“Increasing the accuracy of the FMEA method”

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Increasing the accuracy of the FMEA method

Abstract

FMEA is often used in practice and not just in the field of quality assurance, respectively environment. The main advantage of this method is its versatility, but a major disadvantage is the relatively low accuracy, and subjectivity of the evaluation. This article describes the modification of the FMEA method focusing on increasing its accuracy. In the classic FMEA method the authors handle individual parameters as a point estimate of discrete random variables. In this article described modification of the FMEA method the researchers handle individual parameters as a continuous random variable, distribution of which is characterized by the quantiles.

Keywords: probabilistic risk assessment, theory of estimation, FMEA, training.
JEL Classification: C25, C35, G32, L15.

Introduction

Making mistakes is human. Errors as adverse events accompany us our whole life. Ability to prevent mistakes is a privilege of wisdom and experience. Errors occur also in the product development as with any human activity. Their consequences can be different. By moderate cost increases through loss creation to the catastrophic industrial accidents. Therefore it is appropriate if for various business processes we ensure that the possibility of errors can somehow be predicted. There are several methods, particularly with regard to security, that are trying to predict the possible emergence of errors by risk estimation in such a way that an early intervention can prevent its occurrence, thus eliminating their negative effects (Tkáč, 2001).

In this article we will focus on a relatively conventional method FMEA/FMECA (Failure mode and effect analysis Failure mode, effects and criticality analysis) (Bouti et al., 1994) that mainly due to its simplicity, has been applied in many areas. The production organizations come across with FMEA method mainly in the development as well as in quality assurance, safety and environmental protection (Zgodavova, 2015; Hajduová, 2014). The objective of FMEA is to identify the most critical and most likely causes of errors of the process and to introduce measures to eliminate them (Ben-Daya, 1996).

1. FMEA/FMECA methods

FMEA (Stamatis, 2003) and FMECA (Failure mode and effect critical analysis) (Bertolini et al., 2006) methods are based not only on qualitative but also on subjective estimation of the risk level of error occurrence, performed generally by a group of experts. Although there are several different modifications of the above-mentioned methods in practice, each of them somehow deals with the estimation of the likelihood of errors. Whether this estimate is based on the theory of confidence (design FMEA) (Narayanagounder et al., 2009), on a short-term capability index (process FMEA) (Estorilio, 2010), or on a frequency of occurrence (FMECA) (Ganesan et al., 2005), it is still a more or less comprehensive but still a subjective estimation of the assessor. With a little hindsight, we could say that it is a standard measurement process where the assessor acts as a measuring device. Whereas such methods in practice utilizing the principles of teamwork, we can obtain more or less useful results using statistical evaluation of estimates obtained from the assessment team. Evaluation of FMEA and FMECA methods is very similar. In this article a modification of FMEA method is described with no changes applicable also for use with FMECA.

The FMEA method is generally based on a subjective estimation of quantitative expression of three basic error attributes (Seyed-Hosseini, 2006). In the integer range between 1 and 10 there are independently characterized following characteristics: P – the likelihood of errors, V – meaning errors and Z – probability of detection, or disclosure of errors.

By multiplying these numerical estimates we assign each cause of the error a value of M also referred to as MR/P (degree of risk/priority):

$$M = P \cdot V \cdot Z.$$

Based on this characteristic, it is possible to organize all considered errors. The largest value representing the highest degree of risk, but at the same time numerically lowest, it means highest priority in order to corrective measures implementation.

The key benefits of the FMEA method is its simplicity and versatility. However it also brings some negatives related the reduction in accuracy, ambiguity and relative high subjectivity in estimation as well as when interpreting the results. There are several reasons why in the present FMEA method in practice does not bring the expected results:

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1.1. No structuring of the method. Another drawback is the lack of structuring of the method. The FMEA method is rather problematic in determining all the possible occurrence of errors. Individual errors, their causes and consequences are written in rows in some specified structure, and it is possible that some errors are not identified. There are many cases in the technical practice when a relatively large error occurred, that was not even mentioned in the FMEA or FMECA, simply because no one thought that even such an eventuality is possible. Unlike e.g. the FTA (Fault Tree Analysis) method, there has no, exactly determined logical links between the individually marked errors.

1.2. Subjectivity. FMEA is a subjective method and is generally elaborated by team of experts from the area for which it is oriented. Team processing means team responsibility. Moreover, individual FMEA problems are solved by so called consensus, which often means that it accepts the opinion of the most active members.

1.3. Alibism. If FMEA analyzes a major shortcoming, it is necessary to take action in the shortest time. Such corrective action represents a certain cost, respectively it may threaten the continuity of the production. Such intervention is unpopular, and the one who suggests it generally bears the consequences of a work interruption, delay, etc.

1.4. Inaccuracy of the method. As we already mentioned the FMEA method is subjective and therefore the estimates of parameters *P*, *V* or *Z* are resulting from how the assessor perceives the objective reality. Error of the method is based on, that by each of the aforementioned factors, the assessor must decide on a single number (ranging from 1 to 10). It is therefore only a point estimate. In case that there won't be a consensus reached between individual assessors, there will be a problem to determine the final evaluation as the output of the whole team of assessors.

We are going to describe a certain modification of the FMEA method, which aims to improve the accuracy of FMEA and FMECA hence. This modification is in principle based on the idea of replacing the point estimate of the numerical values of individual characteristics with three quantiles. We will consider the particular characteristics as continuous random variables and the quantiles will serve for the purpose of estimating the distribution of these continuous random variables.

Certain reduction of complexity, but also synchronization of how the evaluation will be performed by individual assessors will be achieved by training designed for this purpose. The next section will briefly describe how this training can be performed.

2. Quantil FMEA

The term Q-FMEA (quantil FMEA) is understood as modification of FMEA to the intent that the integral ranges from 1 to 10 for the individual parameters *P*, *V*, *Z*, that will be replaced by the intervals of real numbers. It means that individual characteristics may acquire any real value in the range $< 1,10 >$. Moreover, the evaluator will estimate above mentioned values of each parameter by means of quantiles characterizing the distribution of random values. Such an approach brings in itself and gives more information about the quality of the estimation than a point estimation. Using quantile method, it is possible to estimate not only the confidence interval, but approximately also the shape of the density of distribution of random quantity. In doing so, we go out from the subjective definition of probability.

Further, we will show why the point estimate in standard FMEA causes reduction in accuracy of the method. Parameter *M*, which is the basis for the assessment of any pair, error – cause, as we know, arises as a product of probability of occurrence *P*, significance of error *V* and the probability of detection *Z*. At classic FMEA, the assessor can choose only integral number from 1 to 10 for each factor. Resultant number M can acquire only some of integral values. If the frequency of occurrence of these values is processed in histogram (Figure 1, see Appendix), wherein the red line represents the density of Weibull distribution as the distribution of values that best characterizes the file. Median of above mentioned distribution has a value of $\tilde{x}$ = 166.375. However, if at the specific cause of error we get number *M* that is less than 125, it means in most cases acceptable risk which does not need any intervention. If we consider values *M* responding to critical state ($M > 500$) we keep at our disposal 17 different values from all 120 mutually different number values that is 15%. Provided that from 500 to 600 there are 7 possible values, from 600 to 700 there are 4 possible values, from 700 to 800 there are 3 possible values, from 800 to 900 there are 2 possible values and over 900 there is 1 possible value.

Mentioned state can be considered poor resolution of the method. Let us consider relation $M = P \cdot V \cdot Z$, but $P \in < 1,10 >$, $V \in < 1,10 >$, $Z \in < 1,10 >$ a $M \in <1,10 >$.

Unlike point estimation, now we will understand above mentioned values as continuous from the interval from 1 to 10. Value *M* is therefore also a continuous value from 1 to 1000. Let us mark by $P_{0.05}$, $P_{0.5}$ and $P_{0.95}$ such values from the interval $P \in <1,10>$ which represents respective quantiles of density of continuous distribution over the mentioned interval characterizing the estimation of the assessor and his/her conviction that real value of the objective reality is governed by density proportionality of which is determined just by above mentioned quantiles.

Figure 2 (see Appendix) shows the density and consequently the empirical distribution function of estimation of parameters *P*, *V*, *Z*. On *X*-axis particular quantiles are shown. The density as well as the distribution function is from the expected uniform distribution.

In Figure 3 (see Appendix), we have the density and the distribution function of value *M* while for each *i* of the closed interval from 0 to 1, it applies that:

$$M_i = P_i \cdot V_i \cdot Z_i \,. \tag{2}$$

In a form of Q-FMEA the assessor enters to each identified combination of error, cause of error and consequence of error respective quantiles for each characteristics of *P*, *V*, *Z* as shown in Figure 3 (Table 1).

Table 1. Values of particular quantiles at quantil FMEA

a)				b)
Δ	$p_{0.05}$	$v_{0.05}$	$z_{0.05}$	$M_{0.05}$
•	$p_{0.5}$	$v_{0.5}$	$z_{0.5}$	$M_{0.5}$
∇	$p_{0.95}$	$v_{0.95}$	$z_{0.95}$	$M_{0.95}$

Source: Processed by authors.

At Q-FMEA, the assessor makes estimation for each of factors consisting of three numbers (Table 1a). By simple product of the respective quantiles, we achieve value M_i (Table 1b). We suggest to use, as a first estimation, quantile 0.05, second estimation – quantile 0.5 (median) and third estimation – quantile 0.95. The assessor may use non-integral values and therefore he/she estimates a whole interval of values which is by him/her admissible. Q-FMEA has therefore significantly finer range and the assessor does not do point estimation but by means of quantiles he/she makes an estimation of distribution function. In layman's terms, it can be interpreted so that lower limit of the estimation (Δ) expresses the lowest expected number of the respective parameter, i.e. for example the smallest expected significance of error.

The mean value (•) corresponds to median of distribution and upper value of estimation (∇) present the highest possible expected number, i.e. in case of significance the biggest expected significance. The assessor so first by determines the "optimistic value", i.e. the lowest number corresponding to the smallest value. Then he/she determines the "mean" and finally the "pessimistic" estimation, i.e. such which is indicated by him/her as high as possible. By product of mutually corresponding quantiles of particular parameters *P*, *V*, *Z* we get the first iteration (some first value) of the estimation of the density of distribution function for parameter *M*. As it is an estimation achieved by calculation, the assessor can make any final correction of any quantile at his/her own discretion. As an example we introduce the proposal of the form for Q-FMEA (Table 2).

Table 2. Q-FMEA form

<table>
<tr><td colspan="3" rowspan="4">PROJECT NAME</td><td colspan="5">Analysis of the possibility of error and its consequences</td><td colspan="6" rowspan="2">Name of the assortment:</td></tr>
<tr><td colspan="5">Q-FMEA</td></tr>
<tr><td colspan="5">Confirmation by respective department:</td><td colspan="6">Model / system / design:</td></tr>
<tr><td colspan="5">Process definition:</td><td colspan="6">Elaborated (Name/department/date):</td></tr>
<tr><td>Place / function</td><td>No</td><td>Possible errors</td><td rowspan="2">Error consequences</td><td rowspan="2">D</td><td rowspan="2">Cause of error</td><td colspan="2">Current status</td><td></td><td></td><td></td><td></td><td rowspan="2">Recommended measures</td><td rowspan="2">Responsible</td></tr>
<tr><td>Step</td><td></td><td></td><td colspan="2">Control measures</td><td>PV</td><td>VZ</td><td>PO</td><td>M</td></tr>
<tr><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td>Δ</td><td></td><td></td><td></td><td></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>•</td><td></td><td></td><td></td><td></td></tr>
<tr><td>∇</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td>Δ</td><td></td><td></td><td></td><td></td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>•</td><td></td><td></td><td></td><td></td></tr>
<tr><td>∇</td><td></td><td></td><td></td><td></td></tr>
</table>

The compilation of the form by assessors does not provide to partial assessors (team members) any significant complications. To reach the final estimations of the parameter *M*, final assessor can use a specialized statistical software.

Since we have 5%, 50% and 95% percentile, we interpolate the rest of the distribution for each estimated characteristic. Let $q_i\,(e)$ be the *i*-% quantile of assessor – expert e. The internal range is obtained with k% exceeding coefficient. First, we find the minimum and maximum values based on relationships

$$k = \min\{q_5(e),\, r/e\},\ h = \max\,\{q_{95}(e),\, r|e\},$$

where *r* is the value of realization. Then applies

$q_k = k - 0{,}1 \times [h\text{-}k]$

alike

$q_h = h + 0.1 \times [h\text{-}k]$.

The natural (native) margin is therefore $[q_k, q_h]$. The distribution function of expert e is then obtained using linear interpolation of quantile information (q_k; 0), (q_5; 0.5), (q_{50}; 0.5), (q_{95}; 0.95), (q_h; 1). It is a distribution with minimum information with respect to the single distribution on the natural range which incorporates all experts' quintiles (Figure 4).

Using interpolation of evaluation of experts in combined overall assessment, i.e. in the estimation of distribution linking all distribution of experts, so called combined expert will be created.

The previous approach determines the distribution function $F_e(t)$ for each expert and each queried variable. At the number of experts n the combined distribution function has a shape $\frac{1}{n}\sum_e F_e(t)$, as shown in Figure 5. With such a combination of distribution functions of individual experts we have gained a collective assessment of all the group members represented by just described combined estimate.

We conclude that all assessors, experts are equal while evaluating various characteristics in the combined estimate. In order to avoid unnecessary disproportion between assessors, training aimed to ensure the same approach of assessors while evaluating is recommended. Before we proceed with the training of individual assessors, it is appropriate to make a comparison (sort of calibration) generally among smaller groups of experts (often there is only one expert – lecturers/moderators), who have experience with classical FMEA, respectively with the risk assessment and then focus on the second group which is significantly wider. We speak about assessors who will implement the above mentioned methods in particular practical conditions.

2.1. Preparation of lecturers/moderators for FMEA training. Team called lecturers/moderators should be 1EXP and should include experts from area for which the method will be used. It is not excluded that the group in question includes only a single assessor. In such situation it is recommended to create a so called "virtual assessor" where the individual "calibration errors" are gathered from the literature, from similar operations, or from other available sources. The term "calibration error" stands for a combination of errors and their causes, whose correct estimates of the characteristics are known to the members of this group, i.e. lecturers/ moderators. Please note that the "correct answer" is a consensus of all members of the first team, thus the virtual assessor will only be used for "calibration" – synchronization of responses of members of the second team. The advantage of real experts is that they assess specific operation in real-time situation. More accurate calibration can be made on the basis of their responses and it is necessary to evaluate the other group. As we have noted, for calibration or synchronization of answers of second team members, only those calibration errors, whose evaluation among all members of the first team was achieved by consensus will be used.

The second group of assessors is composed of experts from the practice, usually people directly involved in the process, for which the FMEA error estimation method is the subject of assessment. The advantage of these experts is that they usually understand well the principle and essence of the assessed area. The purpose of training is to utilize the information available to a broader group of such experts, despite the fact that they do not know the method and principles of PRA (Probability Risk Analysis).

Before the actual training begins it is necessary to explain the process and the significance of Q-FMEA method to all assessors from the second group. We can explain how to fill in the Q-FMEA form using specific examples. When clarifying the various terms it is not necessary to give their exact definition. It is sufficient to explain the meaning and how the evaluation should be carried out to members of the second group (future assessors) e.g. quantile q_5 represents such estimated value of characteristics, that it is highly unlikely (probability less than 5%) that the real value of a given characteristic will be smaller than the q_5. Quantile q_{95} on the other hand represents such a value that it is very unlikely (with a probability of less than 5%), that the actual value of the characteristic is larger than q_{95}. Quantile q_{50} – median represents the value that comes closest to the point estimate used by the classic FMEA. Verification whether the training participants understood the procedures of implementation of Q-FMEA method will be done using the already mentioned calibration errors. The set of such calibration errors (best from the environment where the Q-FMEA method is implemented) will be prepared by lecturers (members of 1EXP) considering the orientation and expertise of assessors (members of 2EXP). In practice, the following process for calibration errors definition was proved. Selected experts from the first group extend the existing evaluation methodologies that has been based on conventional FMEA methods which has been developed under the conditions of analyzed process in terms of Q-FMEA. This evaluation will be later considered as the evaluation of the virtual assessor. Subsequently they conducted independently from each other (not necessarily other evaluators from 1EXP) the same evaluation without point estimates of classical FMEA that were available. This evaluation is thus the result of an estimate of group members 1EXP since they have not been affected by prior evaluation, i.e. point estimate of classical FMEA. In case, when the evaluation of calibration errors obtained by both methods, will be vastly different from each other, and a consensus cannot be reached, the error in question will be earmarked from the list of calibration errors. Please note, we do not expect a full compliance when comparing the two evaluation methods. A small variation in the evaluation of experts from the first group represents the so called inherent variability. This variability of estimates will be used as the basis for comparison of evaluations of calibration errors of members from the second group. Variability in their response which is comparable to the inherent variability will be considered acceptable. As we already mentioned, the training will consist of creation of estimates of quantiles of individual characteristics for calibration errors by members of 2EXP. Mutual comparison will be performed using the pairwise correlation matrix, respectively using the three-dimensional regression analysis. In practice, the graphical presentation of these correlations, respectively regression functions that convincingly demonstrated the disproportion of evaluation of specific calibration errors between the members of 1EXP and 2EXP, proved successful. If the estimates of the member of the group 2EXP insufficiently correlated with estimates of group members 1EXP then the 2EXP group member had to repeat the training on a modified calibration error set. Using the three-dimensional regression we can show to each assessor which estimates within the defined range comes closest to the evaluation of members 1EXP. By such training the 2EXP group members gain an idea, but also a certain habit as how to evaluate errors in the framework of Q-FMEA method in the future. For this reason, such training is the more effective, the more the calibration errors converge to real errors of analyzed process, that will a trained member of 2EXP evaluate in future.

2.2. Training of Q-FMEA method accuracy improvement. To illustrate the course of training success evaluation we will briefly describe the results obtained during Q-FMEA method implementation in one steel company. The operation, which was the subject of our research, a list to 200 calibration errors was drawn up based on the available data from previously existing FMEA, for which the candidates for an expert group 2EXP had to perform evaluation.

In Figure 6 (see Appendix) there is the result of the pair comparison of linear correlations between the calibration questions (answer to questions known to the assessor) prepared by expert 1EXP1 and four experts from second group.

In the upper triangular matrix – above the diagonal of the pair correlations table the pair correlations are graphically presented. We note that the contour lines – of the ellipse show the higher dependence the further they differ from a circle. In the lower triangular matrix then there are the correlation coefficients for each pair of experts stated by color and numerically. From a numerical expression it is clear that successful were the first three experts who achieved a correlation of 0.5, and thus can be recruited to the team of assessors. Expert 2EXP4 did not fulfill this condition and therefore was excluded from the group.

In Figure 7 (see Appendix) three-dimensional regression function based on the processing of the 200 calibration questions is shown.

On the *x*-axis and the *y*-axis the values from expert assessment of the first group 1EXP1 and virtual assessor 1EXP2, i.e. the answers to the questions drawn from years of experience evaluated using classical FMEA are presented. Differences from these two ratings, i.e. real assessment of the assessor 1EXP1 who is an expert on the PRA, but has no experience of specific operations and on the other hand, virtual expert 1EXP2 (this is the document from which the questions were created – time-honored classic FMEA). The *z*-axis – the difference of the first expert from the second group compared to answers from the abovementioned two calibration experts are presented. As we can see, the greatest differences have been achieved in low values of expert 1EXP1 and high values of expert 1EXP2, i.e. from documentation. Graphical display of regression function graphically assisted to experts from second group to realize what the differences in the assessment of actual errors are. Similarly the expert 2EXP2 from the second group was evaluated (Figure 8, see Appendix).

The regression graph shows the main discrepancy with the first expert while smallest differences are in assessments about 200 and then over 900. Expert no. 3 shows similar differences as an expert no. 2 but its score differs from the expert EXP2, i.e. from documentation (Figure 9, see Appendix).

The aforementioned graphs only confirm the fact that expert 2EXP1 operates at workplaces for a short time while experts 2EXP2 and 2EXP3 are longtime employees who have experience with classical FMEA.

Conclusion

In the presented article, we showed some modification of the classical method of FMEA while replacing the point estimate of the discrete random variable by quantile estimate of continuous random variable for the entire estimated characteristic used in the Q-FMEA method. This modification creates very good conditions for an experienced assessor to characterize the random variable representing any of the three characteristics significantly more accurate using quantiles than the point estimate in a discrete random variable, which is used in classical FMEA. For less experienced assessor, however, the mentioned modifications may seem excessively difficult. For these assessors it is appropriate to carry out training. Instead of explaining the relatively complicated theory concerning quantile and distribution functions it is possible within the training to focus attention on specific evaluation of the individual characteristics of the method Q-FMEA under practical conditions. In this paper we presented one possible way of how relatively effectively we can organize but also evaluate the success of such training. By considering individual evaluation characteristics and continuous random variables, the correlation analysis of the linkage between the lecturers and the evaluation of other assessors could be performed in the training framework. We have shown that by using three-dimensional visualization regression function it is possible to explain to assessor (for group 2EXP) how his evaluation differs compared to trainers (for group 1EXP). By simple interpretation of the aforementioned visualization it is possible to achieve synchronizing of the assessors (members of group 2EXP) on the basis of evaluation of trainers (members of group 1EXP).

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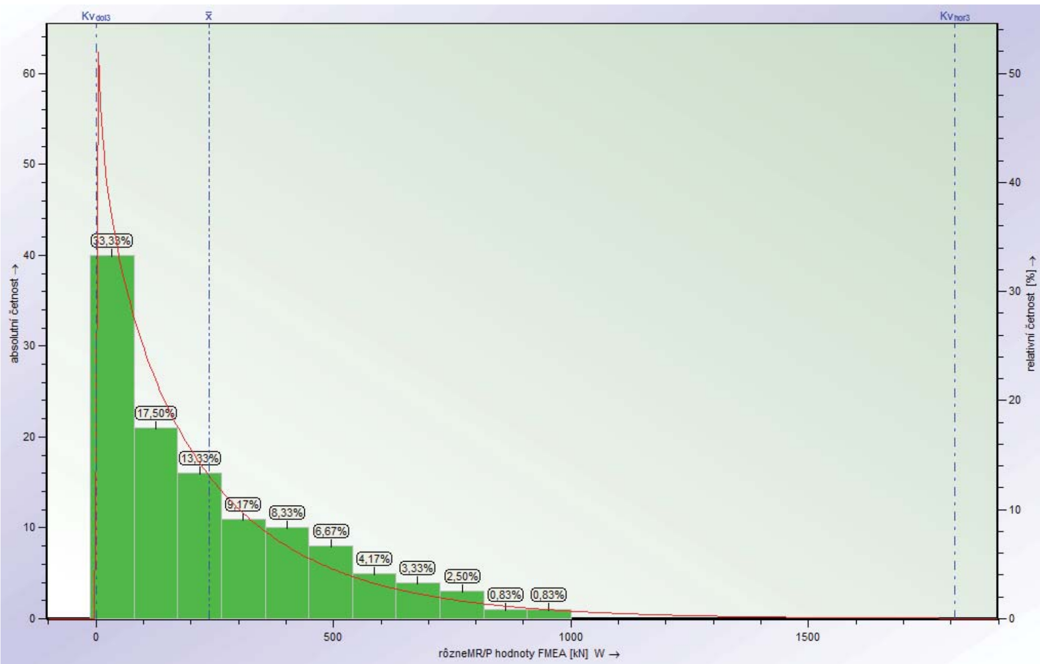
Appendix



Source: Processed by authors.

Fig. 1. Histogram of different values of parameter *M*

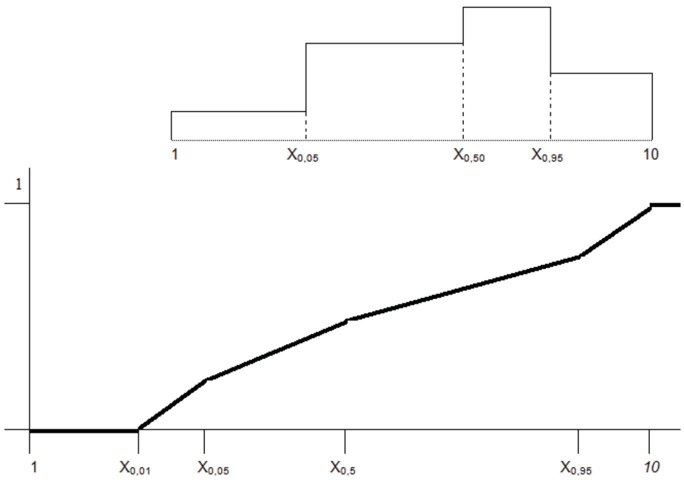
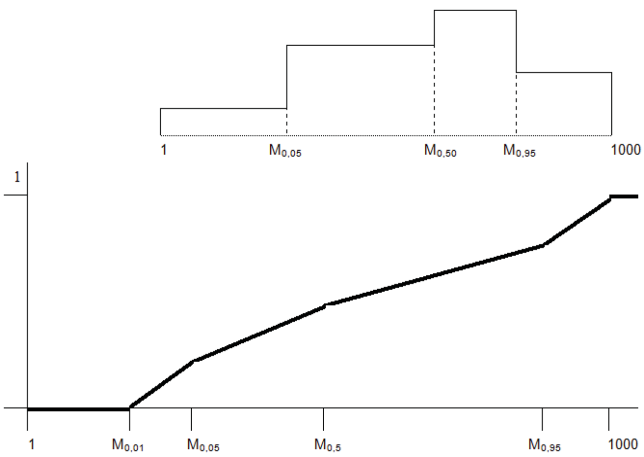


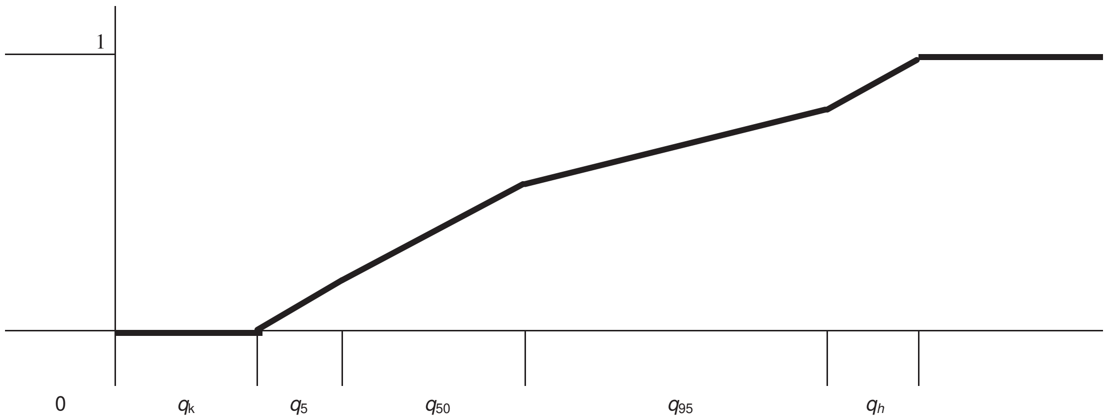
Fig. 2. Density and distribution function of parameters *X*

Source: Processed by authors.



Source: Processed by authors.

Fig. 3. Density and distribution function of parameter M_i



Source: Processed by authors.

Fig. 4. Interpretation of quintiles – characteristic estimation

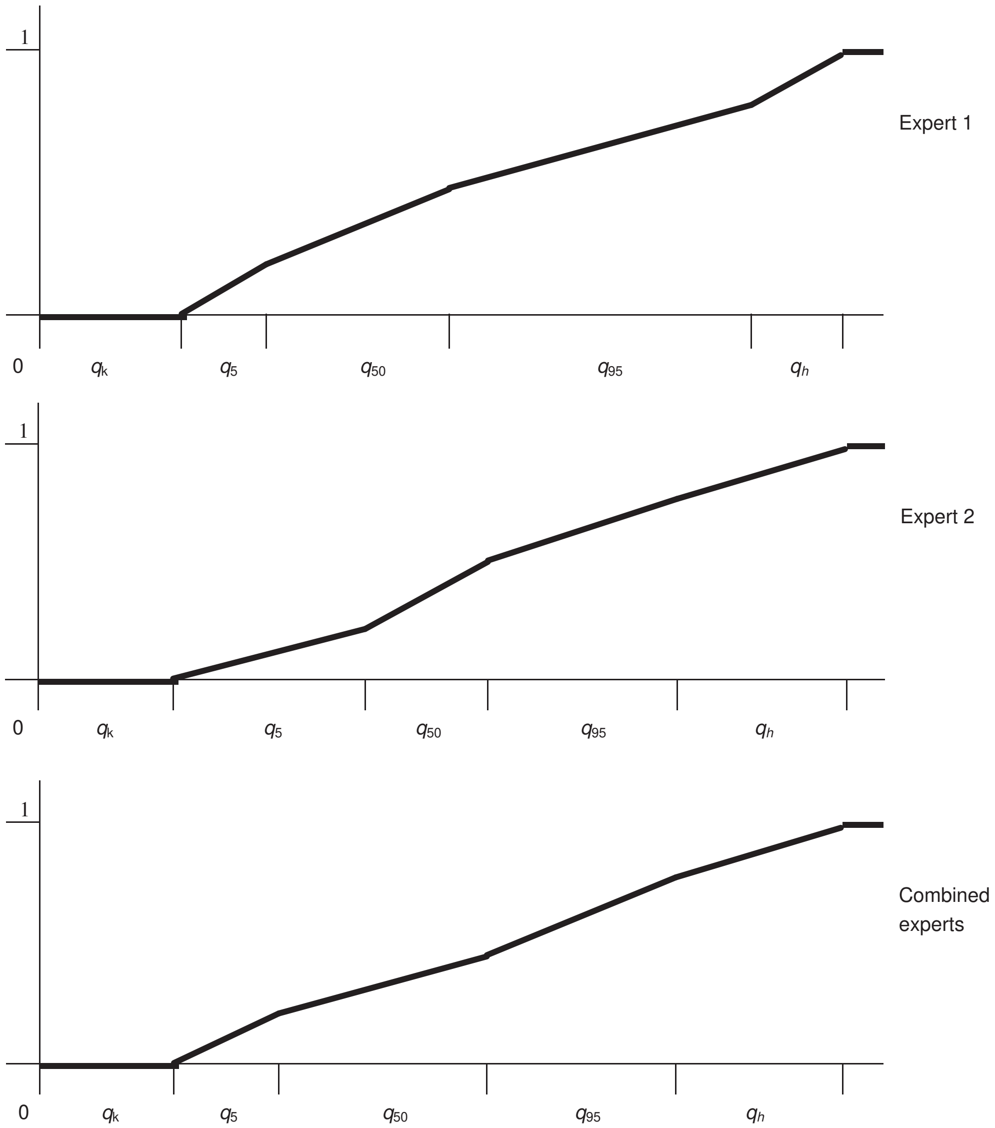


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Fig. 5. A combination of experts distribution (combined estimate)

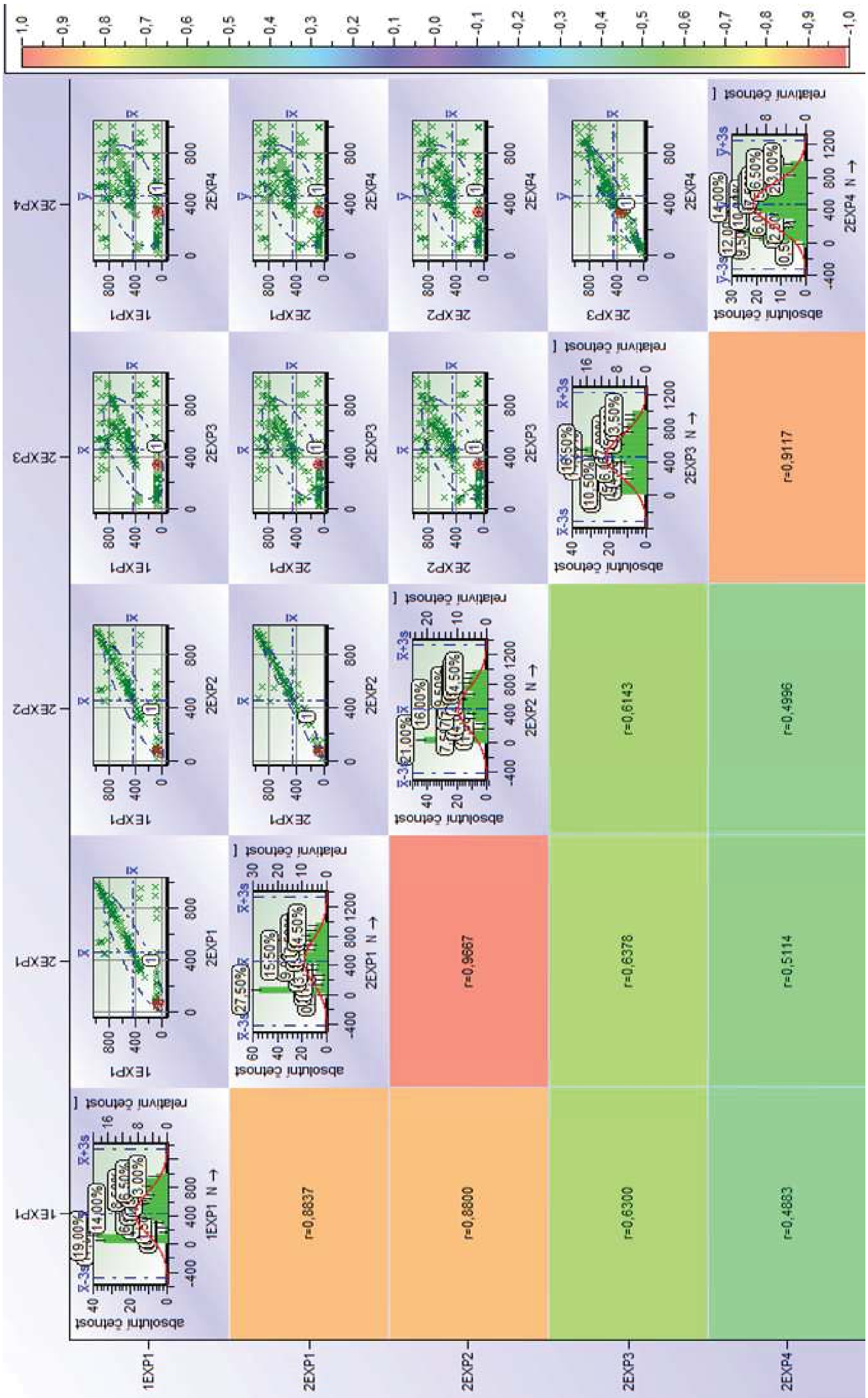

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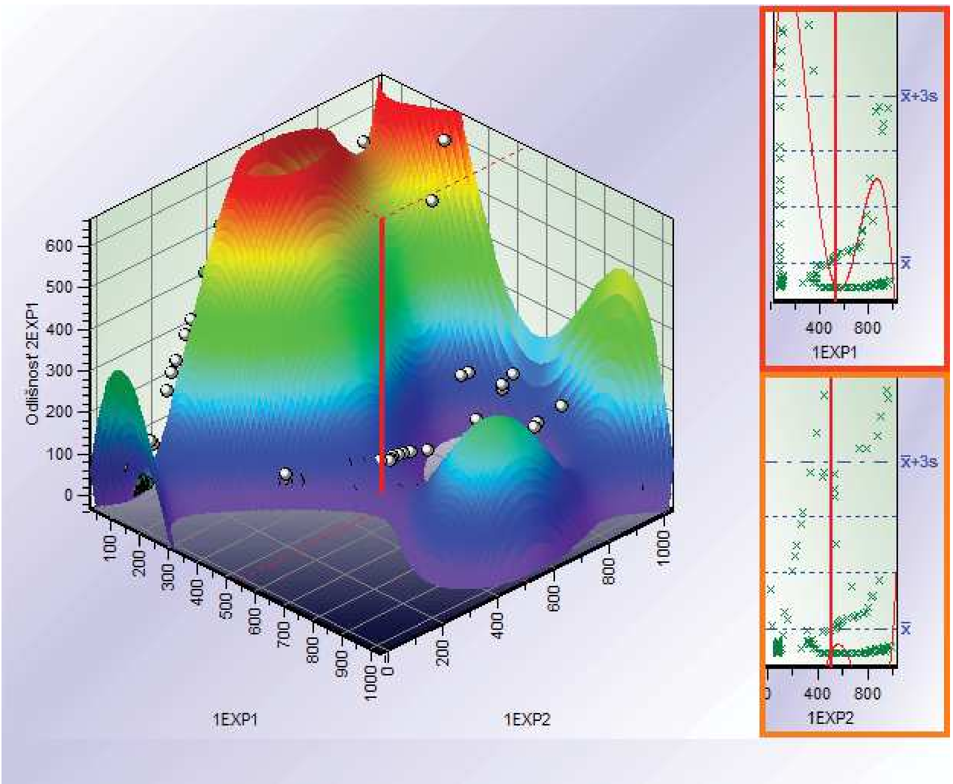
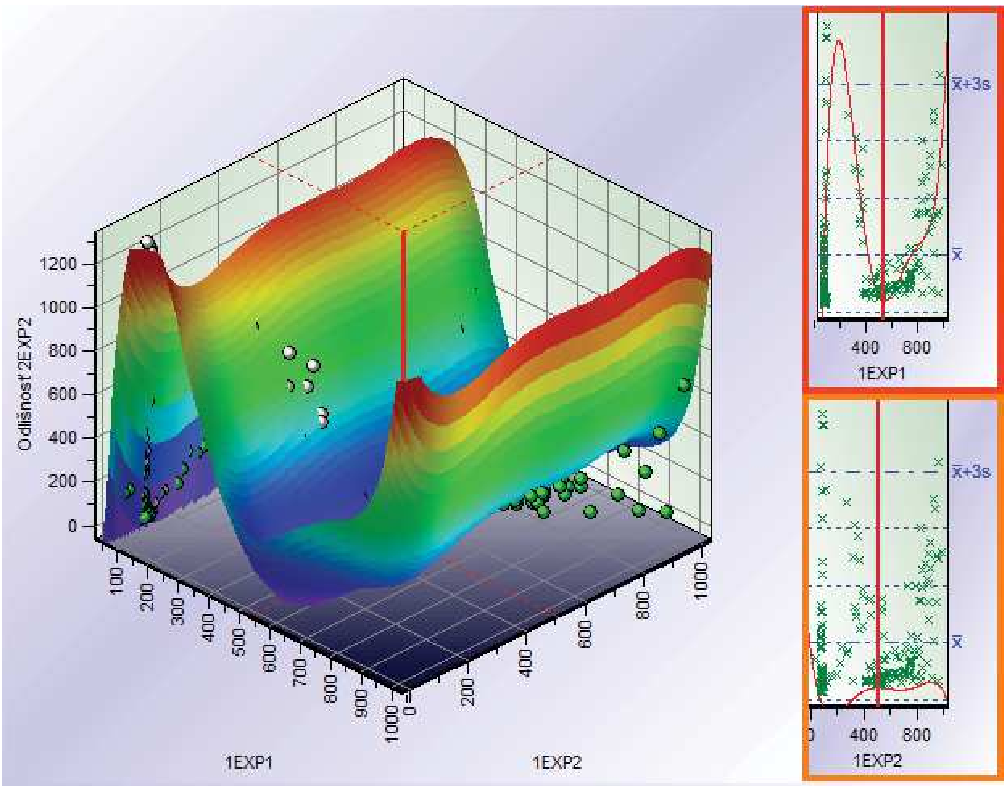
Fig. 6. The correlation coefficient matrix of pair comparison



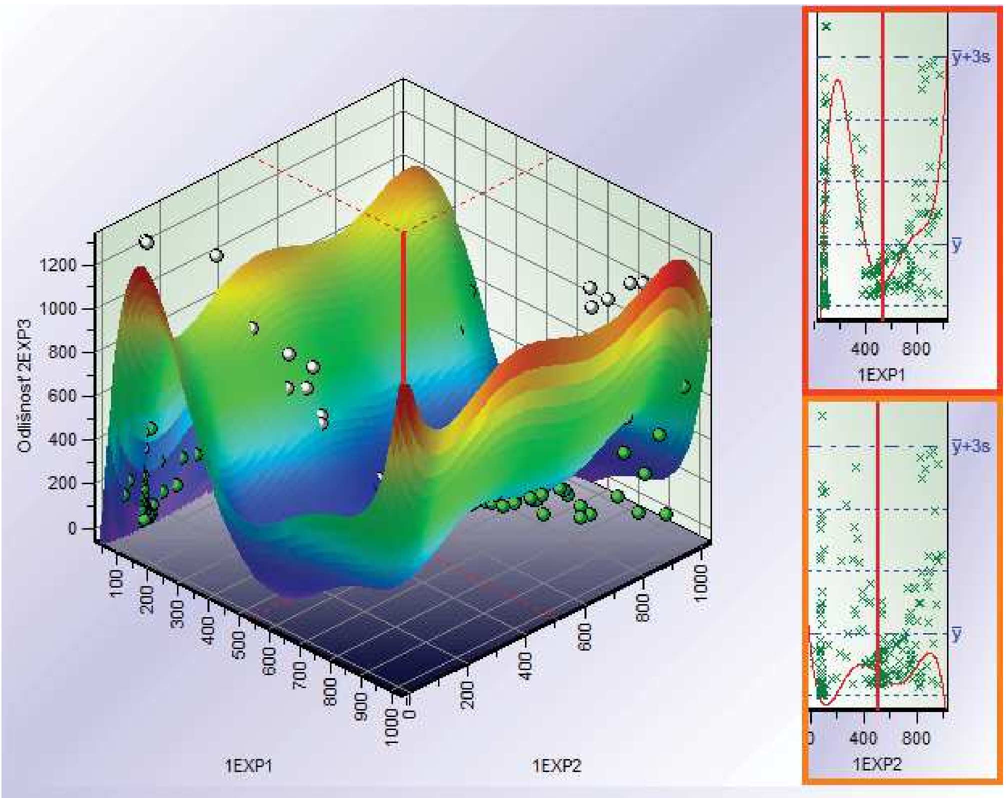
Source: Processed by authors.

Fig. 7 Conformity assessment visualization of 2EXP1 with 1EXP1 and 1EXP2



Source: Processed by authors.

Fig. 8. Conformity assessment visualization of 2EXP2 with1EXP1 and 1EXP2



Source: Processed by authors.

Fig. 9. Conformity assessment visualization of 2EXP3 with 1EXP1 and 1EXP2