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Procedures and methods of quality planning and their use for forming process optimization

Jiří Plura
VSB-Technical University of Ostrava, Faculty of Metallurgy and Materials Engineering
Czech Republic

1. Introduction

Present development in the all fields of people activities is connected with increased requirements for product quality. Totally essential influence on products quality belongs to quality planning. According to terminological standard of ISO 9000´s standards family quality planning is defined as "part of quality management focused on setting quality objectives and specifying necessary operational processes and related resources to fulfil the quality objectives". Quality planning represents many of activities, which decide about resulting quality. For example these partial activities are included in quality planning (Plura, 2001):

- Quality objectives identification and their development in organization
- Product quality characteristics planning (the development of products, which meet customer (and other stakeholders) requirements
- Quality plan processing
- Planning of methods, which will be used for achievement of required product quality
- Processes quality planning (the development of processes, which will be able to assure required product quality and their capability verification)
- Preventive actions planning for possible problems risk minimization
- Planning of ways of product and process quality measurement and monitoring
- Measurement systems planning and their suitability verification
- Planning of data collection and needed quality records, etc.

Quality planning is realized especially in pre-production phases. Activities in these phases decide about customer satisfaction, product competitiveness and organization profit. While in the past production phase was regarded as key phase for product quality, at present it is generally recognized, that pre-production phases contribute to final product quality approximately by eighty percent. This state is considerably influenced by the increasing complexity of present products and used technologies, competitive market conditions and enhanced customer requirements.

The importance of quality planning is also connected with fact, that in pre-production phases much more non-conformities arise than in production and other phases. In addition, the removal of non-conformities during pre-production phases is much cheaper, that their

removal after production launching. However, up to now many organizations pay insufficient attention to these phases. Often it is lack of time and money for sufficient design processing and quality planning, but later must be much more time and money for removal of problems occurring in realization phase.
Arguments for focusing on quality planning can be summarized to these points (Plura, 2003):

- Quality planning on principle influences customer satisfaction
- The way of product quality planning is important attribute of organization competitiveness
- Product quality planning is the way to prevention of non-conformities during product realization and use
- The most of non-conformities arise in pre-production phases, where quality planning activities are especially realized
- The removal of non-conformities in pre-production phases requires the lowest costs and the shortest time
- By using of procedures and methods of quality planning organization proves, that it utilized all means for customer satisfaction achievement and for non-conformities prevention
- Product quality planning results increase customer reliance on products of organization.

2. Product Quality Planning Methodology and Methods

Process of product quality planning cannot be a set of chaotic activities. Using of suitable quality planning methodology and suitable methods are very important for effective product quality planning.

2.1 Approaches to Product Quality Planning Methodology

Classical approach to product quality planning was processed by J. M. Juran (Juran, 1988). He characterized process of product quality planning as quality planning road map, which includes following activities:

1. Identify customers
2. Discover customers needs
3. Translate customers needs to our language
4. Establish units of measure
5. Establish measurement
6. Develop product
7. Optimize product design
8. Develop process
9. Optimize process and prove process capability
10. Transfer to operations

In the past the individual activities of this road map were realized in sequence. In the traditional organization structure various departments according to this sequence became responsible for individual activities. Marketing department identified customer needs and obtained results presented to design and development department, design and development department deals with product development and results presented to engineering department etc.

However this sequential (phase) approach has many weaknesses, main cause of them is insufficient communication between the departments (at presenting results only). At present conditions, which are characterized by the increasing complexity of products and used technologies, enhanced customer requirements and competitive market conditions this approach becomes unsatisfactory.
During 1980´s simultaneous engineering started to develop. Within framework of this approach product design, process design and development of all other elements of product success are understood from the initiation as integrated set of objectives and activities. All activities are realized simultaneously by the product development team. Very important benefits of this approach is better meeting of customer needs, shortening time of product design and development, saving costs, better manufacturability of designed product etc. (Clausing, 1994).
Simultaneous engineering was developed to the Integrated Product and Process Development (IPPD). This approach is defined as management process that integrates all activities from product concept through production/field support, using a multifunctional team, to simultaneously optimize the product and its manufacturing and sustainment processes to meet cost and performance objectives.
The fundamental elements of simultaneous engineering and integrated product and process development are included in methodologies of product quality planning, which are used within the framework of automotive industry quality management system standards. The most famous example is methodology APQP (Advanced Product Quality Planning and Control Plan), which was developed by American car producers Chrysler, Ford and General Motors as part of QS-9000 standard (APQP, 2008). Product quality planning is divided to the five overlapping processes in this methodology (see Fig. 1). Before APQP methodology application product quality planning team is organized and involved people are trained. Individual processes are managed with help of determined outputs, which fulfilment is required for progress to the next process.

2.2 Suitable Methods for Product Quality Planning

The effectiveness of quality planning can be considerably increased by using of suitable quality planning methods. Quality planning methods include for example QFD (Quality Function Deployment), Design and Process FMEA (Failure Mode and Effect Analysis), FTA (Fault Tree Analysis), Design of Experiments, Machine and Process Capability Analyses, Measurement System Analysis, group of Seven New Quality Management Tools and other methods and tools. In the field of automotive industry and its suppliers some of these methods must be used.
Various methods are useful in various partial processes of product quality planning. The analysis of suitability of the use of various methods (including seven basic management tools) in selected main processes of product quality planning was performed with using of matrix diagram (Plura, 2003). Results of this analysis are given in Fig. 2. It can be seen, that all given processes can be supported by using of suitable methods.
It is not necessary to use all given methods and tools for effective product quality planning. However, sometimes it is useful to utilize various methods, because they can provide wider spectrum of information needed for quality planning. Methods and tools should not be used separately, they should be interconnected. Several works using suitable combination of methods for effective quality planning were published (Kwai-Sang Chin et al., 2003; Almannai et al., 2008).

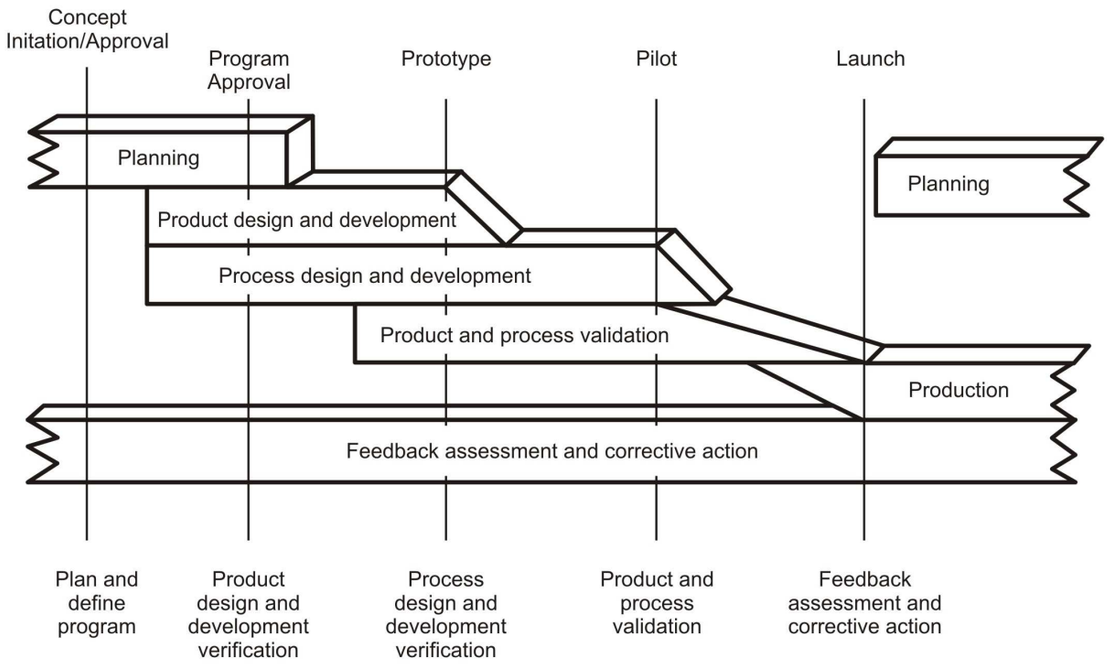

Fig. 1. Product quality planning timing chart according to APQP methodology

2.3 Improved Product Quality Planning Methodology

On the basis of suitable methods analysis and author practical experience the improved product quality planning methodology, which optimizes the use of suitable methods, was processed (Plura, 2004). Product quality planning is divided to the nine partial processes:

1) Customer Requirements Identification

Discovery of customer needs is the main task of customer requirements identification. There is suitable to use wide spectrum of information sources as direct interview with customers, questionnaires, information of traders, information from services etc. Method of quality function development, where team of company employee analyzes expected customer needs, is suitable way for it too.

Obtained information about customer needs must be completed by other product requirements, which are given e.g. by legitimate rules and by producer experience with similar products. Affinity diagram, which facilitates creation of fundamental structure of requirements, and systematic diagram, which makes possible logical decomposition of requirements are suitable methods for customer requirements processing.

2) Design of Product Quality Characteristics

Customer requirements are often given in customer language. The producer must translate these requirements to the concrete measurable product quality characteristics. Quality Function Deployment (QFD), especially so called "House of Quality" application is suitable tool for this translation. Design of product quality characteristics target values takes into consideration e.g. the importance of individual requirements, the evaluated importance of individual quality characteristics and benchmarking results.

METHOD \ PROCESS	Customer Needs Identification	Transformation of Customer Needs to Product	Product Development	Product Design Optimization	Process Development	Process Optimization and Capability Verification
Affinity Diagram	++	+	++	+	++	+
Interrelationship Diagram	+	+	+	+	+	+
Systematic Diagram	++	++	+		+	
Matrix Diagram	+	++	+	+	+	+
Matrix Data Analysis	+	+	+	++	+	++
PDPC Diagram			+	++	+	++
Arrow Diagram			+		+	
QFD	+	++	++	+	++	+
Design FMEA			++	++	+	
Process FMEA					++	++
Fault Tree Analysis			+	++	+	++
Design of Experiments			++	++	++	++
Process Capability Analysis			+	+	++	++
Machine Capability Analysis			+	+	++	++
Measurement System Analysis		+	+	++	+	++
Flow Chart					++	++
Cause-Effect Diagram			++	++	++	++
Data Form	++	+	+	+	+	+
Pareto Diagram	++	+	+	+	+	+
Histogram			+	+	+	++
Scatter Diagram		+	++	++	++	++
Control Chart					++	++

Fig. 2. Matrix diagram of selected suitable methods for use in the main processes of product quality planning

++ method is especially suitable for use in given process

+ method is suitable for use in given process

3) Product Quality Characteristics Optimization

Design of product quality target values should be analysed with aim to achieve optimal solution. Many of suitable methods can be used for this optimization.

Complex analysis of designed product from many points of view can be realized with using design review - systematic team assessment of design, which is done with aim to assess design capability to meet quality requirements, to identify any faults and to propose the way of their solution.

Product failure mode and effect analysis (Design FMEA) is very important part of design review. It is team analysis of possible occurrence of failures in designed product connected

with their risks assessment, which is the base for proposal and realization of actions, which minimize these risks and optimize product. The use of this method represents system approach to failures prevention and makes possible to reveal 70 to 90 % of failures, which could occur during product use.
For detailed identification of causes of possible product failures Fault Tree Analysis (FTA) can be performed.
As suitable tool for quality characteristics optimization design of experiments (DOE) can be used. Appropriate experiments are usually realized on product prototype and the aim of them is to find optimal combination of quality characteristics values, which assure the best product utility value.
In many cases variant solutions are processed during product design and development. Objective ways for the best variant selection should be used in these cases. Usually it is multidimensional task for searching the best variant from many parameters point of view. In this case it is possible to use some numeric or graphical methods of matrix data analysis as principal component analysis, determination of distance between multidimensional variables with using suitable metric, maps or glyphs (Plura, 2001).

4) Design of Parts Quality Characteristics
In the cases when designed product consists of parts it is necessary to deduce from product quality characteristics needed parts quality characteristics. Also identification of the most important (critical) parts, which have the most considerable influence on final product quality is very useful. The both tasks can be effectively realized with using QFD modifications.
It is suitable to start with critical parts identification. The matrix diagram, which analyzes mutual interrelationships between product quality characteristics and individual parts is the base of appropriate QFD modification.
QFD modification for design of parts target quality characteristics uses as base the matrix diagram, which analyzes interrelationships between product quality characteristics and individual parts quality characteristics. This application makes possible to optimize parts quality characteristics, to identify the most important characteristics and to obtain other valuable information.

5) Design of Product Realization Process
Suitable quality planning methods should be used during process design too. For example, needed partial processes can be identified with using affinity diagram, optimal sequence of these processes can be analyzed with using interrelationship diagram and process design can be processed with using flow chart.
Key processes with regard to their influence on product quality can be identified with using QFD modification based on the matrix diagram, which analyzes interrelationships between product or parts quality characteristics and individual processes. Other QFD modification is based on matrix diagram, which analyzes interrelationships between product or parts quality characteristics and individual process parameters. It facilitates design of process parameters target values and gives information about process parameters importance from product quality point of view.

6) Process Design Optimization
Process optimization can be performed with using Process FMEA, which is based on the analysis of possible process failures, their possible effects and causes and risks assessment. In cases when appropriate risk priority numbers (RPN) are higher then critical value suitable actions for risks decreasing are proposed and realized.
More detailed identification of causes of possible failures can be performed with using fault tree analysis method (FTA).
Design for experiments is also very useful method for process parameters optimization.

7) Design of Process Control System
Process control system must be developed simultaneously with process design. This system should assure that designed process will achieve planned parameters. Needed methods of control and inspection of process and product parameters are determined in control plan.
The results of process design and its optimization with using QFD, FMEA and FTA are useful inputs for control plans processing. Design of control plan can be facilitated with using QFD modification based on matrix diagram, which analyzes interrelationships between individual process parameters and the ways of process control and inspection.

8) Measurement Systems Suitability Verification
The use of various measurement systems is planned in the control plan. Quality of measured data can considerably influence correctness of decision-making in the relation to product conformity and course of realized processes. Therefore it is very important to analyze these measurement systems and to verify their suitability for use in given production or tolerance range. Measurement system quality is assessed with using many statistical properties as stability, precision, bias, repeatability, reproducibility, linearity etc.

9) Process Capability Verification
Before full production launching process capability must be verified. Process capability characterizes process ability to produce products meeting required quality criteria. As measure of process capability various process capability indices as C_p, C_{pk}, C_{pm} and C_{pmk} are used. It is necessary to paid sufficient attention to the fact that various process capability indices provide various information. In the case of their correct use and interpretation they makes possible to estimate probability of non-conforming products occurrence and to propose suitable actions for process improvement.

3. Selected Quality Planning Methods and Experience with their Use

3.1 QFD (Quality Function Deployment)
QFD is the method of quality planning and quality improvement, which represents structured approach to defining customer needs and their translation to the quality planning activities during product and process design and development. It makes possible to analyze mutual relations between „What must be done“ and „How it should be done”. It uses the matrix diagram principle and its successful application is based on the teamwork of people representing various functional departments, which are involved in product design and development (Re Velle, 2000).

QFD is most frequently used for the transformation of customer requirements to the product quality characteristics. Combined matrix diagram often called as House of Quality is its graphical result. House of Quality processing produces valuable database of information, which makes possible to propose and optimise target values of product quality characteristics and to evaluate the importance of them.
House of Quality is processed by the team of people from marketing and design and development departments especially. People from marketing give information about product requirements and people from design and development department give the list of product quality characteristics. Product requirements are recorded to the rows of matrix diagram and quality characteristic to the columns of diagram (see Fig.3).
The importance of individual product requirements from customer point of view is assessed at first. Rate of importance (A) is usually evaluated using scale of 1 to 5 with 5 being most important and 1 being of relatively low importance.
After it the ability of organization and its competitors to fulfil individual requirements from the customer point of view is evaluated. Also the scale of 1 to 5 is used. This evaluation makes possible to analyse strengths and weaknesses of organization and its competitiveness in the market. It gives very important information for planning of improvement activities focused to the achievement of better evaluation of the fulfilment of selected product requirements. The measure of the planned improvement is expressed using „improvement ratio" (B), which is calculated by dividing of planned evaluation by present evaluation of ability to fulfil given requirement according to the relation:

$$B_i = \frac{P_i}{N_i} \tag{1}$$

where:
N_i – present evaluation of ability to fulfil given requirement
P_i – evaluation, which organization wants to achieve (plan)

Next evaluation of individual product requirements is focused to the influence of their fulfilment on the product saleability. Recommended values of „sales points" (C) are: 1.5 for strong influence, 1.2 for higher influence and 1 for standard influence on the product saleability (King, 1989).
On the basis of the rate of importance, improvement ratio and sales point the absolute weights of individual customer requirements are calculated according to the relation:

$$D_i = A_i \cdot B_i \cdot C_i \tag{2}$$

where:
A_i - rate of importance of given requirement
B_i - improvement ratio of given requirement fulfilment
C_i - sales point of given requirement

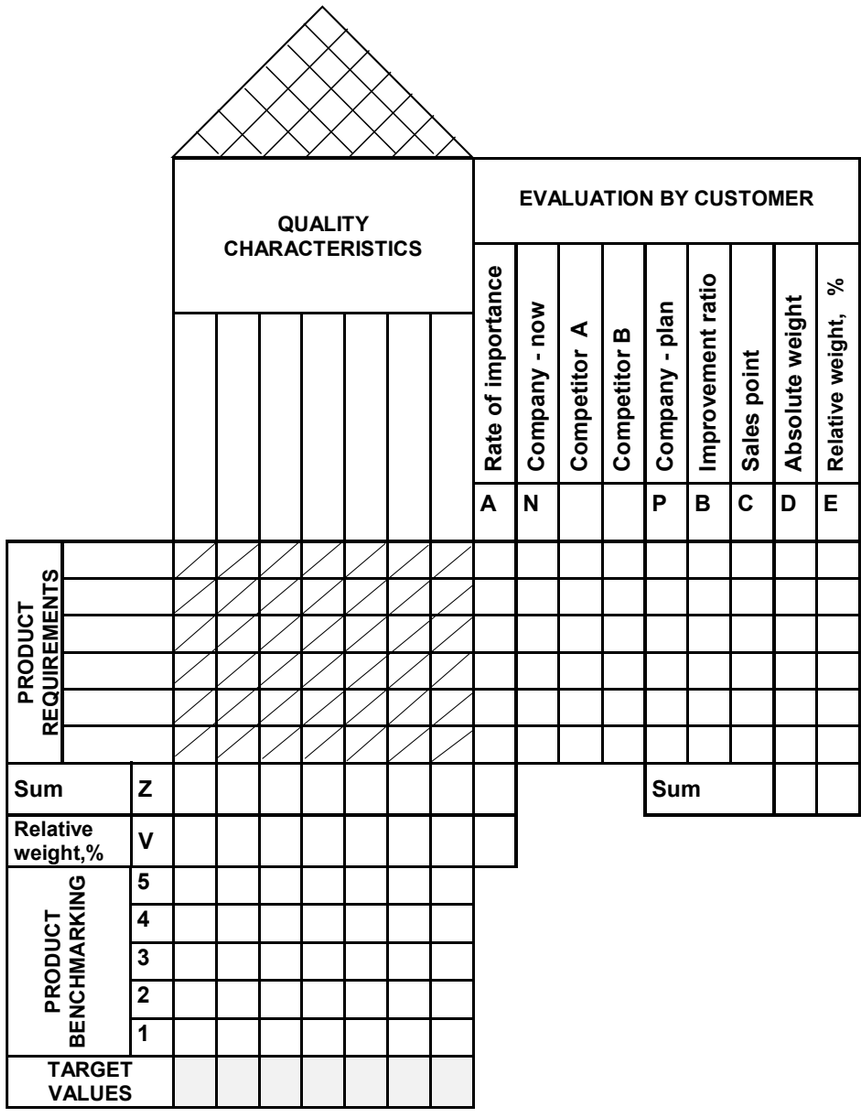

Fig. 3. House of Quality structure

Determined requirement absolute weights are recalculated to the requirement relative weights expressed in percentage according to the relation:

$$E_i = \frac{D_i}{\sum_{i=1}^{n} D_i} \cdot 100 \tag{3}$$

where:
n – number of requirements

The values of relative weights of customer requirements characterize what attention organization must pay to the fulfilment of individual requirements.

In the next phase of House of Quality processing the correlations between individual product requirements and individual product quality characteristics are analysed. They are used four levels of the strength of correlation: strong correlation (k_{ij} = 9), average correlation (k_{ij} = 3), weak correlation (k_{ij} = 1) and no correlation (k_{ij} = 0). Suitable graphical symbols, which are used for appropriate levels, are recorded to proper cells (for no correlation no graphical symbol is used).
Very useful information can be obtained on the basis of the graphical symbols location analysis. For example, if any row remains empty, it means that it is no quality characteristic, which correlates with given product requirement and it is necessary to add suitable one. If any column is empty, it means that given quality characteristic is not interest from given customer requirements point of view (if it isn´t customer expectation, which wasn´t declared). Analysis makes possible also to estimate important quality characteristics (these, which have the most relations to product requirements).
In the individual cells where any correlation was identified the relative weight of customer requirement is multiplied by factor k_{ij} according to relation:

$$S_{ij} = k_{ij} \cdot E_i \tag{4}$$

where:
k_{ij} – coefficient expressing the strength of correlation

Calculated values of S_{ij} characterize the importance of individual quality characteristics in relation to individual product requirements.
For individual quality characteristics the sums of these S_{ij} values is calculated according to the relation:

$$Z_j = \sum_{i=1}^{n} S_{ij} \tag{5}$$

The appropriate value of the sum (Z_j) characterizes the importance of given quality characteristic from the point of view of the all product requirements fulfilment. It is usually recalculated to the percentage expression of relative weight of characteristic according to the relation:

$$V_j = \frac{Z_j}{\sum_{j=1}^{m} Z_j} \cdot 100 \tag{6}$$

where:
V_j – relative weight of given quality characteristic in percentage
m - number of quality characteristics

The relative weight of quality characteristic quantifies the importance of individual quality characteristic towards given set of product requirements. Their values take into consideration the importance of individual product requirements, organization objectives oriented to the improvement of some requirements fulfilment and the influence of individual product requirements fulfilment on product saleability. This evaluation makes possible to determine priorities of product quality planning.

On the basis of information about technical parameters of similar competitor´s products team evaluates ability of organization and its competitors to achieve needed values of individual quality characteristics. It is used also the scale of 1 to 5.
In the next phase QFD team analyses mutual correlations between individual quality characteristics. The rates of correlation are recorded to the House of Quality roof.
In the processed House of Quality team has now enough information for designing of product quality characteristic target values. In this designing also other aspects should be taken into consideration; difficulty of individual quality characteristic achievement, adequacy of quality characteristic in relation to product costs, product manufacturability etc. Designed target values of quality characteristic are recorded to the base of the House of Quality. Besides target values acceptable tolerance limits should be determined.
House of Quality is most frequently used QFD application. However possibilities of QFD are much wider. In the so called Four Matrices Approach the House of Quality is followed by next applications which make possible to plan parts quality characteristics, process parameters and ways of process control (Re Velle, 2000). Comprehensive set of another applications within the framework of QFD is offering by so called Matrix of Matrices, which includes thirty of various matrix diagram applications useful for quality planning (King, 1989).

Practical Experience with QFD Applications
QFD is very useful tool for quality planning or quality improvement, but its potential is not sufficiently utilized in practice. Lack of information and incorrect application can be the main causes of it. On the basis of author experience with House of Quality practical applications it is possible to point out especially these deficiencies of House of Quality processing:

- Team members have insufficient knowledge in conditions of using product by customer
- It is confusion of product requirements and quality characteristics
- Team members have lack of information about competitive products
- Comparison with competitors does not respect customer opinion
- Some of product requirements are included more times (by various formulations).

Very positive finding of QFD practical applications was fact that team members understood that QFD can considerably enhance customer satisfaction and product competitiveness and that QFD application does not mean time loss, on the contrary, it can considerably shorten time needed for new product launching on the market.

3.2 FMEA (Failure Mode and Effect Analysis)
Failure Mode and Effect Analysis represents team analysis of possible failures or non-conformities in designed product or process. This analysis is associated with risk assessment, which is the base for proposal and realization of preventive actions, leading to these risks minimization and product or process optimization (Stamatis,1995). The use of FMEA represents system approach to non-conformities prevention and to design optimization and creates valuable database of information, which is usable for similar products and processes. Effective use of this database in other FMEA applications is subject of some research works (Teoh, P.C. & Case Keith, 2004).

FMEA application leads to decreasing of the loss associated with low product or process quality, to product or process development time shortening and to customer satisfaction increasing. The costs needed for its processing are negligible in comparison with possible costs in case of real failures occurrence.
FMEA is used for two basic applications especially; as Design FMEA and Process FMEA. Design FMEA makes possible to minimize risks of possible failures, which can originate during designed product use, Process FMEA makes possible to minimize risks of possible failures, which can originate during designed process realization. Both applications are required by quality management systems standards for automotive industry.
FMEA is the method, which should be applied by the cross-functional team, because knowledge and experience of many of specialists are utilized. People from R&D department, quality department, testing laboratories, services, designers, technologists etc. are suitable team members. Methodical leadership by experienced facilitator is very important for effective teamwork.
Procedure of FMEA application includes analysis of potential failure modes, identification of their possible effects and causes and analysis of used preventive actions and actions for failures detection. The risk of possible failures is assessed with using of risk priority number (RPN), which is calculated on the basis of assessment of failure severity, probability of occurrence and probability of detection. In the cases, when risk priority number is higher than critical value, design changes assuring sufficient risk reduction are proposed and realized.

Practical Experience with FMEA Applications
FMEA is very effective tool of design optimization from the risk of potential failures point of view. However author experience indicates, that practical applications of FMEA have many deficiencies. Frequent deficiencies of FMEA practical applications are:

- FMEA is not processed by the team
- Team have insufficient time for FMEA processing
- Potential failure modes are incorrectly identified (replacement with failure effects or causes)
- Possible failure causes are incorrectly identified (mixing of Design FMEA and Process FMEA)
- Possible failure causes are insufficiently concrete (problems during preventive actions proposal)
- Preventive actions and actions for possible failures detection are confused
- Actions for possible failures detection are incorrectly identified (difference between DFMEA and PFMEA)
- Assessment of individual criteria is too optimistic
- Assessment after preventive actions realization doesn´t respect type of action
- The influence of realized preventive actions on the other potential failures risks assessment is not analysed
- Updating of analysis results in cases of new facts finding is not performed.

It is necessary to avoid given deficiencies, because incorrect FMEA application gives not only incorrect results but also loss of confidence in this method.

3.3 Process Capability Analysis

Product quality is considerably influenced by process quality. Process quality is evaluated by means of process capability analysis. Process capability can be defined as process ability to produce permanently products meeting required quality criteria. As measure of process capability various process capability indices are used.

Knowledge of process capability is very useful for both customer and producer. For customer it gives important information whether conditions of production assure regular keeping of product specification limits. Producer can evaluate on the basis of this knowledge the suitability of given process for product realization, risk of nonconforming products occurrence, efficiency of process improvement actions, etc. Process capability analyses are required by quality management system standards for automotive industry.

For correct process capability assessment it is necessary to keep correct procedure. In the case of measurable quality characteristic it should include these steps:

1. choice of quality characteristic
2. measurement system analysis
3. data collection from running process
4. exploratory data analysis
5. process statistical stability verification
6. data normality verification
7. process capability indices calculation and its comparison to required values.

Very important are especially the way of data collection (collected data must characterise all usual causes influencing process) and the fulfilment of limiting conditions (process must be in statistical control and data, in case of using common formulas, must correspond to normal distribution).

Process Capability Indices

Process capability is evaluated by various process capability indices (Kotz & Lovelace, 1998; Bothe, 1997). In practice, C_p and C_{pk} indices, which evaluate potential and real ability of process to produce products meeting tolerance, are most frequently used. In lower extent C_{pm} index, which especially evaluate process ability to achieve target value of quality characteristic, and C_{pmk} index, which evaluates both aspects, are used.

C_p index

C_p index is the ratio of maximum allowable range of given quality characteristic to the range over which the process is actually varying. It characterizes potential process capability only, because takes into account only characteristic variability and not characteristic position with regard to tolerance limits:

$$C_p = \frac{USL - LSL}{6\sigma} \tag{7}$$

where: LSL - lower specification limit
USL - upper specification limit
σ - standard deviation

Actual variability is expressed by 6σ, which for normally distributed data represents range, in which given quality characteristic will be with probability 0,9973. For example, C_p=1 means that expected proportion of non-conforming products will be 0,27 % at minimum.

This minimum value can be achieved only in case, when characteristic mean will lie in the centre of tolerance limits.

C_{pk} index

C_{pk} index takes into account not only characteristic variability, but also its position with regard to tolerance limits. It characterizes actual process capability to meet tolerance limits and due to this it is the most frequently used process capability index in practice. As only one from discussed capability indices the C_{pk} index is directly related to the expected occurrence of non-conforming products. C_{pk} index is expressed as ratio of the distance from characteristic mean to near tolerance limit to the half of actual characteristic variability (3σ):

$$C_{pk} = min\left\{C_{pL}; C_{pU}\right\} = min\left\{\frac{\mu - LSL}{3\sigma}; \frac{USL - \mu}{3\sigma}\right\} \tag{8}$$

where:

μ - characteristic mean

C_{pk} index is crucial criterion of process capability assessment. Processes are usually classified as capable in cases, when C_{pk} value is 1,33 at minimum. Within the framework of Production Part Approval Process (PPAP) used in automotive industry (PPAP, 2006), where process preliminary capability is assessed during pilot production the required value of C_{pk} is 1,67 at minimum.

The relation between C_{pk} and C_p indices can be expressed by this equation:

$$C_{pk} = C_p - \frac{\left|\frac{USL + LSL}{2} - \mu\right|}{3\sigma} \tag{9}$$

Both indices have same value only in case, when characteristic mean lies in the centre of tolerance limits. (The potential capability is fully utilised in this case.) The higher is the distance from quality characteristic mean to the centre of tolerance limits, the higher is difference between C_{pk} and C_p indices. For example, when characteristic mean lies one sigma from the centre of tolerance, the difference between C_{pk} and C_p is 0,33.

C_{pm} index

C_{pm} index compares maximum allowable quality characteristic range with the actual characteristic variability around the target value:

$$C_{pm} = \frac{USL - LSL}{6 \cdot \sqrt{\sigma^2 + (\mu - T)^2}} \tag{10}$$

where:

T – target value

This index takes into account both given quality characteristic variability and the rate of target value achievement. Its use is recommended only for cases, when target value lies in the centre of tolerance limits.

C_{pmk} index

C_{pmk} index compares the distance from characteristic mean to the near tolerance limit with the half of actual variability of characteristic around the target value:

$$C_{pmk} = min\left\{\frac{\mu - LSL}{3\cdot\sqrt{\sigma^2 + (\mu - T)^2}}; \frac{USL - \mu}{3\cdot\sqrt{\sigma^2 + (\mu - T)^2}}\right\} \tag{11}$$

C_{pmk} index utilises good property of C_{pk}, especially its ability to recognise whether values of given characteristic actually lie inside tolerance limits, which combines with the rate of target value achievement. It is possible to derive this relation between C_{pmk} and C_{pk} indices:

$$C_{pmk} = \frac{C_{pk}}{\sqrt{1 + \left(\frac{\mu - T}{\sigma}\right)^2}} \tag{12}$$

The ratio within brackets under square root represents distance from characteristic mean to the target value expressed by the number of standard deviations. For example in case of quality characteristic mean shifting by one standard deviation from the target value C_{pmk} index will be 1,41 times lower than index C_{pk}. Both indices has same value in case, when characteristic mean is equal to the target value.
For the cases when both tolerance limits and target value of given characteristic are specified this procedure of capability indices practical use can be recommended:

1) Firstly C_{pk} index should be determined for the evaluation of real process capability to meet tolerance limits
2) C_p index should be determined because its comparison to C_{pk} index makes possible to evaluate how potential process capability is utilised and to find suitable way for process improvement
3) C_{pmk} indices should be determined for obtaining information about rate of target value achievement. It makes sense especially in cases, when process is capable to meet required tolerance limits.

At process capability evaluation one must keep in mind that various capability indices give various information about process capability. Integrated information can be obtained using suitable combination of capability indices. For objective process capability assessment it is necessary also to visualise distribution of quality characteristic (e.g. by using histogram) with regard to tolerance and to assess all factors, which influence quality of capability indices values.

Practical Experience with Process Capability Analysis Applications
On the basis of author experience many of deficiencies occur in process capability analysis in practice, e.g.:

- Measurement system analysis is not performed (process variability can be distorted by the measurement system variability)
- Data from process are collected only during short time (data does not include all sources of process variability)
- Small number of data is processed (insufficient confidence of calculated capability indices)
- Graphical tools of exploratory data analysis are not used (histogram, box plot etc.)

- Process statistical stability is not verified
- Various ways are used for estimation of standard deviation
- Unity of used tolerance limits with customer requirements is not verified
- Calculated capability indices are not correctly interpreted.

It is very important to avoid these deficiencies. In the contrary case the results of process capability analysis can be valueless.

4. Use of Selected Quality Planning Methods for Forming Process Optimization

Discussed quality planning methods (QFD, FMEA, Process Capability Analysis) can be used in various situations. Results of their using for forming process optimization are given thereinafter.

4.1 Use of QFD for Process Optimization

QFD applications were focused to process quality planning for production of forgings for automotive industry. The design and development of this product was realized by customer. Supplier should develop process, which is capable to assure required product quality.

Relevant information for process quality planning is knowledge about partial production processes importance with regard to forgings quality. The first QFD application was processed with aim to assess this importance and to identify key processes.

Identification of required quality characteristics was the first step of solution. Information was obtained from drawing documentation, supplemental specifications and supplier experience with customer requirements for similar forgings. Resulting set of required forging quality characteristics is given in Table 1.

Important forging dimensions, required hardness and surface quality were the main required quality characteristics. As to surface quality it was necessary to assure forgings surface without scales, without corrosion and without any surface defects, especially cracks.

	Quality characteristic		Quality characteristic
1	Dimension 25,9 mm	10	Dimension 59,75 mm
2	Dimension 52,8 mm	11	Dimension 46,3 mm
3	Dimension 194,4 mm	12	Hole diameter 20 mm
4	Dimension 130,9 mm	13	Hardness 238-280 HBW
5	Shift max 0,8 mm	14	No scales
6	Burr max 1 mm	15	No surface defects
7	Deflection max 0,9 mm	16	Roughness max 6,3 μm
8	Diameter 70,8 mm	17	Without corrosion
9	Diameter 50,7 mm		

Table 1. Required forging quality characteristics

On the basis of forging quality characteristics required partial production processes were identified. After it the proposal of technological process was worked up with using flow chart.

QFD application processing was started by the assessment of individual forging quality characteristics importance with using scale from 1 to 5. Results of this assessment can be seen in Fig. 4. In the next step the relations between individual processes and individual quality characteristics were analyzed. At the same time the strength of relations was

assessed. In accordance to QFD methodology strong influence of given process on given characteristic was expressed by coefficient 9, middle influence by coefficient 3 and weak influence by coefficient 1 (see Fig. 4). Values of these coefficients were multiplied by assessment of quality characteristic importance and appropriate results were summarized for individual columns. Obtained sums express the importance of given process with regard to all required forging quality characteristic. For better interpretation they were recalculated to percentage expressions, which characterize relative importance of individual processes.

		PARTIAL PROCESSES												
		Characteristic importance	Material cutting	Heating	Upsetting	Preliminary forging	Forging	Trimming	Sizing	Palletization	Cooling	Blasting	Blasting after NDT	Holes machining
PRODUCT QUALITY CHARACTERISTICS	Dimension 25,9 mm	3	1	3		3	3		1					
	Dimension 52,8 mm	3	1	3		3	1		1					
	Dimension 194,4 mm	3		1		9	1	3	1					
	Dimension 130,9 mm	3		1		9	1	3	1					
	Shift max 0,8 mm	3				1	1	1						
	Burr max 1 mm	2						3						
	Deflection max 0,9 mm	3						1	9					
	Diameter 70,8 mm	4		3		9	1		1					
	Diameter 50,7 mm	4		3		9	1		1					
	Dimension 59,75 mm	5												3
	Dimension 46,3 mm	5												3
	Hole diameter 20 mm	5												3
	Hardness 238-280 HBW	5									9			
	No scales	3	1	9	3							9		
	No surface defects	3	1			3				9				
	Roughness max 6,3 µm	3												9
	Without corrosion	3											9	
	Total		12	75	9	156	29	30	47	27	45	27	27	72
	Relative importance, %		2,16	13,49	1,62	28,06	5,22	5,40	8,45	4,86	8,09	4,86	4,86	12,95

Fig. 4. QFD application for assessment of partial processes importance with regard to forging quality

Final matrix diagram with obtained results is given in Fig. 4. It can be seen higher occurrence of strong relations to forging quality characteristic especially for preliminary forging process. This fact is confirmed by the highest value of this process relative importance (28,1 %). Next processes with highest relative importance were heating of input material (relative importance 13,5 %) and holes machining (relative importance 12,95 %). All results were illustrated with using Pareto diagram (see Fig. 5).

On the basis of Pareto analysis with using criterion 50 % of cumulative percentage these partial processes can be considered as "vital few" of partial processes with regard to final forging quality. These findings were utilized during designing of production process. There were proposed suitable control systems for these processes including suitable means of automation which assure minimizing of human factor influence.

Next part of solution was focused to the design of target values of processes parameters needed for the achievement of required forging quality characteristics. With using teamwork main parameters of partial processes were firstly identified. In total 36 controllable process parameters were found. After it the QFD application based on matrix diagram analyzing the influence of individual process parameters on forging quality characteristics was processed. Used processing procedure was similar to procedure described above. Because of large extent this matrix diagram is not presented.

Material locating in die before preliminary forging was evaluated as the most important process parameter with regard to forging quality characteristics. Summary of eight the most important process parameters is given in Table 2. On the basis of Pareto analysis with using criterion 50 % of cumulative percentage these process parameters can be considered as "vital few" of parameters with regard to final forging quality. On the basis of given results it was proposed to pay special attention to these process parameters. It was recommended to include these parameters to the set of special characteristics, which need special control regime.

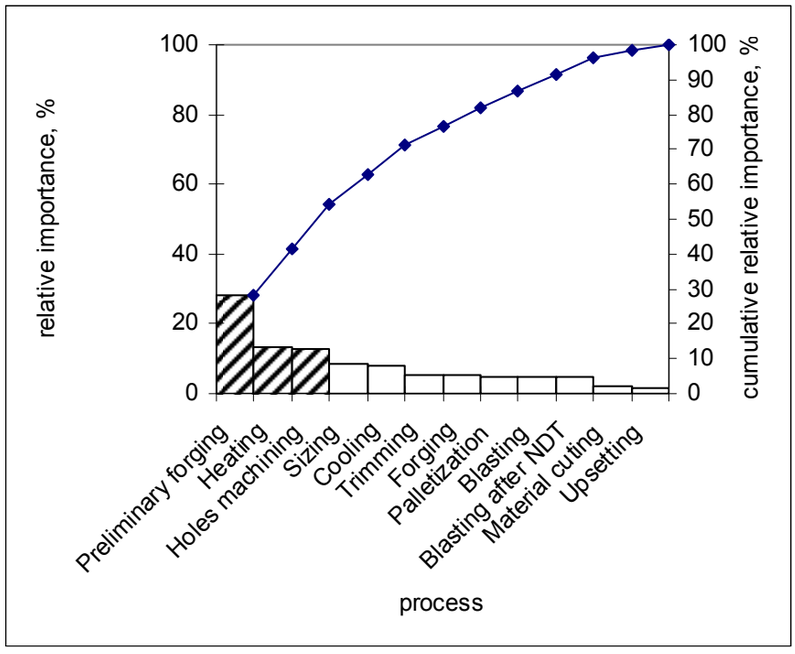

Fig. 5. Pareto diagram of the partial processes importance with regard to required forging quality

Processing of this QFD application was used for the optimization of target values of individual process parameters. Some of parameters was later little changed on the basis of process FMEA and process capability analysis, which was applied for proposed process optimization.
Benefits of given applications were not only in achieved results, they considerably contributed to better understanding of relations between individual forging quality characteristics and individual processes and their parameters.

Importance order	Process parameter	Relative importance, %	Relative cumulative importance, %
1	Preliminary forging - material locating in die	14,60	14,60
2	Holes machining - tool sharpness	6,87	21,47
3	Holes machining - speed	5,15	26,62
4	Material heating - temperature homogeneity	4,87	31,49
5	Material heating - material temperature	4,87	36,36
6	Holes machining - rate of feed	4,58	40,94
7	Holes machining - clamping method	4,58	45,52
8	Sizing - machine capability	4,48	50,00

Table 2. The most important processes parameters with regard to forging quality characteristics.

4.2 Use of FMEA for Process Optimization

Proposed forging production process was in the next phase analyzed with using Process FMEA. For individual partial production processes potential failure modes, potential failure effects, potential failure causes, preventive actions and actions for failures detection were identified. Special attention was paid to the processes, which was during QFD application assessed as very important.
FMEA results were written to the FMEA form. Together with knowledge of process conditions they were the base for assessment of severity of individual possible failures, their occurrence during proposed process and probability of their detection by the means of used inspection procedures. The scale from 1 to 10, according to assessment tables for automotive industry, was used for these criteria assessment. On the basis of individual criteria values Risk Priority Number (RPN) was determined according to the relation:

$$RPN = Severity \times Occurrence \times Detection \tag{13}$$

In the cases of all possible failures, where Risk Priority Number was greater than critical value 100 or where possible failure could mean any dangerous effect, suitable preventive actions for risk minimization were proposed. The example of FMEA part is given in Fig. 6 .

Process Function --------- Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Criticality	Potential Cause(s) Mechanism(s) of Failure	Occurrence	Current Process Control - Prevention	Current Process Control - Detection	Detection	RPN	Recommended Action(s)	Respon-sibility Target date	Actions Taken	Severity	Occurrence	Detection	RPN
Forging	Dimension 46,3 is not kept	Nonconforming product	8		Incorrect die dimension	2	Die inspection at shift beginning	Dimension measurement, 3 pieces per shift	5	80	No actions			8	2	3	48
Dimension keeping					Die wearing	3	Die inspection at shift beginning	Dimension measurement, 3 pieces per shift	5	120	Dimension measurement, 2 pieces per hour		Inspection procedure established	8	3	3	72
No scales					Unsuitable material temperature	3	Temperature control in the furnace	Dimension measurement, 3 pieces per shift	5	120	Dimension measurement, 2 pieces per hour		Inspection procedure established	8	3	3	72
No surface defects	Dimension of shift is not kept	Nonconforming product	8		Incorrect machine setting	2	Machine setting at shift beginning	Dimension measurement, 3 pieces per shift	5	80	No actions			8	2	3	48
Roughness max 6,3 µm		Problems at assembly			Incorrect material locating in die	3	Staff training before production	Shift measurement, 3 pieces per shift	5	120	Shift measurement, 2 pieces per hour		Inspection procedure established	8	3	3	72
Hardness 238-280 HBW	Scales	Nonconforming surface quality	7		Incorrect technology	3	Staff training before production	Visual inspection 3 pieces per shift	4	84	No actions						
	Surface cracks	Nonconforming product	8		Unsuitable material temperature	3	Temperature control in the furnace	NDT hundred-percent inspection	2	48	No actions						
					Unsuitable chemical composition	2	Certified material	NDT hundred-percent inspection	2	32	No actions						

Fig. 6. Part of Process FMEA results record

4.3 Use of Process Capability Analysis for Process Optimization

Process preliminary capability analysis was the next step of die forging process optimization. After implementation of preventive actions for possible failures risks minimization based on FMEA results the pilot production was realized (520 of forgings were produced as a whole). During production every time four forgings after production of twenty forgings were measured. They were measured the most important quality characteristics according to QFD and FMEA results. Attention is paid only to the one of key characteristic - dimension 46,3 mm in the next text.

Basic exploratory data analysis with using box plot and histogram was performed firstly. It was found that measured data does not include any outliers and data distribution is approximately symmetric and similar to the normal distribution. Process statistical stability was assessed with using control charts for subgroup averages and standard deviations. It was found that no average or standard deviation lie outside control limits and no non-random patterns occur (see Fig. 7). It means, that achieved dimension 46,3 variability is influenced by random causes only and forging process is (in light of this quality characteristic) in control.

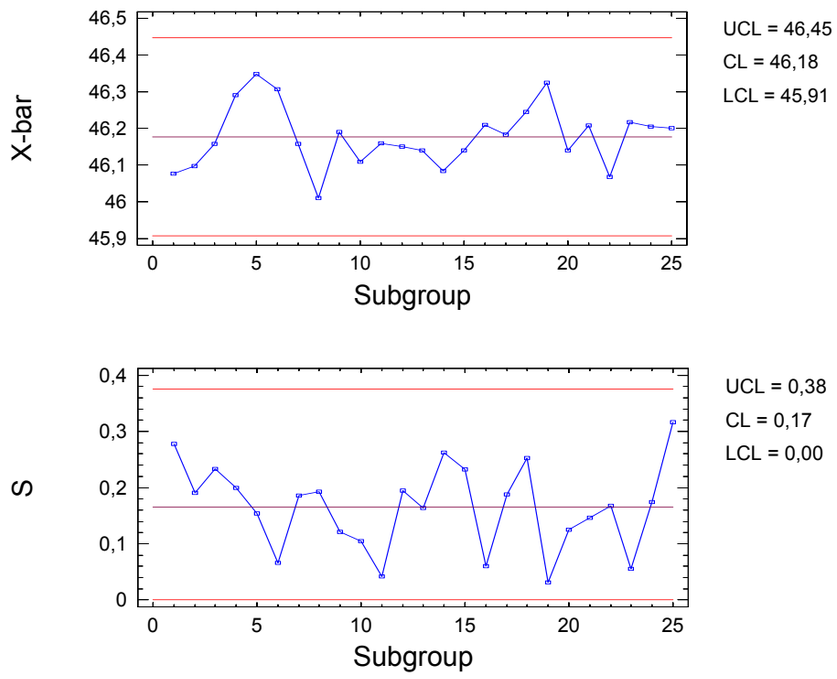

Fig. 7. Die forging process statistical stability analysis with using control charts $\bar{x}, s$

In the next step of data processing the data normality was verified with using Shapiro-Wilk test. Since data normality was confirmed, it was possible to calculate preliminary capability indices. Graphical assessment of process preliminary capability analysis including appropriate capability indices values is given in Fig. 8.

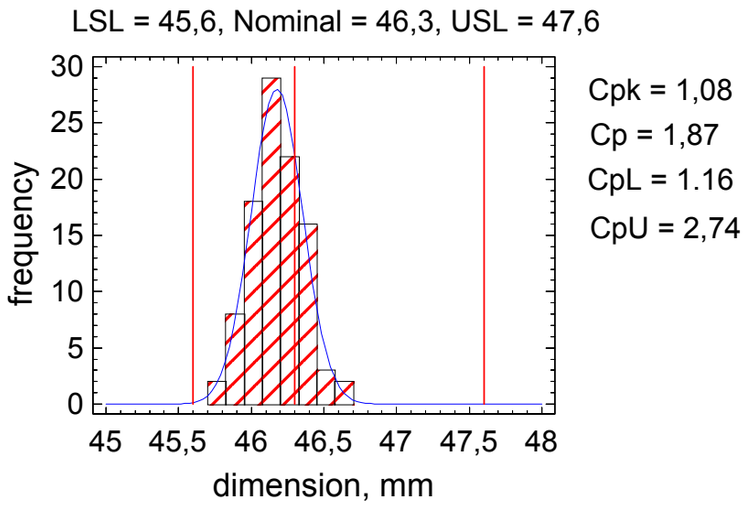

Fig. 8. Die forging process preliminary capability analysis

It can be seen that values of dimension 46,3 are shifted to the lower tolerance limit and C_{pk} index value is 1,08. Since this value is much lower than required minimum value for process preliminary capability 1,67, it was necessary to consider process as incapable to keep required tolerance limits. However, positive finding is fact that C_p index value is 1,87. It means that forging process has no problem with variability of given quality characteristic, because it is sufficiently small compared with given tolerance width. It means that unsuitable process setting is the cause of process incapability.
On the basis of these process preliminary capability analysis results it was proposed to set-up the process so that mean value of dimension 46,3 will correspond to the centre of tolerance limits. This setting-up assures (in the conditions of same process variability) C_{pk} value corresponding to C_p value (i.e. 1,87) and considerably decreases probability of non-conforming products occurrence.

5. Conclusion

Emphasization of quality planning importance and presentation of possibilities of using quality planning methodology and methods for processes optimization was the main objective of this chapter. Quality planning is in principle optimization problem, in which optimality criteria are especially rate of product requirements fulfilment, organization competitiveness and realization process capability.
Effectiveness of both quality planning and optimization can be considerably enhanced by using of suitable quality planning methods. In this chapter attention is paid to the Quality Function Deployment (QFD), Failure Mode and Effect Analysis (FMEA) and Process Capability Analysis.
Given methods were successfully used for die forging process optimization. QFD applications were applied for key processes and key process parameters identification and for the proposal of processes parameters target values. FMEA was focused to proposed process optimization aimed at risks of potential failure modes minimization. Process Capability Analysis made possible to verify running process stability and to minimize probability of non-conforming products occurrence.

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University Campus STeP Ri
Slavka Krautzeka 83/A
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Phone: +385 (51) 770 447
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