]. When a fuzzy sample is asymmetric, these representative values result in different scalars, and so control charts based on these representative values may result in different decisions. This is due to the loss of information when fuzzy samples are transformed into crisp numbers. In fact, in fuzzy space, sample data need to be monitored as a fuzzy number without any transformation, and then decisions based on the fuzzy data should be derived from fuzzy sets theory. Hence, fuzzy control charts must monitor "the grade to which the process is in control." Then, SPC practitioners can decide whether or not the process is in control.

The area under the membership function has been considered to be an appropriate measure of fuzziness, and a new methodology for fuzzy process control was presented, which monitors processes with fuzzy outcomes represented by *LR* fuzzy sets in the paper [64]. The approach constructs the fuzzy in-control region, and the chart measure determines the grade of membership, i.e., the degree to which the process belongs to the out-of-control state. Compared with existing fuzzy control charts, the proposed approach is quite different in the sense that it does not require the use of any representative values of fuzzy sets and the out-of control states are thoroughly determined in accordance with fuzzy sets theory. To keep the chart simple and more practical, it is recommended to plot both the Shewhart $\bar{X}$ and the proposed chart measure together. This enables quality experts to analyze warnings and out-of-control signals easily and to detect unusual trends in the process mean.

4 Management and Planning Tools Selected for Enhancement Using Fuzzy Approach

4.1 Enhancement of the Arrow Diagram

4.1.1 Basics of the Arrow Diagram

Arrow diagram (or Network diagram) – is a quality tool for process scheduling and following process managing.

Arrow diagram is a tool to plan the optimal time performance of all required work for the fast and successful implementation of a set goal. Japanese Union of Scientists and Engineers in 1979 included the arrow diagram of the seven methods of quality management.

This tool is used to ensure that the planned time for all the work and its individual stages is optimal for achieving of established goal. This tool is widely used not only in planning, but also for the subsequent implementation of planned activities. Especially this tool is widely used in the development of various projects and production planning. This method is based on Critical path method and Program evaluation and review technique (PERT) where for representation and algorithmization of certain actions or situations used network models, the simplest of which - network diagrams. (Fig. 14)

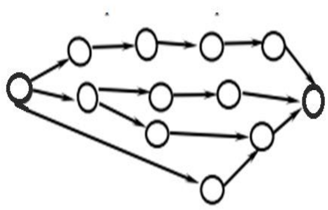

Figure 14. Graphical representation of the arrow diagram

The use of this tool is possible only after:

1) the problems to be solved are identified,

2) the necessary measures are identified,

3) the timing and stages of measures implementation are identified.

The traditional method of such planning is a method that uses the arrow diagram or in the form of so-called Gantt chart (Gantt). A Gantt chart is only necessary because it includes the information, which is not in the arrow diagram. For example, using a Gantt chart, you can plan the timing of the service.

Gantt chart is a horizontal line chart on which the objectives of the project are presented extended in time segments characterized by start and end dates, delays, and possibly other temporal parameters. Example of the Gantt chart is as following in table 1.

Table 1. Gantt chart for a project planning

№	Operation	Month's day					
		5	10	15	20	25	30
1	a	→					
2	b		→				
3	c		→				
4	d						
5	e						
6	f						
7	g						
8	h (Testing and delivery)						

Gantt chart is approved to be quite suitable for process visualization.

Gantt charts have its own technology. Operation is called work. Each operation is assigned with a serial number. Followed by the title of the work. The rows corresponding to the operations, reflects the start time, duration of operation and the end time.

As in any other process, unexpected undesired events can appear in production process, risk analysis or quality control process. It is about critical moments when risk of control loss over the flow of the process will be amplified. And Gantt chart doesn't include such information. That is a disadvantage of this process.

The steps how to create an arrow diagram is as following:

a. Form a team of specialists concerned into considered topic.

b. Clearly state the problem to be solved.

c. Determine the necessary measures.

d. Define terms and stages of the work.

e. Construct a chart of work progress reflecting sequence of actions required to achieve the desired result.

f. To carry out the continuous monitoring of the work execution.

As a result, precise plan of work for achieving the ultimate goals will be obtained.

Advantages are a visibility, ease of development and use. And obvious disadvantage is the lack of selection rules and criteria for assessing the viability and proper efficiency options for the implementation of all the necessary work.

The sequence of operations and the impact of a transaction on the course of subsequent operations are shown at the arrow diagram. Therefore, the arrow diagram is more convenient to follow the progress of the work than the Gantt chart, which considers the works as they are not related to each other [66].

The most common area to use arrow diagram is for various projects or works that form a set of interrelated activities. Its application allows determining the timing and completion of the project to identify possible options for reducing the timing works. As elements in the diagram are inter-related by time, it gives you the opportunity to monitor progress.

Professor of Political Science of Columbia University M.J. Peterson, whose researches include world politics, international institutions, international political economy, technology, and technological change, developed the way of using of arrow diagrams to understand claims. In his work he insists and proving, that arrow diagrams are very useful when dealing with a relational claim. Whether you are trying to understand someone else's argument or are formulating your own, arrow diagrams can help you keep track of the claim whenever the claim involves a statement of relationship. However, arrow diagrams are very useful when dealing with a relational claim. Arrow diagrams start becoming useful when a one-part relational claim links three or more elements. Professor notices that arrow diagram has opportunity to be as complex as you need it and that is a big advantage of the tool [67]. Example problems for the course named *Critical Path Methods* were published. This course contains a number of tasks, which include study of network constructions, when activity is on arrow and activity is on node, event approach and missing floats when activity–on-arrow scheduling, and many other tasks. This information can help to understand the essence of the arrow diagram tool and its application as well as calculate critical path of a process [68].

4.1.2 Fuzzy approach to the Arrow Diagram

Inherently arrow diagram is a graph whose nodes represent the event (or state of the object at a time), and the arcs connecting nodes reflect work. There is another option representing arrow diagram, when the nodes of the graph are the works and the arcs show only the relationship between them. This option is used more often. It is part of the method of CPM (Critical path method).

Approach when arcs represent work is used in the thesis.

A practical case for demonstration of using of fuzzy logic for optimization of a process of a mobile phone repair follows. Theoretical approach is presented at first.

Let us assume a production process consisting of four steps. A goal is to improve the effectiveness of a process by resolving timing problems using arrow diagram supported by fuzzy logic.

We consider a single action from a production process. Figure 15 shows an example of an arrow diagram, where AB, BC, CD and DE are a process actions. The timing of the actions is defined by the brainstorming group. The estimation of timing of actions AB, BC and DE is possible to assign with sufficient accuracy while estimation of action CD has been made in a wider time interval. Therefore, the time of action CD has been estimated with the support of fuzzy logic.

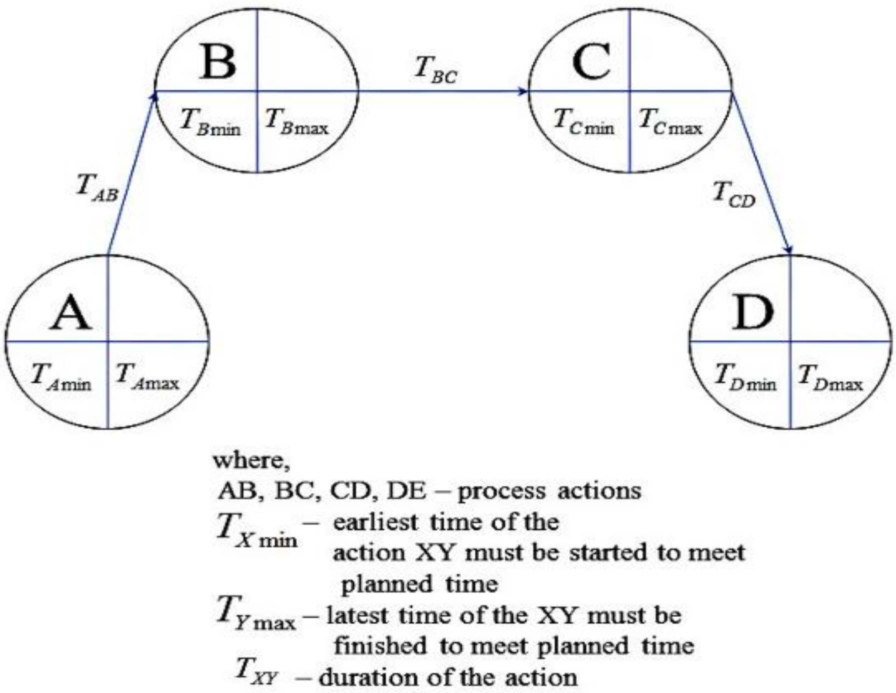

Figure 15. Arrow diagram for a process

First, a fuzzy rating scale for timing analysis must be created, and some linguistic variables and the corresponding fuzzy numbers must be established. Table 2 presents linguistic variables along with the corresponding values (periods of time) and fuzzy numbers used to assess the duration of the CD process. We assume that the duration of the action CD is x_n . Fuzzy ratings on a ten-point scale for the duration are given in the table. Variables x_1 ... x_n are time intervals. Variable R_1 ... R_n are fuzzy numbers.

Table 2. Fuzzy rating scale for the duration of CD process

Rating	Corresponding period	Fuzzy number
Minimum period	x_1	R_1
Extremely short	x_2	R_2
Sufficiently short	x_3	R_3
Quite short	x_4	R_4
Optimum min time	x_5	R_5
Optimum max time	x_6	R_6

Quite long	x_7	R_7
Sufficiently long	x_8	R_8
Extremely long	x_9	R_9
Maximum period	x_{10}	R_{10}

After the rating scale is completed, the brainstorming team analyzes the process to detect the most suitable time for CD action.

A triangular membership function was chosen with respect to sufficient accuracy of estimation.

Based on the above information and taking into account data from Table 4, membership functions for timing analysis of CD are created (Figure 16). There are now several fuzzy sets of numbers representing the fuzzy character of the membership options, because the linguistic variable does not indicate a particular number.

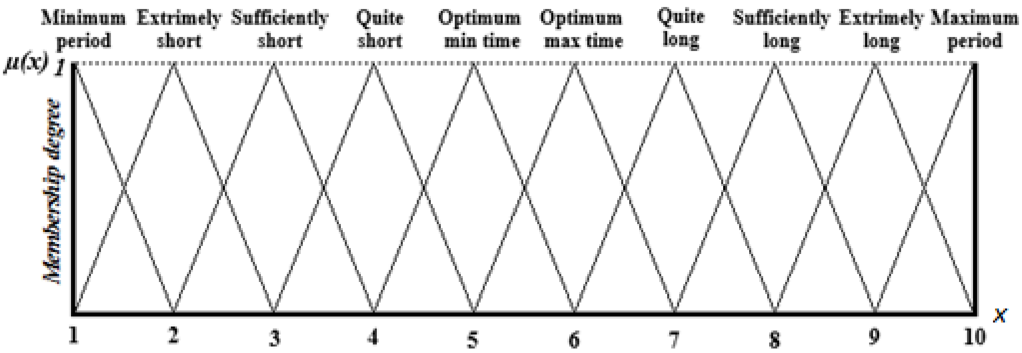

Figure 16. Membership functions of timing analysis fuzzy ratings

Let $R_{i(j)} = (R_{i(j)L:}, R_{i(j)M}, R_{i(j)U})$ are the fuzzy numbers of the *i*th linguistic variable chosen by team member *j*. Let $TM_1,...,TM_m$ are team members of the brainstorming group with the relative importance weights $W_1,...,W_m$ respectively, where $\sum_{j=1}^{m} W_j = 1$ and w_j >0 for j=1,…,m. Based upon these assumptions, the fuzzy analysis of brainstorming can be defined by the following formula 9 [22] :

$$\tilde{R} = \sum_{j=1}^{m} R_{i(j)} W_j = (\sum_{j=1}^{m} (W_j R_{i(j)L}, W_j R_{i(j)M}, W_j R_{i(j)U}), i = 1,..., n \quad (9)$$

Table 3 below shows aggregated fuzzy assessment information for the timing analysis of the assumed problem. The importance weight of each member of the group was also taken into account to obtain results that are more precise.

Table 3. Fuzzy assessment information for the duration analysis of BC process

Member	Importance weight of every member	Fuzzy rating according to members' opinions	Assessment of duration of action CD
Member 1	W_1	$R_{i(1)}$	$W_1 R_{i(1)}$
Member 2	W_2	$R_{i(2)}$	$W_2 R_{i(2)}$
Member 3	W_3	$R_{i(3)}$	$W_3 R_{i(3)}$
Member 4	W_4	$R_{i(4)}$	$W_4 R_{i(4)}$
Member 5	W_5	$R_{i(5)}$	$W_5 R_{i(5)}$
Member 6	W_6	$R_{i(6)}$	$W_6 R_{i(6)}$
Member 7	W_7	$R_{i(7)}$	$W_7 R_{i(7)}$
		Results	$\tilde{R}$

After the best timing solution for the action CD was found. Figure 17 shows the membership function (triangular) of the optimum time for a single period of CD. Since the time rating scale is fuzzy, the obtained result is a fuzzy number.

To complete the assigned task, a defuzzification method is applied to the results. Defuzzification method *Mean of maximum* is chosen as the easiest and precise way to defuzzify the result to the crisp number. In case of a triangular membership function the highest degree of fulfillment are taken into account. Then if it is assumed that the result is crisp defuzzified value is x^* and fuzzy set is (a,b,c), then $x^* = b$ (Fig. 17).

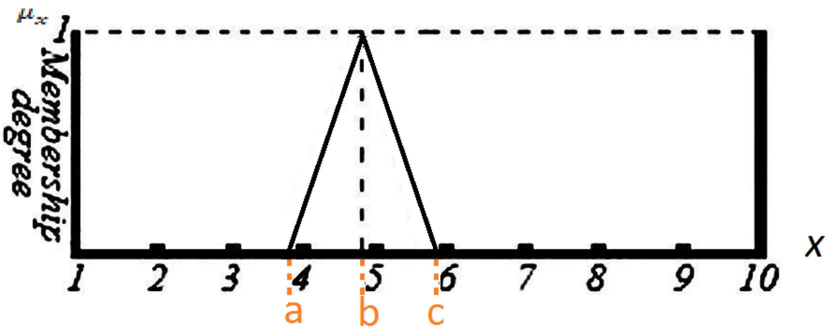

Figure 17. Membership function of optimum time of a proces

4.1.3 Application of the Arrow Diagram with a Support of Fuzzy Logic to the Mobile Phone Functionality Problem

Data of solution of this case have been obtained at *Uralov Technology* repair service, Czech Republic, Prague. Practical application of arrow diagram with a support of fuzzy logic is shown on solution of a mobile functionality problem. The entire period of mobile phone reparation, from failure identification to the problem solution, is indefinite and varying. In such case, to determine the time interval more accurately the arrow diagram that supports fuzzy logic can be used.

Time intervals of every stage are indefinite, but employees need to calculate the time of the problem solution as precisely as possible to meet requirements of customers. It is necessary for the smooth operation of both the client and the mobile phone reparation service itself.

The essence of the arrow diagram with a support of fuzzy logic method is that a group of members is collected: workers, technicians, engineers, and brainstorming is launching. Opinions are noted on the table and based on the results further calculations are carried out. Fuzzy logic brings preciseness to the calculation results.

The goal of the arrow diagram constructed is to estimate time interval that will be needed for the mobile phone with such an error reparation. In following part an action consisting of failures of a mobile phone, which occur due to dipping to water are presented.

Let us assume that a process of repair consists of a four actions. The goal of this chapter is to present improvement of quality of a process by resolving timing problems using the arrow diagram supported by fuzzy logic.

A single action from a process of repair was chosen. Figure 18 shows an arrow diagram, where *Diagnostics with the goal to find a cause of a problem*, *Arrangement with a customer*, *Solving the problem* and *Testing* are production process actions. The timing of the actions is estimated by the brainstorming group.

An estimation of the time needed for an action *Diagnostics with the goal to find a cause of a problem* using Arrow diagram with a support of fuzzy logic is presented as follows.

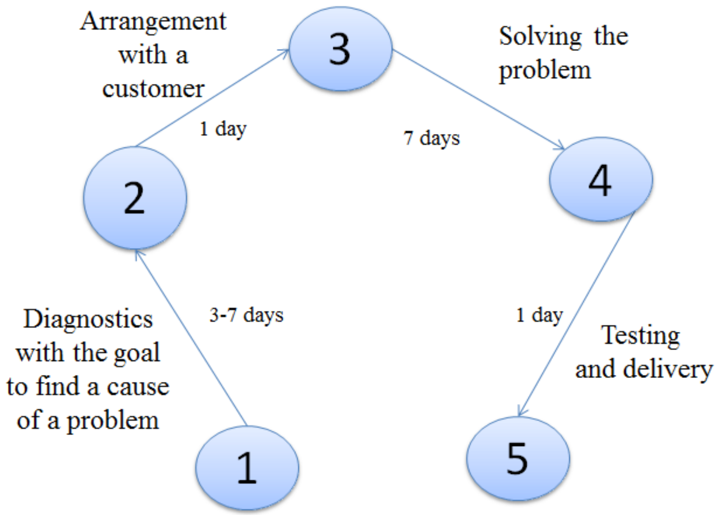

Figure 18. Arrow diagram of unexpected shutdown of a mobile phone problem

Diagnostics with the goal to find a cause of the mobile phone problem consists of several activities:

1. Opening the phone.
2. Oxidation cleaning.
3. Partial dripping of tracks on the board, if they are damaged or flooded.
4. Attempting to turn on - does not respond.
5. Replacing the power controller.
6. Attempting to turn on - does not respond.
7. Replacement of the coil, which is responsible for supplying the display.

8. Attempting to turn on - does not respond.
9. Complet disassembly and providing a full drip of tracks on the board.
10. Attempt to turn on - responds, but the camera, speaker and network signal are not working.
11. Replacing the camera.
12. Attempting to turn on - the camera works.
13. Replacing speakers.
14. Attempting to turn on - the speaker works.
15. Checking the coaxial cable, due to it is very thin, so there may be break or departing from the board. In case of damage, replacing the coaxial cable.
16. Attempt to turn on - the network signal still does not work.
17. Warm-up (reballing) of the modem.
18. Attempt to turn on - the network signal works.

In the process of repairing the phone, first action which is *Diagnostics with the goal to find a cause of a problem* takes the uncertain time among all the service activities. This happens because in the case of dipping the phone to water, every phone has break down of different components; therefore, there are no exact time of diagnostics for every mobile phone. To find a solution, service center is replacing the non-working components with working ones, and diagnostic lasts approximately from 3 to 7 days, due to possible absence of some components at the service, which then need to be ordered. This information leads to estimation of time for this activity with the support of fuzzy logic.

First, a fuzzy rating scale for timing analysis was created, and some linguistic variables and the corresponding fuzzy numbers were established. Table 4 presents linguistic variables along with the corresponding values (periods of time) and fuzzy numbers used to assess the duration of the first action of a process. Fuzzy ratings on a ten-point scale for the duration of this activity are given in the table. Firstly, for making fuzzy analysis possible, transforming the days to hours format. Then 3-7 days is 72-168 hours.

Table 4. Fuzzy rating scale for the duration of *Diagnostics with the goal to find a cause of a problem* action

Linguistic term	Clarification	Fuzzy number
Minimum period	72 hours - 79 hours	(1;2)
Extremely short	80 hours - 89 hours	(1;2;3)
Sufficiently short	90 hours - 99 hours	(2;3;4)
Quite short	100 hours - 109 hours	(3;4;5)
Optimum min time	110 hours - 119 hours	(4;5;6)
Optimum max time	120 hours - 129 hours	(5;6;7)
Quite long	130 hours - 139 hours	(6;7;8)
Sufficiently long	140 hours - 149 hours	(7;8;9)
Extremely long	150 hours - 159 hours	(8;9;10)
Maximum period	160 hours - 168 hours	(9;10)

After the rating scale is completed, the brainstorming team analyzes the process to detect the most probable time for the action.

Based on the above information and taking into account data from table 4, membership functions for timing analysis of *Diagnostics with the goal to find a cause of a problem* are created (Fig. 19). There are now several fuzzy sets of numbers representing the fuzzy character of the membership options, because the linguistic variable does not indicate a particular number.

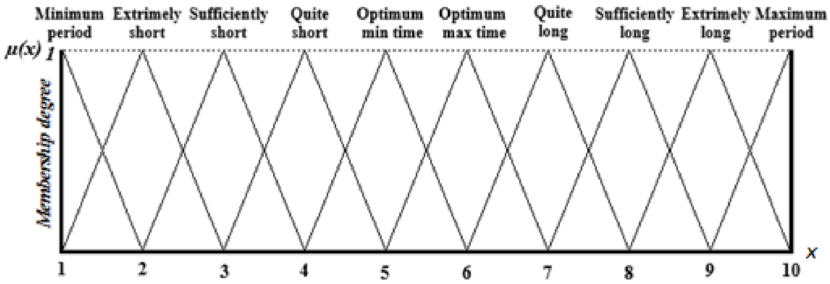

Figure 19. Membership functions of timing analysis fuzzy ratings

Then every team member announces the judgement for the first action of a reparation process and it is analyzed mathematically as follows.

The relative importance of the six members of the brainstorming group is shown in Table 5, which also specifies member opinions about the timing of the first action.

Table 5. Importance weights for brainstorming team members and their opinions

Member №	Member relative weight	Solving the problem
Member 1 (TM1)	15%	Quite long
Member 2 (TM2)	5%	Sufficiently long
Member 3 (TM3)	20%	Quite long
Member 4 (TM4)	15%	Optimum max time
Member 5 (TM5)	30%	Extremely long
Member 6 (TM6)	15%	Optimum max time

Let $R_{i(j)} = (R_{i(j)L:}, R_{i(j)M}, R_{i(j)U})$ be the fuzzy ratings of the *i*th fuzzy variable. $TM_1, TM_2, TM_3, TM_4, TM_5, TM_6$ are the members of the brainstorming group with the relative importance weights $W_1 = 0.15, W_2 = 0.05, W_3 = 0.2, W_4 = 0.15, W_5 = 0.3, W_6 = 0.15$ respectively, where $\sum_{j=1}^{m} W_j = 1$ and W_j >0 for j=1,…,m. Based upon these assumptions, the fuzzy analysis of brainstorming can be defined by the formula 9.

Table 6 shows results of the brainstorming and the following fuzzification of the results for further mathematical treatment. That is, the terms are converted to fuzzy numbers.

Table 6. Fuzzification of brainstorming results

Member №	Linguistic term	Fuzzy number
Member 1	Quite long	(6;7;8)
Member 2	Sufficiently long	(7;8;9)
Member 3	Quite long	(6;7;8)
Member 4	Optimum max time	(5;6;7)
Member 5	Extremely long	(8;9;10)
Member 6	Optimum max time	(5;6;7)

Table 7 below shows aggregated fuzzy assessment information for the assumed problem. The importance weight of each member of the group was also taken into account to obtain results that are more precise.

Table 7. Fuzzy assessment information for the *Diagnostics with the goal to find a cause of a problem* activity

Member	Importance weight	Fuzzy rating according to members' opinions			Assessment of duration of action BC		
Member 1	15%	6	7	8	0.9	1.05	1.2
Member 2	5%	7	8	9	0.35	0.4	0.45
Member 3	20%	6	7	8	1.2	1.4	1.6
Member 4	15%	5	6	7	0.75	0.9	1.05
Member 5	30%	8	9	10	2.4	2.7	3
Member 6	15%	5	6	7	0.75	0.9	1.05
Results					6.35	7.35	8.35

Result of the first action of the reparation process was found. Figure 20 shows the membership function for the activity. Since the time rating scale is fuzzy, the obtained result is a fuzzy number, namely (6.35; 7.35; 8.35). A triangular fuzzifier was applied to the result.

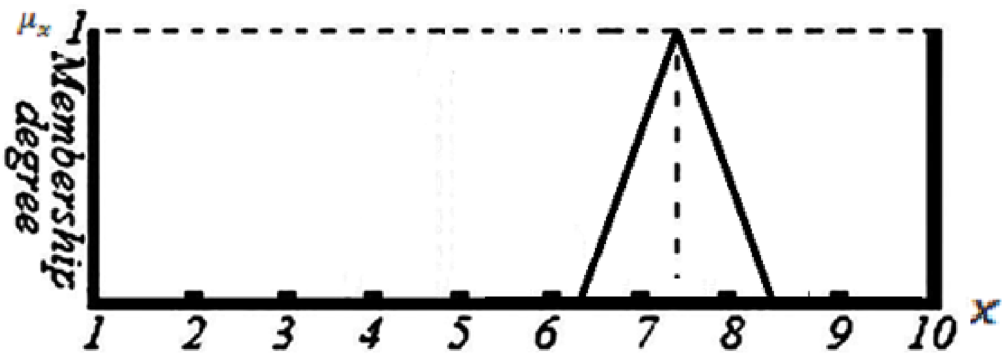

Figure 20. Membership function of the timing analysis

To complete the assigned task, a defuzzification method is applied to the results. Method of M*ean of maximum* is chosen. In case of a triangular membership function the highest degree of fulfillment are taken into account. Then if it is assumed that the result is crisp defuzzified value x^* and fuzzy set is (6.35; 7.35; 8.35), then $x^* = 7.35$.

This shows that the Diagnostics with the goal to find a cause of a problem activity belongs to an interval named Quite long and that this activity requires 130-139 hours of repairing time.

Result represents interval that is smaller and sounds more realistic and precise than initial one (3-7 days), that means that customer will get clearer information about terms of diagnostics of his mobile. The timings of the other actions are known and does not need to be analyzed in this way. The repairer is able to tell more accurate estimation of repair time right after diagnostics, he will surely know if he must order spare parts for the mobile or it is available at the service. Then according to new information about the time which reparation service spends for diagnostics of single mobile, repairer can better organize timing of his work either. Therefore, obvious advantages for both – customer and reparation service – are reflected.

4.1.4 Comparison and Discussions

The traditional method of planning is a method that uses the arrow diagram without support of fuzzy logic. This tool is used to ensure that the planned time for all the work and its individual stages is optimal for achieving of established goal. This tool is widely used not only in planning, but also for the subsequent implementation of planned activities.

Using the fuzzy logic the time interval of activity *Diagnostics with the goal to find a cause of a problem* was found with accuracy higher in comparison with accuracy which can be achieved using a standard arrow diagram.

The result depends on an ability of members of a brainstorming team to estimate the time interval needed. With respect to the fact that specialists focused on the first action of the reparation process were chosen as members of the brainstorming team, therefore it is assumed that highly qualified estimations were presented in brainstorming.

Level of qualification of the members of the brainstorming team is reflected in relative importance weights (W_i). Therefore, the most experienced members of the team influences the result the most.

This approach can be applied to any kind of mobile phone with the same damage (dipping into water). In the thesis, the implementation of this technique complemented with fuzzy approach is proposed. The goal of fuzzy approach is to identify precise time for an action in a process. The time initially set based on experience in the reparation service was from 3 to 7 days. With respect to customer needs to know how much time reparation will take. The reparation service personnel must give information of upper limit of this interval (7 days or 168 hours). Usage of the fuzzy logic decreased the time interval of provided service to 139 hours. Therefore, the information served to a customer is more accurate and reparation service can better organize its work.

4.2 Enhancement of the the Affinity diagram

4.2.1 Basics of the Affinity Diagram

Affinity diagram is intended for grouping and arranging a large number of qualitative (non-numeric) data. Grouping based on the principle of related information that is associated with a specific topic (question). Each group of data dedicated to its own attribute.

This tool relates to the seven new quality tools. Combining of information to groups is mainly due to no logical connection between this information, but rather due to the associations.

Affinity diagram is used when you want to compare a large number of disparate facts or ideas, when it is difficult to immediately cover and understand the relationships of complex data or in a situation when work team has difficulties in reaching agreement on the decision making step.

As a rule, the affinity diagram is used to process the results of "brainstorming" or surveys and questionnaires.

Procedure of affinity diagram making is as follows:

1. Determine the subject of study. It can be mismatches during process, frequently occurring defective good etc.

2. Various disparate data collected on the selected subject matter. In the course of this step is important to pay attention to the fact that data are collected "randomly" – i.e. without a targeted search on any narrow direction.

3. Data is being classified into different groups with common characteristics or features. Distribution of data is carried out on an intuitive basis. In order to have more opportunities to group data, you should not give the group a name at this stage.

4. Data in each group are reviewed, and released a common attribute or general idea, bringing together all elements of the group. If you cannot formulate a common attribute and the number of elements in the group is large enough, then the group is divided into subgroups, i.e. the previous step is performed, but with the elements of the selected group only.

5. Each group is assigned the name of the data, which reflects common attribute for every element of the group.

6. Finally affinity diagram is drawn.

Affinity diagrams are frequently used to collect and organize input data from across a group or a team. When compared to brainstorming technique, affinity diagrams often provide the greatest opportunities for equitable, objective input from all team members.

In the [69] is introduced DADS (Digital Affinity Diagram System), which separates two essential tasks of affinity diagram creation: input and collaboration. Using a dual extended monitor system, DADS is designed for one screen to act as a private input screen while the extended monitor shows a distributed interactive screen for collaboration.

Continuous Improvement Toolkit where affinity diagram plays dual role as a data gathering tool and data displaying tool was created in the [70]. The affinity diagram was used to set requirements for telephone answering machine. The affinity diagram brings structure to a large or complicated issue and breaks down a complicated issue into easy-to-understands categories.

In the work *The systems thinking toolbox* affinity diagram as the tool that supports both convergent and divergent way of thinking, because, affinity diagram serves for generating information and organizing information was proposed. These two activities require different mental skills and often referred to as divergent thinking and convergent thinking respectively. Where, divergent thinking concerned with generating information and ideas about a problem or situation. Associated with creative thinking it requires the use of both logical and lateral thinking and the suspension of the human mind’s tendency to self-censor. But, convergent thinking concerned with organizing, categorizing and making sense of information and ideas. This represents logical thinking. It is often a destructive activity with the removal and consolidation of ideas and information. To support the two types of thinking a number of tools are available and affinity diagramming is particularly powerful because it integrates both the divergent and convergent thinking activities providing a single approach. He suggested a simple example about washing machine requirements problem in his job. More information you can find in the [71].

According to *Affinity consulting* from Canada, there are many benefits to be gained from using this tool. Among the foremost are the following: causes breakthroughs to emerge, builds teamwork, causes connections to be discovered between various elements of information, builds critical thinking skills within the team, builds communication skills within the team, allows for full contribution of each team member, but as you use the tool, you will no doubt discover other benefits that are unique to your team [72].

4.2.2 Fuzzy Approach to the Affinity Diagram

In the thesis, application of fuzzy logic to the process affinity diagram is applied to increase the accuracy of the process affinity diagram in comparison with process affinity diagram format by a standard way [10].

Consider that a process is consisting of two process operations and every operation consisting of two steps. One or more failures can occur in every step. The process can be described in a structure of the affinity diagram (Fig. 21).

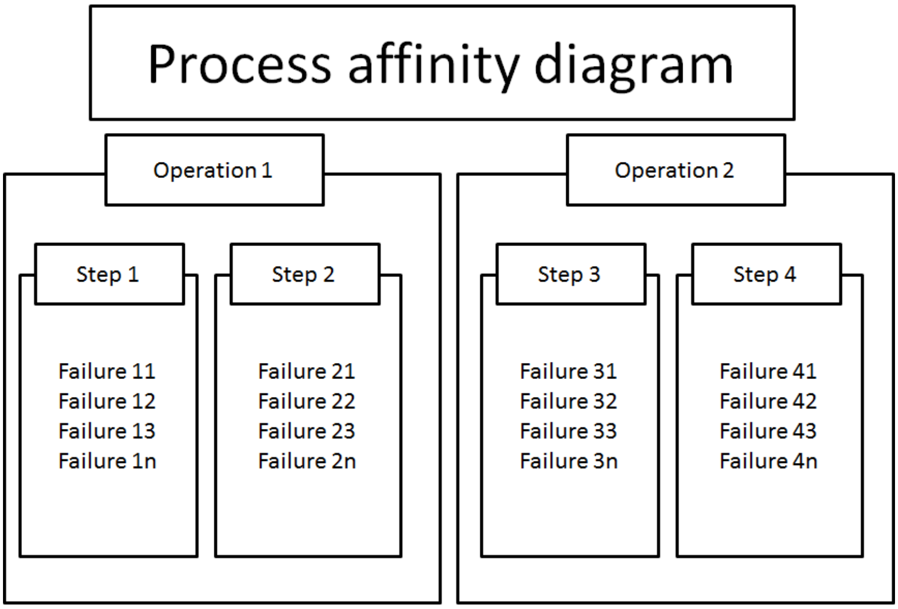

Figure 21. Structure of the process affinity diagram

Quality and functionality of the process depends on quality of every operation and step of the process. However, it is also possible to meet with a case, when if in step 1 occurs e.g. failure 13 and in parallel or subsequently in the step 2 occurs failure 22, then a new failure of the type 1322, as a combination of previous two ones, occurs in the step 3 (see Fig. 22).

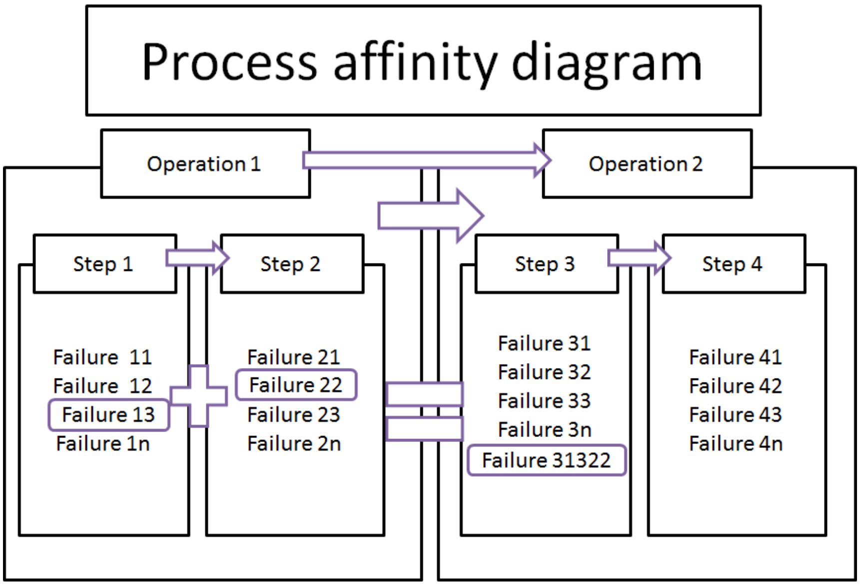

Figure 22. Process affinity diagram

The research in this direction is carried out with the goal to identify unexpected failures, which are provoked by occurrence of failures in previous operations.

On the one hand, the occurrence of failures can be determined by just two options: YES (failure occurs) or NO (failure does not occur). According to boolean logic, we could assign two values for failure variable – 1 (true) and 0 (false).

Table 8 shows an example of possible linguistic variables used for assessment of the influence of previous failures occurrence on generation of a failures in the following process. Fuzzy ratings can be represented in a ten-point or five-point scale for an influence factor. Variables $x_1 \dots x_n$ are levels of influence of the failures. Variable R_1 ... R_n are fuzzy numbers.

Table 8. Fuzzy ratings for influence factor of the failures

Rating	Level of influence	Fuzzy number
Critical influence	x_1	R_1
Strong influence	x_2	R_2
Moderate influence	x_3	R_3
Small influence	x_4	R_4
Minor or no influence	x_5	R_5

Taking into account all above information and based on table 8, an example of membership functions of fuzzy ratings for a level of influence factor to the failures was created (Fig. 23).

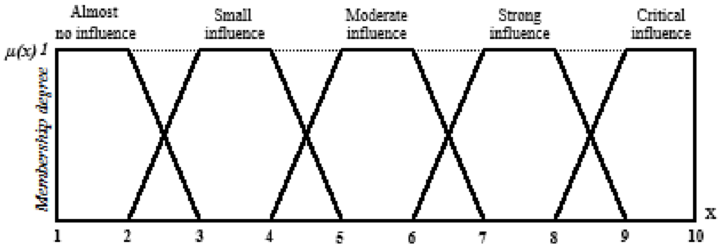

Figure 23. An example of membership functions of fuzzy ratings for level of influence to the failures

Now there are several fuzzy sets of numbers representing the fuzzy character of the brainstorming team members' opinions because the linguistic variable cannot be shown as a particular number.

Let's assume that the failure 13 of the step 1 will occur together with the failure 22 of the step 2. This situation creates conditions for occurrence of a new type of failure 1322 in the step 3.

Brainstorming group consisting of 5 team members provides the careful analysis of the process and the failure occurrence. Let $R_{i(j)} = (R_{i(j)L:}, R_{i(j)M1}, R_{j(j)M2}, R_{i(j)U})$ be the fuzzy number of the *i*th fuzzy variable. $TM_1 \dots TM_n$ are the members of brainstorming group who has relative importance weights $W_1,...,W_m$ correspondingly. Where $\sum_{j=1}^{m} W_j = 1$ and W_j >0 for j=1,…,m. Based upon these assumptions, the influence factor can be defined by formula 9.

During brainstorming every team member proposes own idea about how srong the influence of the failure of previous step to the next steps. Then the table with all collected data is created. Table 9 shows an example of results of brainstorming and following fuzzyfication of the results for further mathematical treatment. Other words the linguistic variables were performed as fuzzy numbers. $R_{i(j)}$ – fuzzy number for the corresponding linguistic variable chosen by of the member.

Table 9. Fuzzyfication of a failure influence analysis by brainstorming team

Risk factor	Team members	Opinions (Fuzzy variables)	Fuzzy number
Influence	TM_1	Opinion 1	$R_{i(1)}$
	TM_2	Opinion 2	$R_{i(2)}$
	TM_3	Opinion 3	$R_{i(3)}$
	TM_4	Opinion 4	$R_{i(4)}$
	TM_5	Opinion 5	$R_{i(5)}$

After including of weights of individual TM of brainstorming team it is possible to form a table 10.

Table 10. Example of the assessment information for the failure influence analysis

Risk factor	Team members	Importance weights	Fuzzy ratings		Assessment of failure influence
Influence factor	TM1	W_1	$R_{i(1)}$		$W_1R_{i(1)}$
	TM2	W_2	$R_{i(2)}$		$W_2R_{i(2)}$
	TM3	W_3	$R_{i(3)}$		$W_3R_{i(3)}$
	TM4	W_4	$R_{i(4)}$		$W_4R_{i(4)}$
	TM5	W_5	$R_{i(5)}$		$W_5R_{i(5)}$
Result					$W_jR_{i(j)}$

An example of result is presented in fig. 24 as membership function of the failures 13 and 22 influence degree to the new failure 1322 occurrence.

To complete the assigned task, a defuzzification method is applied to the results. Defuzzification method *Mean of maximum* is chosen as the easiest and precise way to defuzzify the result to the crisp number. In case of a trapezoidal membership function the average of the highest degree of fulfillment are taken into account. Then if it is assumed that the result is crisp defuzzified value is x^* and fuzzy set is (a,b,c, d), then $x^* = (b + c)/2$. (Fig. 24)

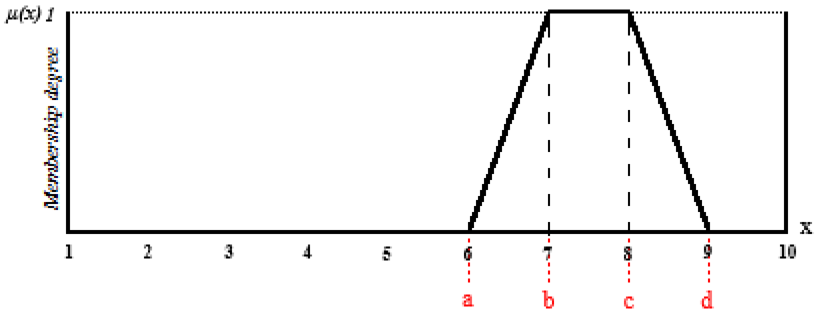

Figure 24. An example of membership function of the failure influence degree

4.2.3 Application of Affinity Diagram to the Joining Based on ECA with the Support of Fuzzy Logic

Data for a solution of this case was obtained at Czech Technical University in Prague from a research project under the name *Diagnostics and materials*. Electrically conductive adhesives (ECAs) are becoming increasingly important in the electronics industry. These materials are used in two main areas of electronics packaging – in mounting of heat sensitive components such as LCDs and in mounting of ultra-fine pitch electronic packages [73].

ECAs create a permanent electrical and mechanical connection between a pad and a component lead. Adhesives on epoxy basis filled with silver conductive particles are used primary. The curing temperature is lower in comparison with the soldering temperature of lead-free solders. Electrical conductivity depends on the concentration of conductive particles in resin, on the shape and on the material of these particles [74].

An appropriate surface pretreatment of joined parts and a detail control of the filler through the analysis of grains are necessary for achievement of good electrical, mechanical and thermal properties of adhesive joints [75]. To achieve parameters of adhesive joints comparable with soldered ones, the process of adhesive joining must be optimized.

Electrical resistivity of adhesives, electrical noise and nonlinearity of the current vs. voltage characteristic are higher in comparison with these parameters of lead-free solders. Mechanical properties and climate resistivity of ECAs are also worst in comparison with solders [76].

There are many parameters, which influence quality of adhesive joints in the process of adhesive joining. Optimization of this process needs the use of proper quality control tools.

As Affinity diagram is intended for managing of a large number of qualitative (non-numeric) data, it was chosen for analysis of adhesive joining process based on electrically conductive adhesives. Grouping based on the principle of related information that is associated with a specific area. Each group of data dedicated to its own attribute.

Procedure of application of affinity diagram to the adhesive joining based on ECA process is as follows:

1. Subject of study was determined. It means failures occurring during adhesive joining based on ECA process.

2. Various disparate data (failures, related to the process) were collected. Data were collected "randomly" – i.e. without a targeted search on any narrow direction.

3. Every group of data is formed of data with common characteristics.

4. Data in each group were reviewed, and released a common attribute or general idea, bringing together all elements of the group.

5. Each group was assigned the name of the data, which reflects common attribute for every element of the group. In this case, each group is the operation of the process and, further, process operations containing steps.

6. The process consists of three process operations and every operation consisting of one, three or four steps. One or more failures can occur in every step. The proces can be described in a structure of the affinity diagram (Fig. 25).

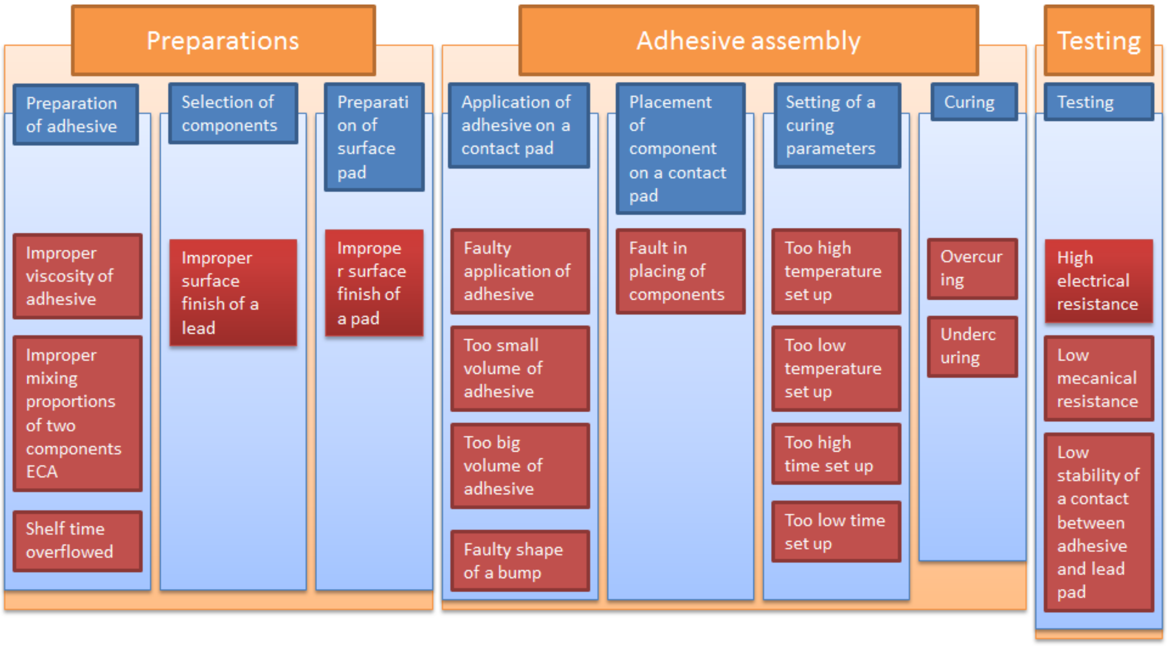

Figure 25. Affinity diagram for the adhesive joining based on ECA process

In the thesis, fuzzy logic to the process affinity diagram to make results more precise is applied.

Quality and functionality of the process depends on quality of every step and operation of the process. However, it is also possible to meet with a case, when occurrence of a failure in a step, can cause a new failure in one of the next steps. It is demonstrated on occurrence of a new type of failure in figure 26.

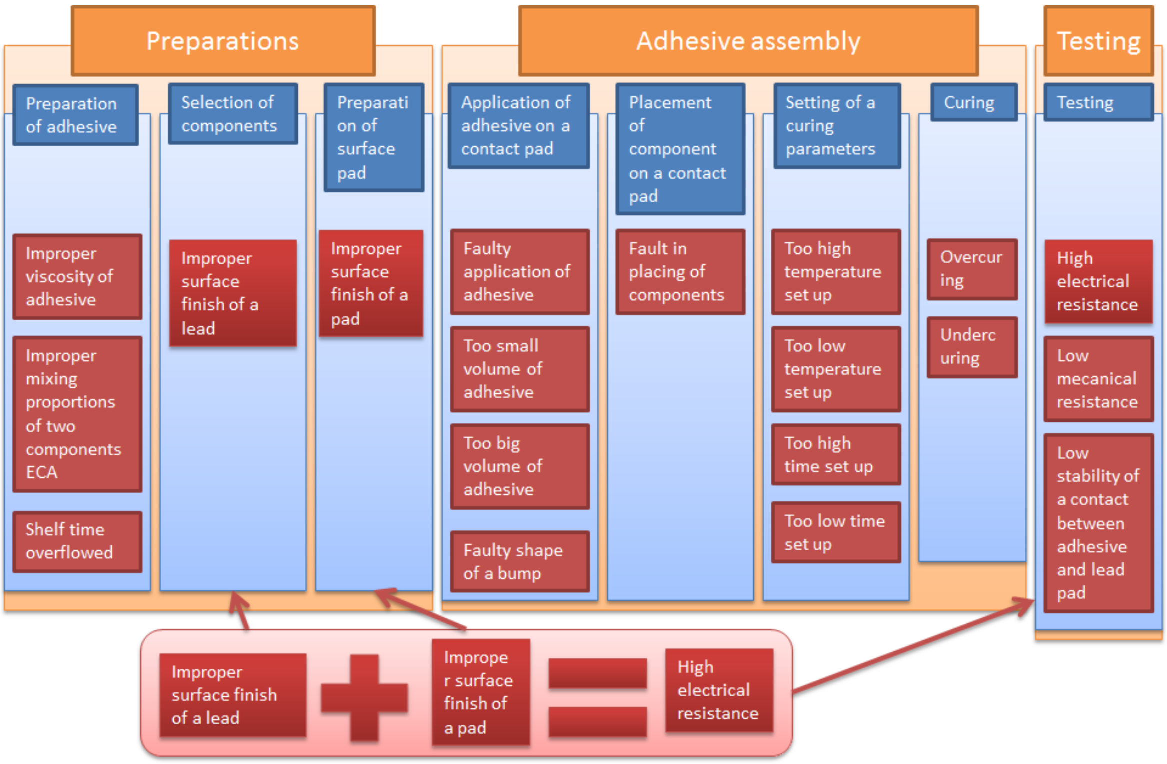

Figure 26. New failure occurrence based on the intrusion of failures

The research in this direction must be provided with the goal to identify unexpected failures, which are provoked by occurrence of failures in previous operations. To identify if the final resulting issue (High electrical resistance) occurs. Brainstorming with following analysis by fuzzy logic was used.

Table 11 shows the linguistic terms and fuzzy numbers used for assessment of the influence factors in this paper. Fuzzy ratings in a ten-point scale for an influence factor are presented in the table. These linguistic variables will be used by brainstorming team for identifying probability of failure occurrence.

Table 11. Fuzzy ratings for influence factor of the failures

Rating	Level of influence	Fuzzy number
Critical influence	Critical influence of the failure of previous step/operation. New failure occurs	(8, 9, 10)
Strong influence	Strong influence of the failure of previous step/operation. New failure occurs with high probability	(6, 7, 8, 9)

Moderate influence	Moderate influence of the failure of previous step/operation. New failure occurs with a moderate probability	(4, 5, 6, 7)
Small influence	Small influence of the failure of previous step/operation. New failure occurs with a small probability	(2, 3, 4, 5)
Minor / no influence	Almost no influence of the failure of previous step/operation. There is almost no way for new failure occurrence	(1, 2, 3)

Taking into account all above information and based on table 11, membership functions of fuzzy ratings for influence factor of the failures was created (Fig. 27).

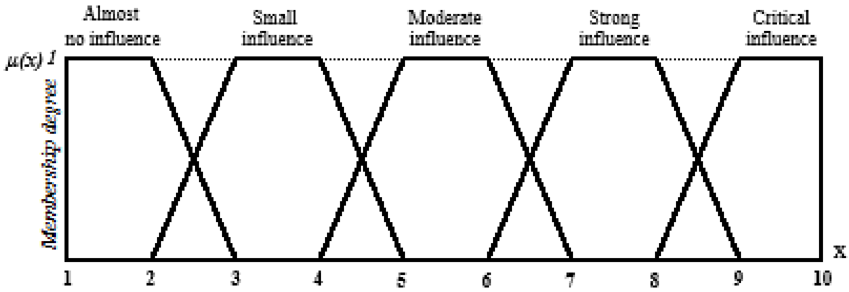

Figure 27. Membership functions of fuzzy ratings for influence factor of the failures

There are several fuzzy sets of numbers representing the fuzzy character of the member opinions because the linguistic variable cannot be shown as a particular number.

Let's assume that the failure *Improper surface finish of a lead* in the step 2 (Operation 2) occurred together with the *Improper surface finish of a pad* in the step *3* (Operation 1). This situation creates conditions for occurrence of a new type of failure *High electrical resistance* in the step 8 (Operation 3).

Brainstorming group consisting of 5 team members provides the careful analysis of the process and the failure occurrence. Let $R_{i(j)} = (R_{i(j)L:}, R_{i(j)M1}, R_{i(j)M2}, R_{i(j)U})$ be the fuzzy ratings of the *i*th fuzzy variable. TM_1, TM_2, TM_3, TM_4 and TM_5 are the members of brainstorming group who has relative importance weights W_1= 0 .25, W_2=0.15, W_3=0.1, W_4=0.15 and W_5=0.35 correspondingly. Where $\sum_{j=1}^{m} W_j = 1$ and w_j >0 for j=1,…,m. Based upon these assumptions, the influence factor can be defined by the formula 9.

Table 12 shows results of brainstorming and following fuzzyfication of the results for further mathematical treatment. Other words the linguistic variables were performed as fuzzy numbers.

Table 12. Fuzzyfication of a failure influence analysis

Risk factor	Team members	Opinions (Fuzzy variables)	Rating
Influence	TM_1	Strong influence	(6, 7, 8, 9)
	TM_2	Moderate influence	(4, 5, 6, 7)
	TM_3	Moderate influence	(4, 5, 6, 7)
	TM_4	Strong influence	(6, 7, 8, 9)
	TM_5	Strong influence	(6, 7, 8, 9)

Following table 13 shows all collected data, importance weights of team members and aggregated fuzzy assessment information for the influence degree of the failure.

Table 13. Assessment information for the failure influence analysis

Risk factor	Team members	Importance weights	Fuzzy variable		Assessment of failure influence			
Influence factor	TM1	0.25	Strong influence		1.5	1.75	2	2.25
	TM2	0.15	Moderate influence		0.6	0.75	0.9	1.05
	TM3	0.1	Moderate influence		0.4	0.5	0.6	0.7
	TM4	0.15	Strong influence		0.9	1.05	1.2	1.35
	TM5	0.35	Strong influence		2.1	2.45	2.8	3.15
Result					5.5	6.5	7.5	8.5

Membership function of the *Improper surface finish of a lead* and *Improper surface finish of a pad* influence factor is shown in fig. 28.

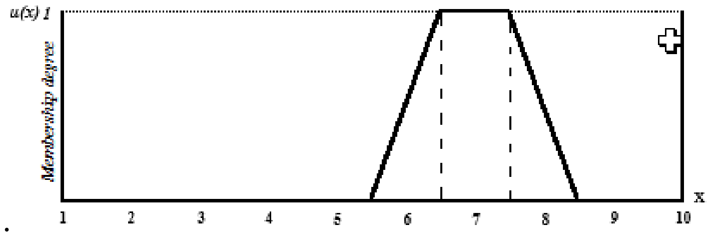

Figure 28. Membership function of the failure influence degree

To complete the assigned task, a defuzzification method is applied to the results. Method of *Mean of maximum* is chosen. In case of a trapezoidal membership function the average of the highest degree of fulfillment are taken into account. Then if it is assumed that the result is crisp defuzzified value is x^* and fuzzy set is (5.5, 6.5, 7.5, 8.5), then $x^* = \frac{6.5+7.5}{2} = 7$.

Result shows that the level of influence is strong (Table 11) that means there is a high possibility of the failure *High electrical resistance* to be occurred. Thus, the failure should be taken in consideration in future discussion.

4.2.4 Comparison and Discussions

Affinity diagram is a tool, which serves to organize big volume of data. It is possible to group disorganized data into small groups based on narrow scope or specific topic. Affinity diagrams are widely used in brainstorming process, as this tool is very helpful for further discussions and searching for solutions in particular areas rather than in huge mess of data where analyst can simply be lost. Otherwise, this tool can be used in any other areas of usage when organization of information is needed.

Affinity diagram method was used for grouping of failures that can occur during the technological process maintenance, because it clearly visualizes possible failures without usage of other tools. An evaluation of significance of non-obvious failures that could be met during testing was analyzed. New types of failures can occur due to occurrence of some other failures. Some of these new types of failures can be predicted, prediction of some others is very complicated. Fuzzy logic makes possible to evaluate the significance of such the failures. This will contribute to prepare preventive actions in time and less faulty pieces will be made at the end.

Without using of fuzzy logic, it would not be possible to evaluate the significance of new types of failures, which can occur by mixing of original ones.

4.3 Enhancement of the Process Decision Program Chart

4.3.1 Basics of the Process Decision Program Chart

Process decision program chart (PDPC) is constructed to identify potential problems in the course of execution of the work plan and implement preventive actions to eliminate them. When a plan of work is ready, PDPC helps to identify risks and develop counter-measures (preventive actions). As a rule, it is built, if the risks are unknown, or if their appearance can have serious consequences.

If you perform a work plan schematically (for example, as a tree diagram or Gantt chart), the risks and the appropriate preventive actions are added to the objectives of the plan.

PDPC chart can be constructed as follows:

1. Determine the purpose of the decision-making chart constructing. For example - to identify risks in the specific area plan and develop countermeasures for those cases where the risk exceeds acceptable level. Before proceeding with the following steps, make sure that the chart decisions are needed.

2. Identify areas of the work plan, which requires the construction of decision diagrams. If the work plan has a large number of elements, an attempt to create a decision-making diagram with respect to all elements of the plan can greatly complicate the task. As a rule, decision diagram only applies to the riskiest areas of the plan.

3. Form a team of experts (brainstorming team). The team should include experts from various fields. This will allow assess the possible risks more objectively.

For example, brainstorming team may include:

 representative of the top management personnel, as they have the ability to see the situation in whole;

 experts in the specific areas of the plan as they have knowledge in specific details;

 specialists in planning and application of PDPC chart, as they could face a similar situation before and be experienced in solving them.

4 . Establish rules for determining the elements on which the decision-making chart will be based.

These rules may include:
 rules for determining the risks;

 rules for determining the severity of risks. For the most significant risks need to develop preventive actions;

 rules for determining preventive actions;

 rules for the preventive actions selection to be implemented.

Factors that should be considered when defining the rules may include:

 time - how long it takes to manage risk? Whether the task on the critical path? How much time will save preventive actions?

 cost - what is the total cost of losses from the failures if they occur? What is the cost of preventive actions implementing?

 control – which capabilities exist to prevent the risk? What risk management techniques will be effective?

 information - what is known about the risk? Is it possible to learn about the risk before its occurrence?

5. Potential problems (risks) are identified for each element of the process. Brainstorming team can be used to determine the widest range of risks. In this case checklist can be very useful. All identified risks are recorded in a list or specified on the cards, so that they can be streamlined in the future. Cards are typically used if a large number of risks found.

6. Making of decision which of risks should be neglected and which of them should be added to the chart. This may need to apply the consensus method, the matrix of priorities or other methods for selection the most important elements. In our case we suggest new fuzzy approach to define a severity of risk.

7. Identified risks are included in the plan. Risks are placed in rectangles (Fig. 32,35-38).

8. For each risk preventive actions are defined. They are found e.g. using brainstorming, Ishikawa diagrams or other quality control tools. Preventive actions may include methods of risk elimination or reduction.

9. Ranking of the preventive actions importance is performed similarly to the ranking of risks. On this step fuzzy approach can be applied. The most important of the actions are selected for placement in the PDPC chart. The number of possible actions for each risk, usually, not more than three are selected.

10 . Preventive actions are included into the plan under the relevant risk events. In order to differ these actions from their elements of the plan, it is also desirable to highlight them visually. The result is a diagram of the decision-making PDPC combined with the work plan.

11. According to the results of PDPC constructing actions that will ensure the proper performance of the process are being made (Fig. 29) [82].

Actions may include:

 changing of the work specified as the original version of the plan, so as to be able to eliminate or modify the operation with high risk;

 adding new elements to the plan - such as additional control actions;

 preparation of situation plans that will only be used in case of a particular risk event.

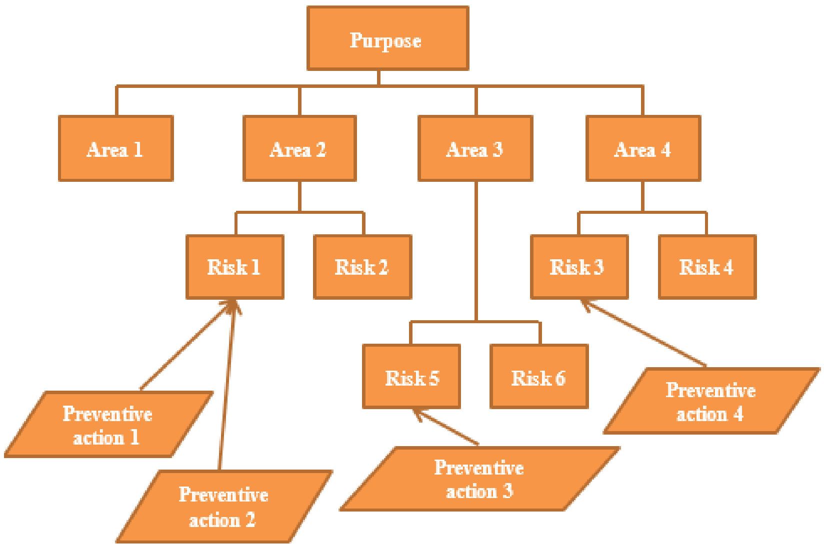

Figure 29. Defined structure of PDPC Chart

4.3.2 Fuzzy approach to Process Decision Program Chart

The use of fuzzy logic is presented when specifying the significance of the risks performed in the design of the PDPC chart. Then the most significant risks are found using fuzzy approach and placed into the PDPC chart.

First, a fuzzy rating scale for severity analysis was created, and then linguistic variables and the corresponding fuzzy numbers must be established. Table 14 presents Ratings (linguistic variables) along with the corresponding values (severity of risks) and fuzzy numbers used to assess severity of risks. Fuzzy ratings on a ten-point scale for the severity of risks are given in the table. Variables $x_1 \dots x_n$ are severity of risks. Variable R_1 ... R_n are fuzzy numbers.

Table 14. Example of a fuzzy rating scale for the risks severity

Rating	Severity of risk	Fuzzy number
None	x_1	R_1
Very minor	x_2	R_2
Minor	x_3	R_3

Very low	x_4	R_4
Low	x_5	R_5
Moderate	x_6	R_6
Strong effect	x_7	R_7
High	x_8	R_8
Very high	x_9	R_9
Catastrophic	x_{10}	R_{10}

After the rating scale is completed, the brainstorming team analyzes the level of severity for every risk.

Based on the data from Table 19, membership functions for risk severity are created (Figure 30). There are now several fuzzy sets of numbers representing the fuzzy character of the membership options, because the linguistic variable does not indicate a particular number.

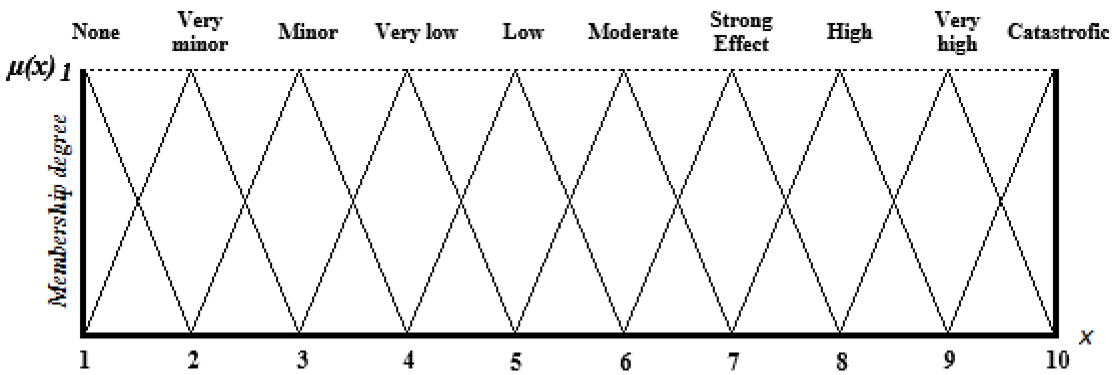

Figure 30. Membership functions of timing analysis fuzzy ratings

The relative importance of the seven members of the brainstorming group is shown in Table 15, which also specifies member opinions about considered risk.

Table 15. Importance weights for brainstorming team members

Member №	Member relative weight	Opinion (linguistic variable)	Fuzzy number
TM 1	W_1	Opinion 1	R_1
TM 2	W_2	Opinion 2	R_2
TM 3	W_3	Opinion 3	R_3
TM 4	W_4	Opinion 4	R_4
TM 5	W_5	Opinion 5	R_5
TM 6	W_6	Opinion 6	R_6
TM 7	W_7	Opinion 7	R_7
TM 8	W_8	Opinion 8	R_8

Considered only one risk from the list of risks. Let $R_{i(j)} = (R_{i(j)L:}, R_{i(j)M}, R_{i(j)U})$ be the fuzzy ratings of the *i*th fuzzy variable. Let $TM_1,...,TM_m$ are team members of the brainstorming group with the relative importance weights $W_1,...,W_m$ respectively, where $\sum_{j=1}^{m} W_j = 1$ and W_j >0 for j=1,…,m.

Table 16 below shows aggregated fuzzy assessment information for the severity of risk of the assumed problem. The importance weight of each member of the group was also taken into account to obtain results that are more precise.

Table 16. Example of fuzzy assessment information for the risk severity

Member	Importance weight	Fuzzy rating	Severity of risk
Member 1	W_1	$R_{i(1)}$	$R_{i(1)}W_1$
Member 2	W_2	$R_{i(2)}$	$R_{i(2)}W_2$
Member 3	W_3	$R_{i(3)}$	$R_{i(3)}W_3$

Member 4	W_4	$R_{i(4)}$	$R_{i(4)}W_4$
Member 5	W_5	$R_{i(5)}$	$R_{i(5)}W_5$
Member 6	W_6	$R_{i(6)}$	$R_{i(6)}W_6$
Member 7	W_7	$R_{i(7)}$	$R_{i(7)}W_7$
Member 8	W_8	$R_{i(8)}$	$R_{i(8)}W_8$
Results			$\tilde{R}$

Result ($\tilde{R}$) of a risk severity was found using formula 9. Figure 31 shows the membership function (triangular structure) of the risk severity. Since the time rating scale is fuzzy, the obtained result is a fuzzy number. A triangular fuzzifier was applied to the result.

To complete the assigned task, a defuzzification method is applied to the results. Defuzzification method *Mean of maximum* is chosen as the easiest and precise way to defuzzify the result to the crisp number. In case of a triangular membership function the highest degree of fulfillment are taken into account. Then if it is assumed that the result is crisp defuzzified value is x^* and fuzzy set is (a,b,c), then $x^* = b$ (Fig. 31).

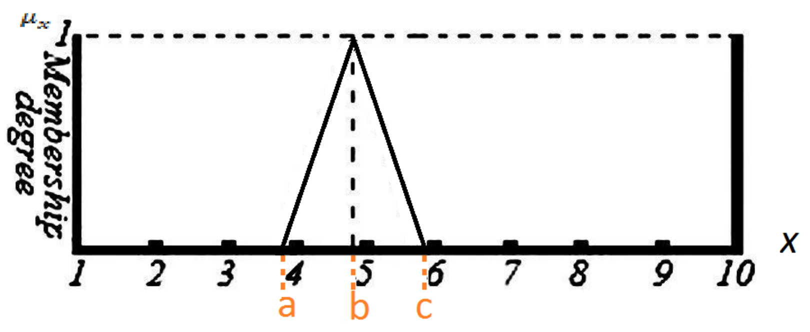

Figure 31. Membership function of optimum time of a process

4.3.3 Application of PDPC to the Joining Based on the Wave Soldering process with Support of Fuzzy Logic

Process decision program chart (PDPC) is constructed to identify potential problems in the course of execution of the work plan for the joining based on the wave soldering process and implement preventive actions to eliminate them. When a plan of work is ready, PDPC helps to identify risks and develop counter-measures (preventive actions) [8].

Double-sided PCB assembly (Through hole technology and surface mount technology) is considered. PDPC diagram consists of 4 operations, as you can see on the following figures 32-35. First and third operations are acted on one side of the PCB and Second and fourth operations are acted on the other side of the PCB:

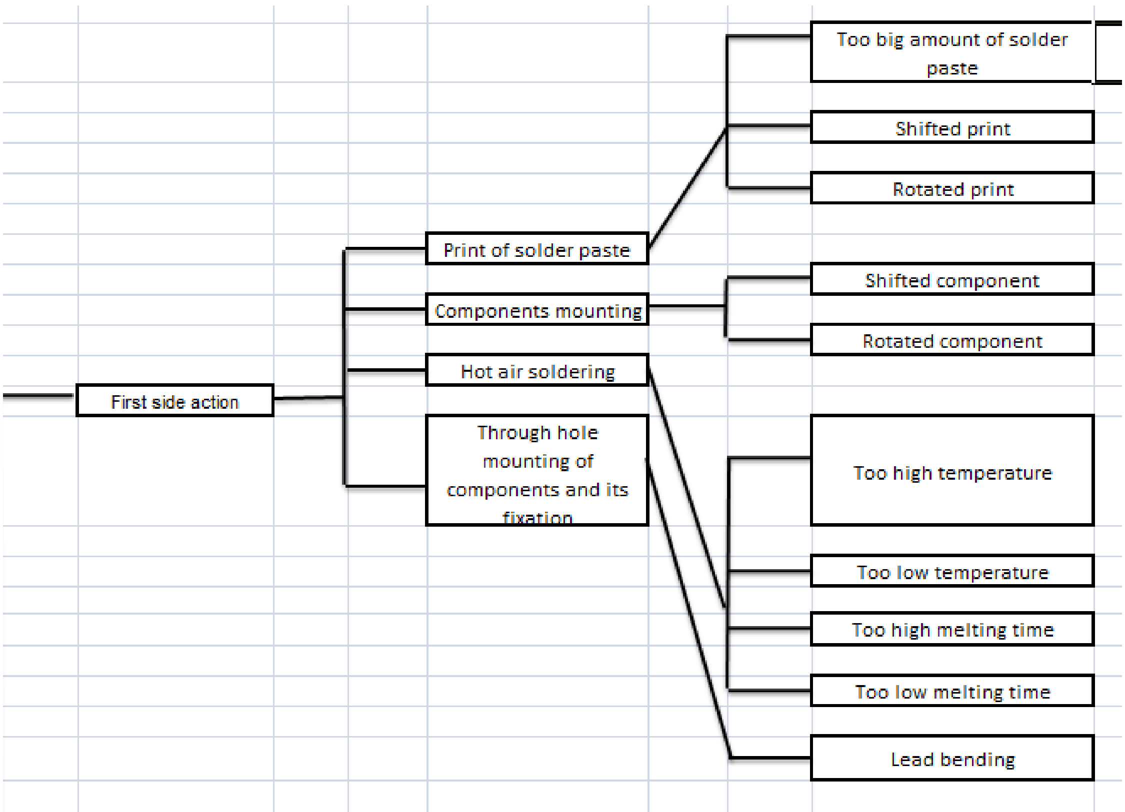

Figure 32. First step for PDPC of the double-sided PCB assembly

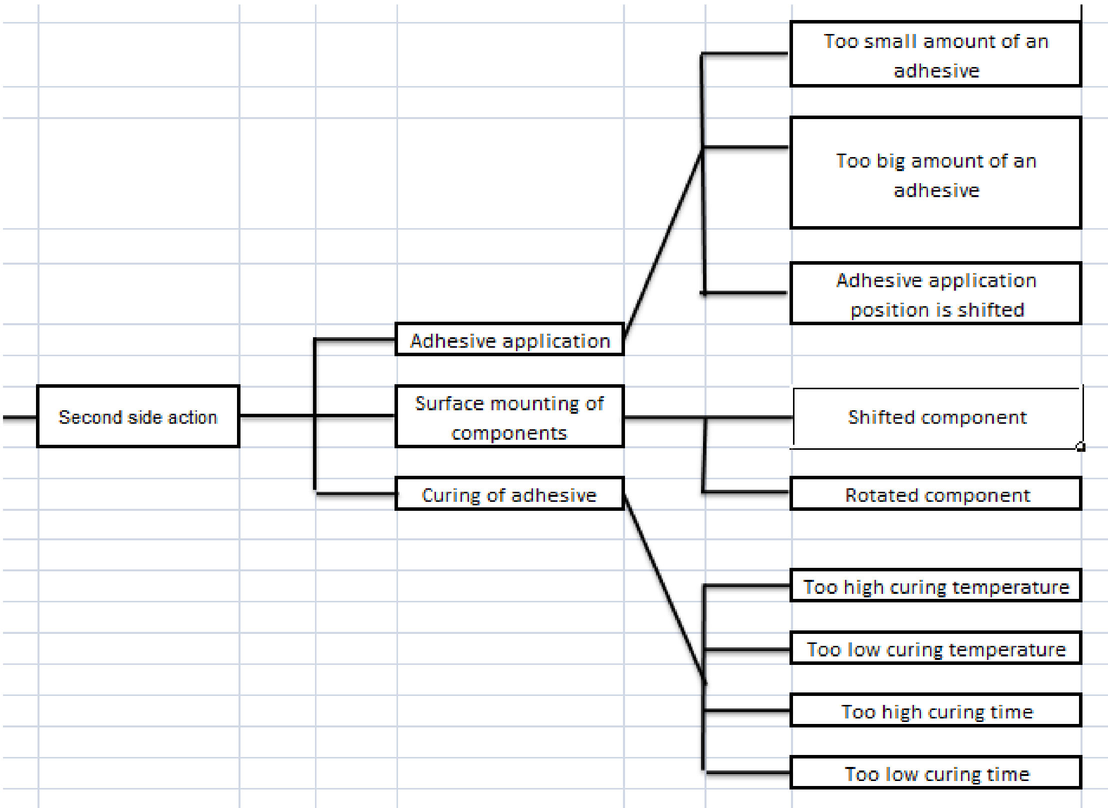

Figure 33. Second step for PDPC of the double-sided PCB assembly

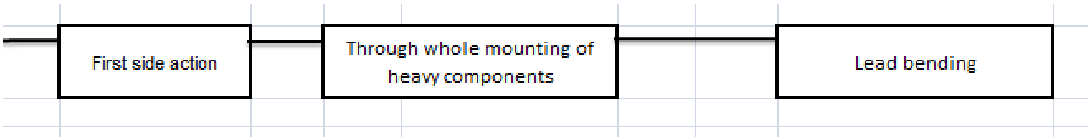

Figure 34. Third step for PDPC of the double-sided PCB assembly

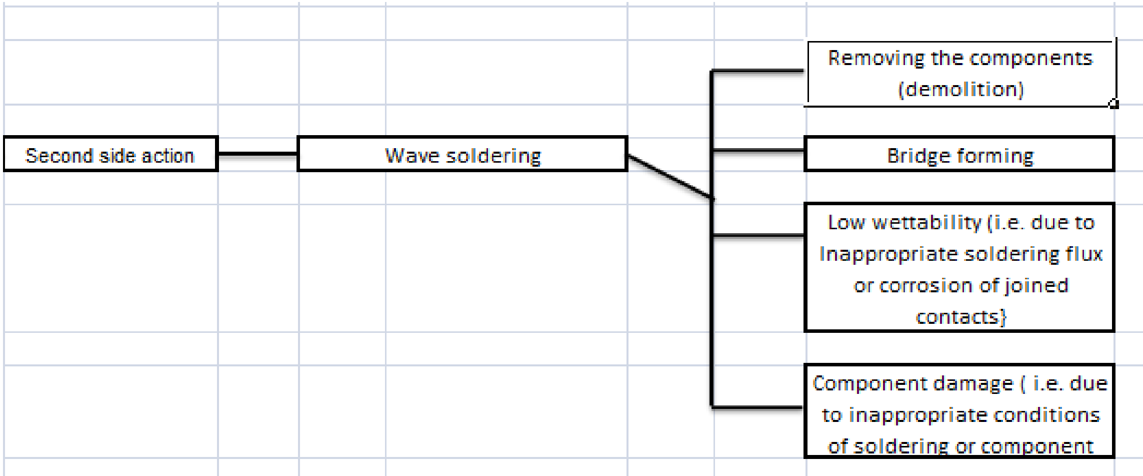

Figure 35. Fourth step for PDPC of the double-sided PCB assembly

At the moment it is necessary to analyze all listed risks and define which of those should be added to the PDPC chart and which should be neglected. To simplify the process, a fuzzy rating scale is created (table 17), that will be done by the brainstorming team for the risk analysis.

Table 17. Fuzzy rating scale for the risks severity

Rating	Severity of risk	Fuzzy number
None	Risk can be accepted without any preventive action, no need to add the risk to the PDPC.	(1;2)
Very minor	Risk can be accepted without any preventive action, no need to add the risk to the PDPC.	(1;2;3)
Minor	Risk can be accepted without any preventive action, no need to add the risk to the PDPC.	(2;3;4)
Very low	Risk can be accepted without any preventive action, no need to add the risk to the PDPC.	(3;4;5)
Low	Risk can be accepted without any preventive action, no need to add the risk to the PDPC.	(4;5;6)
Moderate	Risk cannot be accepted. Preventive actions must be assigned. Must be added to the PDPC.	(5;6;7)
Strong	Risk cannot be accepted. Preventive actions must be assigned. Must be added to the PDPC.	(6;7;8)
High	Risk cannot be accepted. Preventive actions must be assigned. Must be added to the PDPC.	(7;8;9)
Very high	Risk cannot be accepted. Preventive actions must be assigned. Must be added to the PDPC.	(8;9;10)
Catastrophic	Risk cannot be accepted. Preventive actions must be assigned. Must be added to the PDPC.	(9;10)

After the rating scale is completed, the brainstorming team analyzes the level of severity for every risk.

Based on data from table 17, membership functions for risk severity are found (Figure 36). There are now several fuzzy sets of numbers representing the fuzzy character of the membership options, because the linguistic variable does not indicate a particular number.

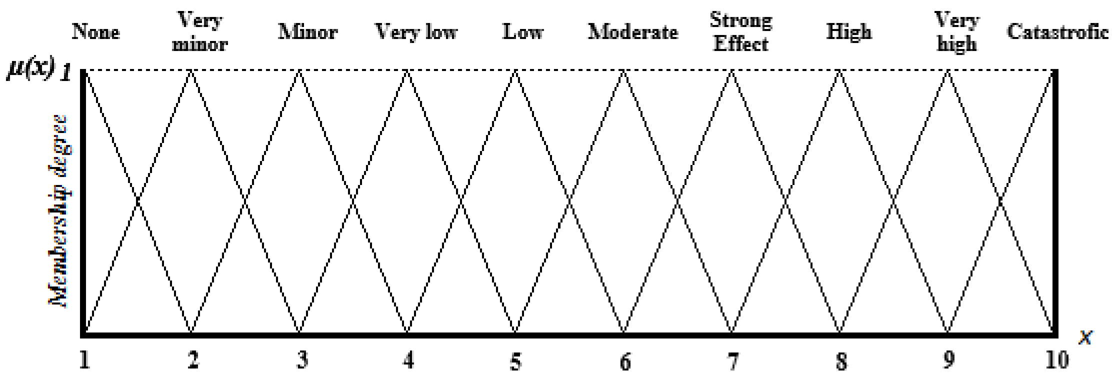

Figure 36. Membership functions for risk severity

Then every team member announces the judgement for every listed risk and it is described by a fuzzy number. In the next part a fuzzy analysis of a risk of failure when Too small amount of solder paste is printed on the PCB pads.

The relative importance of the eight members of the brainstorming group is shown in table 18, which also specifies member opinions about considered risk.

Table 18. Importance weights for brainstorming team members

Member №	Member relative weight	Risk severity
Member 1	10%	Low
Member 2	5%	Very minor
Member 3	25%	Moderate
Member 4	5%	High
Member 5	35%	Strong effect
Member 6	10%	High
Member 7	5%	Low
Member 8	5%	Moderate

As it was just noticed we consider only one risk from the list of risks. Let $R_{i(j)} = (R_{i(j)L:}, R_{i(j)M}, R_{i(j)U})$ be the fuzzy ratings of the *i*th fuzzy variable. $TM_1, TM_2, TM_3, TM_4, TM_5, TM_6, TM_7 TM_8$ are the members of the brainstorming group with the relative importance weights
$W_1 = 0.1, W_2 = 0.05, W_3 = 0.25, W_4 = 0.05, W_5 = 0.35, W_6 = 0.10, W_7 = 0.05, W_8 = 0.05$
respectively, where $\sum_{j=1}^{m} W_j = 1$ and W_j >0 for j=1,…,m. Based upon these assumptions, the fuzzy analysis of brainstorming can be defined by the formula 9.

Table 19 shows results of the brainstorming and the following fuzzification of the results for further mathematical treatment. That is, the terms are converted to fuzzy numbers.

Table 19. Fuzzification of brainstorming results

Member №	Linguistic variable	Fuzzy number
Member 1	Low	(4;5;6)
Member 2	Very minor	(3;4;5)
Member 3	Moderate	(5;6;7)
Member 4	High	(7;8;9)
Member 5	Strong effect	(6;7;8)
Member 6	High	(7;8;9)
Member 7	Low	(4;5;6)
Member 8	Moderate	(5;6;7)

Table 20 below shows aggregated fuzzy assessment information for the assumed problem. The importance weight of each member of the group was also taken into account to obtain more precise results.

Table 20. Fuzzy assessment information for the risk severity

Member	Importance weight	Fuzzy rating			Assessment of duration of action BC		
Member 1	10%	4	5	6	0.4	0.5	0.6
Member 2	5%	3	4	5	0.15	0.2	0.25
Member 3	25%	5	6	7	1.25	1.5	1.75
Member 4	5%	7	8	9	0.35	0.4	0.45
Member 5	35%	6	7	8	2.1	2.45	2.8
Member 6	10%	7	8	9	0.7	0.8	0.9
Member 7	5%	4	5	6	0.2	0.25	0.3
Member 8	5%	5	6	7	0.25	0.3	0.35
Results					5.4	6.4	7.4

Result of a risk severity was found. Figure 37 shows the membership function triangular structure) of the risk severity. Since the time rating scale is fuzzy, the obtained result is a fuzzy number, namely (5.4; 6.4; 7.4). A triangular fuzzifier was applied for the result.

To complete the assigned task, a defuzzification method is applied to the results. Method of *Mean of maximum* is chosen. In case of a triangular membership function the highest degree of fulfillment are taken into account. Then if it is assumed that the result is crisp defuzzified value x^* and fuzzy set is (5.4, 6.4, 7.4), then $x^* = 6.4$.

Result shows that the risk severity is moderate (Table 17), that means that risk *Too small amount of solder paste is printed on the PCB* cannot be accepted. Preventive actions must be assigned and this element must be added to the PDPC chart. Thus, the failure should be taken in consideration in future discussion.

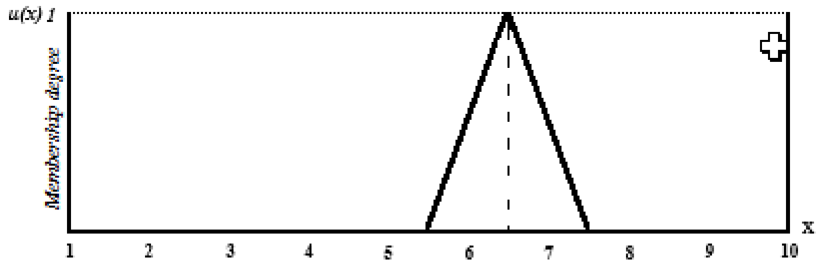

Figure 37. Membership function of the risk severity

Such approach should be applied to every risk, and all risk having higher severity should be added to the PDPC chart.

4.3.4 Comparison and discussions

Typical process decision program chart (PDPC) is a tool that helps to identify possible problems that may arise during implementation of planned activities and as well as to propose appropriate measures. Using of PDPC can minimize the risk of problems occurrence during the implementation of the planned activities.

PDPC diagram is mainly used in cases where it is a new task or new conditions of its solutions, plan of activities is a complex, high risk of failures occurrence or the goal achieving has strict deadlines. Processed PDPC diagram forms the basis of preventive actions plan against the possible problems and contributes significantly to "prosper doing right things at the very beginning".

The fuzzy approach brings new light to the meaning of PDPC chart. It gives more precise outgoing information, which leads to improvement of quality of a process.

Like any other quality management tools, PDPC chart tool has its drawbacks. During making PDPC chart for the multi-functional or multi-step process it can happen that the chart will be so big containing a lot of information, that it will be very difficult to analyze and take into account all the details. It will be time consuming to analyze all the chart elements and with adding of preventive actions it will even multiply job in future. To solve the problem, that is to eliminate a number of elements in the chart, fuzzy logic was used. It will definitely minimize future job in all directions and decrease costs for companies. The same brainstorming team that in the preparation of PDPC can be used for application of fuzzy approach. Fuzzy is used to elimination failures having low significance. This way the PDPC diagram is simplified and is more comfort to solve it. Thus, without the use of fuzzy logic approach to reduce the elements in the chart, the PDPC chart itself may well prove to be unsuitable for further use.

5 Conclusion

Together with advances in new materials, processes, and relevant diagnostics, requirements for quality increase. Volume of information obtained from standard tools for quality management, such as Ishikawa ones or management and planning quality control tools, is often no longer sufficient. There are two ways how to improve this situation: to increase the yield of information of contemporary types of management tools for quality improvement or develop new tools. It is possible to find in the literature using fuzzy approach for enhancement of such quality control tools as FMEA, FTA, control charts, histograms and others.

The thesis is focused on increasing of information yield of three selected types of managerial quality control tools: affinity diagram, PDPC diagram and arrow diagram by fuzzy approach. It allows getting more information from these tools than it would be possible when using the standard procedure. The increase in the volume of information obtained from these instruments by this way is quite new and is not found in the literature

After short description of tools under examination, a basic principle of fuzzy logic is presented.

At first fuzzy approach for better analysis of an arrow diagram is presented. Arrow diagram was used for estimation of the time of repair of a mobile phone at a mobile phones service center. For the smooth operation of both the client and the mobile phone repair there is a need to calculate the time of the problem solution as precisely as possible to meet requirements of a customer. Fuzzy logic as a supporter for arrow diagram was used in order to estimate the time interval of mobile phone repair more accurately.

The phone malfunction was caused by its fall into the water. The repair process consists of several steps. The fuzzy approach was used in the step “Diagnostics with the goal to find a cause of a problem” in order to improve the estimated time of the diagnostics that is connected with the highest uncertainty. Just the time of repair, in which the time needed for diagnostics plays an important role, is one of the most important for the customer.

The estimated time of the repair found by using of fuzzy logic was approximately by 20 % shorter in comparison with the time found by a standard way. As a result, precise plan of work for achieving the ultimate goals is obtained. This will facilitate calculation of the total process time.

The second management and planning quality control tool processed by fuzzy approach is the affinity diagram. The contribution of using of fuzzy approach for processing of this tool is demonstrated first theoretically and then on a practical example.

An affinity diagram to the adhesive assembly based on electrically conductive adhesives with the support of fuzzy logic was created. At the beginning subject of study was determined. Then failures, related to the process, were randomly collected. After a grouping of data affinity diagram was done, a prerequisite for the application of fuzzy logic was created. The research in this direction was provided with the goal to estimate unexpected failures, which are provoked by occurrence of failures in previous operations or steps. Fuzzy logic was used for estimation of possibility of occurrence a new failure in an operation "Testing" in dependence on failures, which can occur in steps "Selection of components" and "Preparation of a surface pad". To estimate the possibility if the final resulting issue "High electrical resistance occurs in the operation" occurs in "Testing" we used brainstorming with using of fuzzy logic. As the result, it was found that this failure should be taken in consideration for future discussion.

Fuzzy logic solves this problem and helps to estimate failures provoked by mixing of failures on previous steps and occurred during testing. This will contribute to prepare preventive actions in time and at the end, less faulty products will be made. Fuzzy logic combined with the affinity diagram provided in-depth review of the process and estimated if a failure on a further step/operation of the process is occurred.

At third using of fuzzy logic for improvement of a process decision program chart (PDPC) formed for electronic assembly based on a wave soldering process is presented. PDPC helps to identify failures and to create the basis for launching counter-measures (preventive actions).

During making PDPC chart for the multi-functional or multi-step process it can happen that the chart focused on failures will be big containing a lot of information, that it will be time consuming to analyze and take into account all the details. Fuzzy logic gives information about significance of individual errors and makes possible simplifying of the PDPC chart by neglecting of errors or failures of lower significance. It will definitely minimize future job in all directions and decrease costs for a manufacturer. Without the use of fuzzy logic approach to reduce the elements in the chart, the PDPC chart would be very big and it will be complicated to use it.

PDPC diagram is consisting of four steps. The fuzzy logic was used to analyze one failure from the list and to decide if it should be added to the PDPC chart or not. High number of different types of failures can occur in a process. Analysis using fuzzy approach was focused on a case when a too small volume of the soldering paste was applied. It was found that the failure based on too small amount of solder paste is a significant failure and must be involved into the PDPC chart. Preventive actions must be assigned.

Such the approach should be applied for every type of a failure and all failures having higher severity should be added to the PDPC chart.

As the result of the thesis, we got working mechanism of quality control tools with approach of fuzzy logic. The practical solution for arrow diagram, affinity diagram and PDPC diagram was demonstrated on data obtained from mentioned real processes. The presented approach can be used for any technological or other type of a process to improve the information yield from these processes. It can be concluded that set goal of the thesis to extend the usage of the fuzzy logic to the selected quality control tools, such as affinity diagram, arrow diagram and process decision program chart was achieved, and new approach to processing of these tools was presented.

6 References

[1] L. A. Zadeh, Fuzzy sets, Information and Control, No.8, pp. 338–353, 1965.

[2] Y. Bai, H. Zhuang, D. Wang, Fundamentals of Fuzzy Logic Control – Fuzzy Sets, Fuzzy Rules and Defuzzification, Advanced fuzzy logic technologies in industrial applications, pp. 2-36, 2006.

[3] E. Cox, Fuzzy Systems Handbook, Academic Press, London, pp. 377-469, 1994.

[4] V.M. An'shin, I.V. Demkin, I.N. Car'kov, I.M. Nikonov, Primenenie teorii nechjotkih mnozhestv k zadache formirovanija portfelja proektov [On Application of Fuzzy Set Theory to the Problem of Project Portfolio Selection] State University-Higher School of Economics, Moscow, Issues of Risk Analysis, 5/3, pp, 8-21, 2008, ISSN 1812-5220.

[5] D. Dubois, H. Prade, Operations on fuzzy numbers, International Journal System Science, vol.9, pp. 613-626, 1978.

[6] V.Kumar, R.R.Joshi, Hybrid Controller based Intelligent Speed Control of Induction Motor, Journal of Theoretical and Applied Information Technology, pp. 71-75, 2005.

[7] P. Vojtas, Fuzzy logic programming, Fuzzy Sets and Systems, 124/3, pp. 361-370, 2001.

[8] Povolotskaya, E., Mach, P. Fuzzy Risk Analysis Approach Test-Case: Lead-Free Soldering Process, In: 35th International Spring Seminar on Electronics Technology. Wien: Technische Universität, 2012, p. 260-265. ISBN 978-1-4673-2241-6.

[9] D.E. Tamir, N.D. Rishe, A. Kandel,, 50 years pf fuzzy logic and its applications, 2015, ISBN 978-3-319-19683-1.

[10] Povolotskaya, E. - Mach, P. Affinity Diagram as a Risk Analysis Tool with Support of Fuzzy Logic In: Advanced Science Letters. 2013. ISSN 1936-6612.

[11] H.J. Zimmerman, Fuzzy Set Theory-and Its Applications, Fourth Edition, Kluwer Academic Publishers, pp. 139-474, 2001, ISBN 978-94-010-3870-6.

[12] M. Dhar, Fuzzy Sets towards Forming Boolean Algebra, International Journal of Energy, Information and Communications, vol.2, no. 4, pp. 137-142, 2011.

[13] S.M. Kazemi, M. Karbasian, S.M. Homayouni, M.R. Vasili, Six sigma project selection by using a fuzzy multi criteria decision making approach: a case study in poly acryl corp., CIE42 Proceedings, CIE & SAIIE, Cape Town, South Africa, pp. 306/1-306/9, 2012.

[14] L. Waltman, U. Kaymak, J. Berg, Fuzzy Histograms: A Statistical Analysis, EUSFLAT – LFA, Rotterdam, The Netherlands, pp. 605-610, 2005.

[15] R. Viertl, W. Trutschnig, Fuzzy Histograms and Fuzzy Probability Distributions, Forschungsbericht SM-2006-1, Wien, Austria, 2006.

[16] Özlem Şenvar and Hakan Tozan, Process Capability and Six Sigma Methodology Including Fuzzy and Lean Approaches, Products and Services, from R&D to Final Solutions, Turkey,pp. 9-178, 2010, ISBN: 978-953-307-211-1.

[17] Siamak Noori, Morteza Bagherpour and Abalfazl Zareei, Applying Fuzzy Control Chart in Earned Value Analysis: A New Application, World Applied Sciences Journal 3 (4), ISSN 1818-4952, IDOSI Publications, Iran, pp. 684-690, 2008.

[18] Chi-Bin Cheng, Fuzzy process control: construction of control charts with fuzzy numbers, Fuzzy Sets and Systems, 154: pp. 287– 303, 2005

[19] John B. Bowles, C. Enrique Peldez, Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis, Reliability Engineering and System Safety, 50, pp. 203-213, 1995.

[20] P. A. A. Garcia, R. Schirru, P. F. Frutuoso e melo, A fuzzy data envelopment analysis approach for FMEA, Progress in Nuclear Energy, Vol. 46, No. 3-4, pp. 359-373, 2005.

[21] H. Tanaka, L. T. Fan, F. S. Lai, K. Toguchi, Fault-tree analysis by fuzzy probability, IEEE Trans. Reliab, N5, pp. 453-457, 1983.

[22] Ying-Ming Wang, Kwai-Sang Chin, Gary Ka Kwai Poon, Jian-Bo Yang, Risk evaluation in failure mode and effect analysis using fuzzy weighted geometric mean, Expert Systems with Applications 36, pp. 1195–1207, 2009.

[23] R. Rojas, Neural Networks, Springer-Verlag, Berlin, pp. 289-310, 1996.

[24] L. A. Zadeh, Outline of a New Approach to the Analysis of Complex Systems and Decision Processes, IEEE Transactions on Systems, Man, and Cybernetics, Volume: SMC-3, Issue: 1, Jan., pp. 28-44, 1973.

[25] L. A. Zadeh, The Concept of a Linguistic Variable and its Application to Approximate Reasoning-I, Information Sciences 8, pp. 199-249, 1975.

[26] Baychenko A.A., Baychenko L.A., Aret V.A., Primenenie nechetkoj logiki v upravlenii predprijatiem pishhevoj promyshlennosti, [Application of fuzzy logic in the management of food industry enterprises], ITMO University, St. Petersburg, Russia, pp. 35-69, 2014.

[27] F.A. Elerian, Razrabotka modeli nechetkoj logiki dlja upravlenija zapasami detalej pri remonte metallorezhushhih stankov , [Development of fuzzy logic for stock management in the repair of machine tools], Peoples' Friendship University of Russia, Vestnik RUDN, Engineering research, 3, 2014, pp.78-86, 2014.

[28] Polte G.A., Saenko A.P., Kolichestvennaja ocenka kachestva izobrazhenij s ispol'zovaniem metodov nechetkoj logiki, [Quantitative assessment of image quality with the use of fuzzy logic methods], Izvestiya vysshikh uchebnykh zavedeniy. Priborostroenie, 3, pp. 32-36, 2011.

[29] O.V Polte G.A., Saenko A.P.,. Lavruhin, Rozrobotka modeli sistemi pidtrimki prinjattja risheni na zaliznichnomu transporti, [The development of a model system of decision support for railay transport], DonIZT, 37, pp. 14-20, 2014.

[30] M.I. Vershinin, L.P. Vershinina, Primenenie nechetkoj logiki v gumanitarnyh issledovanijah, [The application of fuzzy logic in humanitarian research], Bibliosphera, 4, pp.43-47, 2007.

[31] Y.E. Gupanova, Primenenie instrumentarija nechetkoj logiki v ocenke kachestva tamozhennyh uslug, [The use of fuzzy logic tools to evaluate the quality of customs services], Economic Analysis, Theory and Practice, 1, pp. 143-158, 2016.

[32] Willi Meier, Richard Weber, Hans-Jurgen Zimmermann, Fuzzy data analysis — Methods and industrial applications, Volume 61, Issue 1, pp. 19-28, 1994.

[33] Vojtěch Turek, Multivalued logic systems for technical applications, diploma thesis, Brno University of technology, Faculty of Mechanical Engineering, pp. 7-15, 2008.

[34] K. Ang, C. Quek, M. Pasquier, Pseudo Outer Product Based Fuzzy Neural Network Using the Compositional Rule of Inference and Singleton Fuzzifier, IEEE transactions on systems, man, and cybernetics—part B: cybernetics, vol. 33/6, pp. 838-849, 2013.

[35] D. Rutkovskaya, M. Pilinskiy, L. Rutkovskiy, Neyronnye seti, geneticheskie algoritmy I nechetkie systemy [Neural networks, genetic algorithms and fuzzy systems], -Moskva. Goryachie liniya-Telekom, p. 452, 2006.

[36] B. Lee, Y. Sik Yun, The generalized trapezoidal fuzzy sets, Journal of the chungcheong mathematical society, Vol. 24, No. 2, pp. 253-266, 2011.

[37] M.Ingle, M. Atique, S. O. Dahad, Risk analysis using fuzzy logic, IJAET, vol.2, issue 3, July-September, pp. 96-99, 2011.

[38] I. Kaya, C.Kahraman, Process capability analyses based on fuzzy measurements and fuzzy control charts, Expert Systems with Applications 38, pp. 3172–3184, 2011.

[39] V.G. Rubanov, A.G. Filatov, Intellektual'nye sistemy avtomaticheskogo upravlenija. Nechetkoe upravlenie v tehnicheskih sistemah, [Intelligent systems of automatic control. Fuzzy management systems], Federal Agency for Education, BSTU. - 2-nd edition, 2010.

[40] Salah Kermiche, Mohamed Larbi, Hadj Ahmed Abbassi, Fuzzy Logic Control of Robot Manipulator in the Presence of Fixed Obstacle, The international Arab Journal of Information Technology, Vol. 4, No. 1, pp. 26-32, 2007.

[41] Kozlowska E.: Basic Principles of Fuzzy Logic. In Access server [online]. 2012, 10. [cit. 2012-08-02]. ISSN 1214-9675. Available at: http://access.feld.cvut.cz/view.php?cisloclanku=2012080002.

[42] Kaehler S.D., Fuzzy Logic Tutorial. Seattle Robotics Society [online]. ed. [cit. 2012-08-22], 1998. Avaible at: http://www.seattlerobotics.org/encoder/mar98/fuz/flindex.html.

[43] Timothy R. Cory, Thomas Slater, Brainstorming: Techniques For New Ideas, iUniverse Inc., 2003

[44] Ludo Waltman, Uzay Kaymak, and Jan van den Berg, Fuzzy Histograms: A Statistical Analysis, EUSFLAT – LFA, pp. 605-610, 2005.

[45] Sanjay Kumar Tyagi, Diwakar Pandey, Vinesh Kumar, Fuzzy Fault Tree Analysis for Fault Diagnosis of Cannula Fault in Power Transformer, Applied Mathematics, doi:10.4236/am.2011.211188, pp. 1346-1355, 2011.

[46] Sanjay Kumar Tyagi, D. Pandey and Reena Tyagi, Fuzzy set theoretic approach to fault tree analysis, International Journal of Engineering, Science and Technology, vol. 2, No. 5, pp. 276-283, 2010.

[47] Shi-Jay Chen and Shyi-Ming Chen, Senior Member, IEEE, Fuzzy Risk Analysis Based on Similarity Measures of Generalized Fuzzy Numbers, IEEE Transactions of fuzzy systems, vol. 11, No. 1, pp. 45-55, 2003.

[48] Anand Pillay, Jin Wang, Modified failure mode and effects analysis using approximate reasoning, Reliability Emgineering and System Safety 79, pp. 69-85, 2003.

[49] Kwai-Sang Chin & Allen Chan & Jian-Bo Yang, Development of a fuzzy FMEA based product design system, Springer-Verlag London Limited, pp. 633-649, 2007.

[50] J.B. Bowles, An assessment of PRN prioritization in a failure modes effects and criticality analysis, Journal of the IEST 47, pp. 51-56, 2004.

[51] M. Ben-Daya, Abdul Raouf, A revised failure mode and effects analysis model, International Journal of Quality & Reliability Management, Vol. 13 Iss: 1, pp. 43-47, 1996.

[52] Hu-Chen Liu, Long Liu ⇑, Qi-Hao Bian, Qin-Lian Lin, Na Dong, Peng-Cheng Xu, Failure mode and effects analysis using fuzzy evidential reasoning approach and grey theory, Expert Systems with Applications 38, pp. 4403–4415, 2011.

[53] Ching-Torng, L., Mao-Jiun, J. W.: Hybrid Fault Tree Analysis Using Fuzzy Sets. Reliability Engineering and System Safety, 58, pp. 205-213, 1997.

[54] D. Singer, A fuzzy set approach to fault tree and reliability analysis, Fuzzy Sets and Systems, Volume 34, Issue 2, 30 January, pp. 145-155, 1990.

[55] Yanfeng Li, Hong-Zhong Huang, Shun-Peng Zhu, Yu Liu, Ning-Cong Xiao, An Application of Fuzzy Fault Tree Analysis to Uncontained Events of an Areo-Engine Rotor, International Journal of Turbo & Jet-Engines,Volume 29, Issue 4, pp. 309-315, 2012.

[56] T. A. Runkler. Fuzzy histograms and fuzzy chi-squared tests for independence. IEEE international conference on fuzzy systems, 3, pp. 1361-1366, 2004.

[57] J. Van Den Berg. Probabilistic and statistical fuzzy set foundations of competitive exception learning. IEEE International Fuzzy Systems Conference, pp. 1035-1038, 2001.

[58] O. Strauss, F. Comby, and M.J. Aldon. Rough histograms for robust statistics. ICPR’2000 15th International Conference on Pattern Recognition, Barcelona, Catalonia, Spain, 3-8 September, 2000.

[59] O. Strauss, K. Loquin. Fuzzy histograms and density estimation, Advances in Soft Computing 6, vol. 37, pp. 45-52, 2006.

[60] D. J. Fonseca, M. E. Elam, L. Tibbs, Fuzzy Short-Run Control Charts, Mathware & Soft Computing 14, pp. 81-101, 2007.

[61] Gulbay, Murat, Kahraman, Cengiz, Ruan, Da. “α-cut fuzzy control charts for linguistic data.” International Journal of Intelligent Systems Vol.19, pp. 1173-1195, 2004.

[62] Alireza Faraz, M. Bameni Moghadam, Fuzzy Control Chart A Better Alternative for Shewhart Average Chart, Quality & Quantity, Volume 41, Issue 3, pp 375–385, 2007.

[63] Aparisi, F., Sampling plans for the multivariate T 2 control chart, Quality Engineering 10(1), pp. 141-147, 1997.

[64] Alireza Faraz, Arnold F.Shapiro, An application of fuzzy random variables to control charts, Fuzzy Sets and Systems 161, pp. 2684–2694, 2010.

[65] J.-H. Wang, T. Raz, On the construction of control charts using linguistic variables, Internat. J. Production Res. 28, pp. 477–487, 1990.

[66] Kane M.M., Ivanov B.V., Koreshkov V.N., Shirtladze A.G., Systemy, metody i instrumenty menedzhmenta kachestva [Systems, Methods and Tools for Quality Management], [In Russian], Piter Press, 2009.

[67] M.J. Peterson, Using Arrow Diagrams to Understand Claims, Political science 399, Arrow diagrams, pp. 2-12.

[68] P.G. Ioannou, C. Srisuwanrat, Example problems, CEE-536, Critical path method, p. 198.

[69] William Widjaja, Masayuki Sawamura, Making collaborative affinity diagram usable with distributed screen, UBICOMP '14 ADJUNCT, pp. 287-290, 2014.

[70] Cheryl Hawley, Dan Druliner, David Wright, Jeanne Semura, and Ray Hsu LEAN – Continuous Improvement Toolkit, Division of finance & administration, California State University, Chanel islands.

[71] S. Burge, The system thinking toolbox – Affinity diagram, pp. 2-12, 2011.

[72] The Seven Management & Planning Tools, Leadership and Team Development Home of the FACET Leadership Model™ © Affinity Consulting, pp. 2-9, 2000.

[73] H.L. John, C.P. Wong, C.L. Ning, Ricky Lee, Electronics manufacturing with lead-free, halogen-free and conductive-adhesive materials. New York: McGraw-Hill, Steve Chapman, 2003.

[74] Duraj, A.: Using of Electrically Conductive Adhesives for Bonding in Electrical Engineering, PhD Thesis, Prague, Czech technical university in Prague, 2001.

[75] Charles, A., Happer, M., Miller, M.: Electronic packaging, microelectronics, and interconnection dictionary. New York: McGraw-Hill, 1993.

[76] Ageeva, N. D., Vinakovskaya, Y. U., Lifanov, V. N.: Jelektrotehnicheskoe materialovedenie, [Electrotechnical material engineering]. Vladivostok: DVGTU, 2006.

[77] Nur Syazwani Abd Suki, Shahrul Kamaruddin Elmi Abu Bakar, An Improvement on the Handling Time for Unsymmetrical Product during Visual Inspection - A Case Study, Proceedings of the 2014 International Conference on Industrial Engineering and Operations Management, Bali, Indonesia, January 7 – 9, pp. 685-692, 2014.

7 Publications and awarded grants

7.1 Publications

For publications with multiple authors, the share of joint authorship is equivalent.

Publications indexed in WoS

1. Povolotskaya, E. - Mach, P. Failure Analysis of Adhesive Joining in Electronics In: 34th International Spring Seminar on Electronics Technology. Košice: Technical University of Košice, 2011, p. 244-245. ISBN 978-1-4577-2111-3.

   Cited by:

   A) Povolotskaya Evgenia, Mach Pavel, Fuzzy risk analysis approach test-case: Lead-free soldering process, *Electronics Technology (ISSE)* 2012 35th International Spring Seminar on, pp. 260-265, 2012, ISSN 2161-2536.

2. Mach, P. - Povolotskaya, E. Study of Curing Process of Electrically Conductive Adhesives Using Differential Scanning Calorimetry In: 35th International Spring Seminar on Electronics Technology. Wien: Technische Universität, 2012, p. 248-253. ISBN 978-1-4673-2241-6.

   Cited by:

   A) S. Barto, and P. Mach, Analysis of the Curing Process of Electrically Conductive Adhesives Using Taguchi Approach and Full Factorial Experiments Approach, Arabian Journal for Science & Engineering (Springer Science & Business Media BV), 39/6, 2014.

3. Molhanec, M. - Povolotskaya, E., Model based FMEA - An efficient tool for quality management of the free lead soldering In: 35th International Spring Seminar on Electronics Technology. Wien: Technische Universität, 2012, p. 230-236. ISBN 978-1-4673-2241-6.

   Cited by:

   A) S. Mario Mardone Da, Visualização do risco como meio de suporte à tomada de decisão: uma abordagem através da análise de ferramentas de gerenciamento de riscos, PhD diss, Universidade Federal de Pernambuco - UFPE 2016.

   B) M. Molhanec, Model based FMEA method for solar modules, Electronics Technology (ISSE), 2013 36th International Spring Seminar on, pp. 183-188, IEEE, 2013.

4. Molhanec, M. - Tarba, L. - Povolotskaya, E. - Zhuravskaya, O. The ontology based FMEA of lead free soldering process In: 34th International Spring Seminar on Electronics Technology. Košice: Technical University of Košice, 2011, p. 267-273. ISBN 978-1-4577-2111-3.

   Cited by:

   A) O. Daramola, S. Tor, T.Moser, S. Biffl, A conceptual framework for semantic case-based safety analysis, In Emerging Technologies &

Factory Automation (ETFA), 2011 IEEE 16th Conference on, pp. 1-8. IEEE, 2011.
B) X. Zhao, Y. Zhu, Application Research of Ontology-enabled Process FMEA Knowledge Management Method, International Journal of Intelligent Systems and Applications, 4.3, p. 34, 2012..
C) Molhanec, M., Model based FMEA method for solar moduls, Electronics Technology (ISSE), 2013 36th International Spring Seminar on, On page(s): 183-188.
D) Chen, Ying; Ye, Cui: Li, Guoqi, Failure mode databases and their knowledge-based management; Reliability, Maintainability and Safety (ICRMS), 2014 International Conference on, On page(s) 732-736.
E) R.Zobia, and S. Kifor, A Conceptual Architecture of Ontology Based KM System for Failure Mode and Effects Analysis, International Journal of Computers Communications & Control 9.4, pp. 463-470, 2014.
F) L. I. Guoqi, Ontology-based reuse of failure modes in existing databases for FMEA: methodology and tool, IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences 96/7, pp. 1645-1648, 2013.
G) M. Molhanec, E. Povolotskaya, Model based FMEA-An efficient tool for quality management of the free lead soldering, Electronics Technology (ISSE), 2012 35th International Spring Seminar on. IEEE, pp. 230-236, 2012.
H) G. Li, Ontology-Based Reuse of Failure Modes for FMEA: Methodology and Tool. In Software Reliability Engineering Workshops (ISSREW), 2012 IEEE 23rd International Symposium on, pp. 17-18, 2012.
I) Wang, J., Pu, Y., & Li, G., Fault Model Libraries for Safety Analysis and their Ontology-based Reuse. In Computational Intelligence and Security (CIS), 2012 Eighth International Conference on, pp. 301-304, 2012.
J) P. Chhim, R. Babu Chinnam, N. Sadawi, Product design and manufacturing process based ontology for manufacturing knowledge reuse, Journal of Intelligent Manufacturing, pp. 1-12, 2017.
K) Chhim, Peter Panha, Knowledge reuse through electronic knowledge repositories: An empirical study and ontological improvement effort for the manufacturing industry, PhD diss., Wayne State University, 2015.
L) Li, G. Zhang, J., A Novel Ontology-Based Method to Represent and Classify Failure Modes of Sensors. Sensors & Transducers, 25, p.112, 2013.

Publications in peer-reviewed journals

5. Povolotskaya, E. - Mach, P. Affinity Diagram as a Risk Analysis Tool with Support of Fuzzy Logic In: Advanced Science Letters. 2013. ISSN 1936-6612.
6. Povolotskaya, E. - Mach, P. FMEA and FTA Analyses of the Adhesive Joining Process using Electrically Conductive Adhesives In: Acta Polytechnica. 2012, vol. 52, no. 2, p. 48-55. ISSN 1210-2709.

Cited by:

A) J. Vallhagena, J. Madrid, Rikard Söderberg, Kristina Wärmefjod, An approach for producibility and DFM-methodology in aerospace engine component development, Procedia CIRP 11, pp. 151-156, 2103.
B) Winter, D., Ashton-Rickardt, P., Ward, C., Gibbons, P. et al., An Enhanced Risk Reduction Methodology for Complex Problem Resolution in High Value, Low Volume Manufacturing Scenarios, SAE Int. J. Mater. Manf. 9(1), pp. 49-64, 2016.
C) K. Peta, J. Żurek, M. Wiśniewski, A. Piotrowiak,.Zastosowanie metody FMEA do oceny jakości montażu nierozłącznego (lutowania) wybranych wyrobów, [Implementation of FMEA method for quality assessment of inseparable assembly (brazing)] Technologia i Automatyzacja Montażu 4, pp. 34-38, 2016.
D) Mi. Suriani, Analisis identifikasi penyebab gangguan jaringan distribusi listrik dengan menggunakan metode fault tree analysis dan failure mode and effect analysis serta usulan perbaikan di pt pln (persero) rayon gedangan, PhD diss, Universitas Airlangga, 2016.

Publications included in IEEE Xplore Digital Library

7. Povolotskaya, E., Mach, P. Fuzzy Risk Analysis Approach Test-Case: Lead-Free Soldering Process, In: 35th International Spring Seminar on Electronics Technology. Wien: Technische Universität, 2012, p. 260-265. ISBN 978-1-4673-2241-6.

Other publications

8. Povolotskaya, E. - Mach, P. Synergy Effect of Failure Mode and Effect Analysis and Fault Tree Analysis for Adhesive Joining Optimization In: InterTech 2011. Poznaň: Poznan University of Technology, 2011, p. 126-130. ISBN 978-83-926896-3-8.
9. Molhanec, M. - Mach, P. - Tarba, L. - Zhuravskaya, O. - Povolotskaya, E. FMEA Tools Survey [Research Report]. Prague: Czech Technical University, 2011. 13113/03/2011. 16 p.
10. Molhanec, M. - Mach, P. - Povolotskaya, E. - Zhuravskaya, O. - Tarba, L. - et al. Ontology of Soldering Process [Research Report]. Prague: Czech Technical University, 2011. 13113/05/2011. 6 p.
11. Molhanec, M. - Mach, P. - Povolotskaya, E. - Zhuravskaya, O. - Tarba, L. - et al. Ontology Tools Survey [Research Report]. Prague: Czech Technical University, 2011. 13113/04/2011. 12 p.
12. Molhanec, M. - Mach, P. - Povolotskaya, E. - Tarba, L. - Zhuravskaya, O. Classic FMEA of Soldering Process [Research Report]. Prague: Czech Technical University, 2010. 13113/02/2011. 22 p.

7.2 Awarded grants

1. SGS11/118/OHK3/2T/13 Povolotskaya Evgenia, The methodology of risk analysis in electrical engineering production.

2. SGS14/067/OHK3/1T/13 Povolotskaya Evgenia, Application of fuzzy logic in the field of quality control in electrical engineering production.

3. SGS10/267/OHK3/3T/13 Molhanec Martin, The Ontology based FMEA of Lead Free Soldering Process.

4. SGS12/136/OHK3/2T/13 Barto Seba, Analysis of factors, which influence quality of soldered and adhesive joints using DOE and Taguchi approach.

5. SGS14/187/OHK3/3T/13 Molhanec Martin, Seven new quality tools from the perspective of current knowledge engineering.