The evaluation method of human – machine system operation quality

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Abstract: In the paper the issues of the transport systems operation quality assessment are considered. The studies take into consideration the real complex socio-technical (H – M – E) (human – machine – environment) systems. The assessment quality of the systems operation is based on the changes of the systems features values. The features describe the operation of the systems operators, controlled technical objects (vessels, trains, planes or cars) and the environment influence. The assessment and the support the demand quality of the systems operation from the safety, efficiency, economic and reliability point of view is the basic factor of the executed exploitation process. The paper deals with description of rules, on the basis of which the method has been developed. Algorithm of mathematical model of the systems operation quality evaluation has been built. Metrics have been elaborated, essential concepts of metric space have been used and partial order relation as well as appropriate setting systems in order in terms of their operation quality has been applied. The model can serve as a general abstract form for operation quality evaluation of a wide range of real transport systems differing with properties, structure and operation.

Keywords: operation quality, transport system, model, metric.

I. INVESTIGATION OBJECT

All the considerations deal with transport systems performing transportation of passengers and cargo over water, land and air routes. The main operation aim of such systems is realization of transport service within a specific environment, within specific quantity and within specific time by means of technical objects being operated and maintained within the system range.

Having in mind the considerations presented above, based on identifying and analysing the real transport systems it has been determined that the following subsystems may be set on individual levels of their decomposition:

1. logistic, within the ranges of which the actions related to managing the system, information flow and processing as well as keeping usefulness state of the transport means operated and maintained within the system are performed, which is composed of: decision-making subsystem, maintenance subsystem, information subsystem,
2. executive, in which the essential aim of the system is being realized – which is providing the transport service,
3. environment – as a co-working subsystem.

A general scheme of the operation and maintenance system of the transport means is presented in the Figure 1.

The research aim is to present a method, assessment and control way of operation quality for complex socio-technical systems, depending on actions of operators, the machine operation and the impact of factors coming from the environment.

Fig. 1. A general scheme of the operation and maintenance system of the transport means

II. SYSTEMS OPERATION QUALITY

This point includes description of the rules, on the basis of which a method to evaluate the quality of the transport system operation has been formulated.

As it can be seen in Figure 2, an external observer - EO determines the criteria set to evaluate quality of the system operation K. Afterwards he identifies the investigation object, and on this basis he sets the set of features - X describing the system from the point of view of its operation quality.

On the basis of analysing the relevant literature and our own investigations it has been defined that: the operation quality of the system is a set of the system features expressed by means of their numeral values at a given moment t, determining the level of accomplishing the required conditions [3].

In this paper, the criterion term has been defined as one of the significant conditions, imposed on the feature value, which describes the quality of the analysis subject at a given moment t. A feature is a property or quality of the analysis subject. We call a property such a feature which is common for all the subjects which is expressed as a physical quantity, whereas a quality we call such a feature which lets us distinguish some objects which do not have these features [4].
It is to be taken into account that the set of features adopted to describe the quality of the investigated system is composed of two subsets of: measurable features and non-measurable features. The measurable features are the ones which are "beyond the reach" of the possibilities to measure them because of the technical nature problems or because of the lack of knowledge of the investigator. For each measurable feature describing the system under investigation $X_{M_i}$ ($i=1,2,...,n$), the permissible limits of their changeability $X_{M_{i\min}}, X_{M_{i\max}}$ are to be determined, which correspond to the correct (required) quality of the system operation. Likewise, for each feature which is agreed to be non-measurable one, $X_{N_j}$ ($j=1,2,...,m$), it is needed to determine the conditions for the correct quality in a way enabling unambiguous statement whether or not a specific feature meets them. For that reason different values from 0 to m have been tested.

After completed identification of the system, selection of the set of the attributes describing the system from the given point of view (meta-criterion) and estimation of the set of the important criterions and sub-criterions the external observer can start estimation of the quality of the system activity.

The estimation process is to use each criterion from the $K_e$ set to the distinguished attributes from the $X_e$, based on the values measured at the time $t$ (measurable attributes), or based on the states at the time $t$ (non-measurable attributes) by assigning the appropriate distinguishing features to them.

The measure of quality of system activity at the time $t$ is a group of values of important features used for description $\{X_i\}, i=1,2,...,p$.

It should be taken into consideration that for every criterion from the $K_e$ set, the additional criterion sub-sets $k_i, i=1,2,...,m$ could be selected. These sub-sets are the conditions imposed on the attributes values describing the system element $e_i$, $i=1,2,...,n$ from the set $E$. The reason for determining these sets is to make the estimation easier and to allow precise determination of the influence of the system elements on the quality of the system activity.

Using the resultant model built, the values of the separate attributes describing the system and their importance could be estimated, then the quality of the system could be estimated [8].

III. GRAPHIC INTERPRETATION OF TRANSPORT SYSTEMS OPERATION EVALUATION

It has been set that the quality level of the system operation is directly affected by operations of its subsystems and reaction of the environment on each of those subsystems. Therefore, one of the main stages in the process of evaluating quality of the system operation is a detailed identification of it.

Having identified the system, an external observer starts evaluation of its operation quality. The evaluation process is to apply one by one each of the criterion from the set $K$ for the features taken from the set $X$, based on their values measured at the moment $t$ (measurable features), or the states in which they are at the given moment $t$ (non-measurable features), by assigning appropriate discriminates to them. In this connection the quality level of the system operation at given moment $t$ sets the set of significant features $\{X_i\}, i=1,2,...,p$ adopted, from a determined point of view, to describe it.

This way the quality of the system operation set at moment $t$, $t \in < t_0, t_k >$ may be described by means of so called Multidimensional Quality Vector. The set of the features adopted to describe its operation quality ($X_{t_0},X_{t_1},...,X_{t_k}$) sets $p$ – dimensional evaluation space. If the values of the features set at the given moment $t$ are projected on the individual coordinate axes of this space, then it is possible to set point $M'$ with the coordinates $[k_{x_{1(t)}}, k_{x_{2(t)}},..., k_{x_{p(t)}}]$. This point in the multidimensional space is the end of the vector, the beginning of which is the beginning of the coordinate system. The determined vector describing quality of the operation system at the moment $t$ is denoted with the symbol $\overrightarrow{WW1}$. Then in the investigated space, on each of the adopted coordinate axes it is possible to set the point $M$ by projecting model (required) feature values. The point $M$ with the coordinates $[k_{x_{1}}, k_{x_{2}},..., k_{x_{p}}]$ is the end of the vector of the model quality state of the system operation, which has been called the Criteria Quality Pattern and has been denoted with the symbol $\overrightarrow{KW1}$.

The distance between the ends of the vectors $\overrightarrow{KW1}$ and $\overrightarrow{WW1}$, within the adopted $p$ – dimensional space, sets the quality valuation of the system operation $\Delta K$. It may be formulated as follows:

$$\Delta K = \overrightarrow{KW1} - \overrightarrow{WW1} \tag{1}$$

Because the values of the determined features, affected by reactions of the forcing factors, are changed in time, then point $M'$ (being the end of the vector $\overrightarrow{WW1}$), within the time interval with the length $\Delta t$, within the investigated $p$ – dimensional space, draws a trajectory, which represents the changes of the quality of the system operation. It means that the quality of the system operation is changeable in time, because on each axis, within the investigated $p$ – dimensional space, in time $(t+\Delta t)$ the component values of the vector $\overrightarrow{WW1}$ are changed (Fig. 2) [6].

When evaluating quality of the systems operation, some tolerance ranges (boundary values for individual features) imposed on the feature values, being the components of the vector $\overrightarrow{KW1}$ may also be adopted. Then within the $p$ – dimensional space we obtain a $p$ – dimensional solid, in the centre of which the end of vector $\overrightarrow{KW1}$ will be located. The solid created this way sets $p$-th dimensional, model space of the quality of the system operation, which has been denoted with the symbol (W). In this case, the valuation of the quality of the system operation is set by the shortest distance of location of the end of the vector $\overrightarrow{WW1}$ (point M), from the model quality space (W).

When evaluating quality of the system operation also such a case is investigated, in which for all the values of the features setting the point $M'$ (being the end of the vector $\overrightarrow{WW1}$), the tolerance ranges are assigned. Then within the $p$ – dimensional space a $p$ – dimensional solid will be created, in the centre of which the end of the vector $\overrightarrow{WW1}$ will be located.
Each of the nth subsets \(Z_i\) where \(i=1,2,\ldots,n\) is a set of features describing the operation quality of the individual elements of the system. The number of the elements of the system and the features describing it depends on its kind, complexity and characteristics.

Based on our own investigations [8] a general model to evaluate operation quality of the complex transport systems has been built:

\[
\begin{align*}
Z_1(t) &= \{X_1(t), X_2(t), \ldots, X_p(t)\} \\
Z_2(t) &= \{X_{k_1+1}(t), X_{k_1}(t)\} \\
Z_3(t) &= \{X_{k_2+1}(t), \ldots, X_{k_1}(t)\} \\
&\vdots \\
Z_n(t) &= \{X_{k_n+1}(t), \ldots, X_{k_{n-1}}(t), X_{k_1}(t)\}
\end{align*}
\]

where:

- \(k_0 = p; n \leq p; k_0, n, r, p \in \mathbb{N}\);
- \(Z_i\) – feature subsets describing operation of the individual elements of the system, \(Z_i = e_i, i = 1, 2, \ldots, n\),
- \(E = \{e_i\}\) – elements of the system,
- \(X_i\) – set of the features describing comprehensively the quality of the system operation, \(i = 1, 2, \ldots, p\),
- \(i = \{1 < k_1 < k_2 < \ldots < k_r < \ldots < k_n - 1 < k_n = p\}\).

Having in mind, that the paper deals with evaluating the operation quality of the transport systems of \(<H-M-E>\) type, the elements of which are: human (operator) – \(e_1\), machine (technical object) – \(e_2\), environment– \(e_3\), subsequently the resultant model to evaluate its operation quality takes the form which is described with the following dependence [4]:

\[
\begin{align*}
Z_1(t) &= \{X_1(t), X_2(t)\} \\
Z_2(t) &= \{X_{k_1+1}(t), X_{k_1}(t)\} \\
Z_3(t) &= \{X_{k_2+1}(t), \ldots, X_{k_1}(t)\}
\end{align*}
\]

where:

- \(k_1 = p\).

In these considerations it has been assumed that evaluation of the operation quality of the transport system is a reflection of:

\[
Y : T \times \Omega \rightarrow \mathbb{R}
\]

what means that \(Y(t, \omega)\), \(t \in T, \omega \in \Omega\) is a measure of the quality of the system operation at the moment \(t\), which depends on an elementary event \(\omega\), where:

- \(Y\) – measure of evaluating the quality of the system operation,
- being the function of the random variable vector \(X(t)\),
- (representing the length of the vector \(\overrightarrow{AK}\)),
- \(T = (0, +\infty)\) – set of the time moments,
- \(\Omega\) - set of the elementary events,
- \(R\) – set of the real numbers,
- \(\omega\) – elementary event.

For evaluation of the operation quality of the transport systems correct order relation and good order relation have been applied correct order relation.
Let \( t_1 < t_2 < \ldots < t_n \) be the moments, at which the feature values of the operation quality of the investigated system \( S \) were measured. In the set of the vectors \( X(t_1), X(t_2), \ldots, X(t_n) \) it is possible to formulate the correct order relation as stated below. The vector \( X(t_k) \) stays in relation with the vector \( X(t_i) \), if for each \( i \in \{1, 2, \ldots, p\} \) there is:

\[
X_i(t_k) \leq X_i(t_i)
\]  
(7)

The above-mentioned formula means that the system \( S \) at the moment \( t_k \in T \) has higher operation quality grade than at the moment \( t_i \).

In this paper it has been assumed that the equation (2) determines a set of features describing the operation quality vector of the system at the moment \( t \). Whereas \( X_i(t_k), X_i(t_i) \) stand for the same sets of the quality features describing the investigated system at the time moments \( t_i \) and \( t_k \).

The system \( S \) at the moment \( t_k \) has higher operation quality grade than at the moment \( t_i \), if the following inequalities are true:

\[
X_i(t_k) \leq X_i(t_i)
\]  
(8)

for \( i=1, 2, \ldots, p \).

As it can be seen, in order to describe the changes of the operation quality of the investigated systems at the different time moments \( t_k \) and \( t_i \), the partial order relation may be used. The partial order relation described above, let us determine if the investigated system at the moment \( t_k \) has higher operation quality grade than at the moment \( t_i \), only in specific cases.

In order to describe the order relation for any systems, at the set time moments, for the quality vector described with the dependence (2), a function described on this vector is introduced, which takes the values from the set of the real numbers. The values of this function create an ordered set as presented below:

\[
q(X(t)) = q(X(t_1), X(t_2), \ldots, X(t_n))
\]  
(9)

where: \( q \) is a function of \( p \) – variables such that \( q(X(t)) \) is a stochastic process. This function is a measure of the operation quality of the system.

In the considerations regarding the operation quality of the system it has been assumed that each of the coordinate of the vector \( X(t) \) is smaller or equal to a certain limiting value of the pattern for the individual quality features: \( X_i(t_k) \leq q_i \), for: \( t \in T \), \( i=1, 2, \ldots, p \).

The set of values of the quality features, performing the above inequality is represented by the model state of the operation quality of the system (in the geometrical interpretation \( \mathbb{R}^p \)). Applying (9) it is possible to introduce the good order relation of the systems in terms of their operation quality.

The investigated system at the moment \( t_k \in T \) has higher operation quality grade than at the moment \( t_i \in T \), if:

\[
q(X(t_k)) < q(X(t_i))
\]  
(10)

For the investigated system a random process is defined, representing the operation quality of the system, and is formulated as:

\[
Z_x(t) = \sum_{i=1}^{p} \alpha_i X_i(t)
\]  
(11)

\[
\alpha_i \geq 0, \sum_{i=1}^{p} \alpha_i = 1
\]

where:

\( \alpha_i \), \( i=1, 2, \ldots, p \) stand for the values of the quality weights for the individual features, determining the operation quality of the investigated system [9].

\( Z_x(t) \) – is a random process, being a finite mixture of the processes \( X_i(t), i=1, 2, \ldots, p \), \( t \in T \). For the process \( Z_x(t) \) the below inequality is obvious:

\[
Z_x(t) \leq \sum_{i=1}^{p} \alpha_i q_i
\]  
(12)

The above mentioned inequality indicates that the process \( Z_x(t) \) determined by means of the equation (11) is limited, thus the feature values determining the operation quality of the system shall not go beyond the preset threshold, that means the right side of the inequality (12). For the average value it can be noted that:

\[
E(Z_x(t)) = \frac{1}{p} \sum_{i=1}^{p} \alpha_i E(X_i(t))
\]  
(13)

The average value \( E(Z_x(t)) \) is a linear combination of the average values \( E(X_i(t)), i=1, 2, \ldots, n \). The formula (13) is applicable irrespectively of the fact whether the processes \( X_i(t), i=1, 2, \ldots, n \) are dependent. For the process variation (14) there is:

\[
D^2 Z_x(t) = \sum_{i=1}^{p} \alpha_i^2 D^2 X_i(t) + 2 \sum_{i,j} \alpha_i \alpha_j \text{cov}(X_i(t), X_j(t))
\]  
(14)

where: \( \text{cov}(X_i(t), X_j(t)) \) means covariation between the random variables \( X_i(t) \) and \( X_j(t) \).

In case when the random processes \( X_i(t), i=1, 2, \ldots, p \) are independent, all the covariations \( \text{cov}(X_i(t), X_j(t)) \) are equal to zero. In this case the process variation \( Z_x(t) \) is a sum of the variations.

In the real cases the processes \( X_i(t), i=1, 2, \ldots, p \) are dependent and it is to be expected, that the covariations \( \text{cov}(X_i(t), X_j(t)) \) will be positive. This fact may be expressed in such a way that the processes \( X_i(t) \) are positively correlated by pairs. That means that the coefficient of the correlation between the random variables \( X_i(t) \) and \( X_j(t), i,j=1, 2, \ldots, n \), is positive [10,11].

V. OPERATION AND MAINTENANCE INVESTIGATION DIRECTIONS
All the consideration presented in this paper are based on an example of the investigations performed within a real urban transport system, the major aim of which is to provide transport service over the area of 400.000-dweller urban agglomeration and its neighbourhood. It is a complex, real, operational aim-oriented system, representing the socio-technical systems of \((H - M - E)\) type. The system under investigation has been identified and its decomposition has been performed. The operation and maintenance based studies, survey researches, desk researches have been conducted out and a set of criteria has been determined, moreover the valuation process of the features adopted to describe the system from its operation quality point of view was set and carried out. On such basis a criteria and multidimensional quality vector has been set, a resultant system evaluation model has been built and its operation quality evaluation has been performed. A computer simulation algorithm has been determined and the model simulation researches have been carried out [19].

At present there are works in progress aimed at verifying the adopted assumptions and checking the adequacy and sensibility of the model built. The outcomes of these works shall be published in the subsequent papers. On the basis of carried out experimental tests, for each of the distinguished random variables – features Xi, \(i = 1, 2, \ldots, 18\), describing the transport system quality operation, ranges of their admissible changeability were established. Next, their values in different time periods, were determined. The method of matrix of meanings [12] was used and on this basis, weights and their influence on the investigated system operation quality were determined for sets \(Z1, Z2, Z3\) (describing the human, transport means, and the environment) and features assigned to them.

For the purpose of unique interpretation of results a normalization of random variable values has been made, in the range \(0, 10\), according to dependence:

\[
10(Xi - X_{Min})/(X_{Max} - X_{Min})
\]

(15)

Next consistence test \(X^2\) (Pearson’s), and on this basis a verification of zero hypothesis \(H0\), concerning consistence of empirical distribution of particular random variables with hypothetical distributions was performed.

Evaluation of the examined system operation quality was made using metric \(Zx(t)\) (described by dependence 11), which describes the process of the system operation quality changes in time, \(a\), \(i = 1, 2, \ldots, p\) denote values of quality weights for particular features, which determine the operating subsystem operation quality.

In order to check sensitivity of the built model of the transport system operation quality evaluation, a simulation algorithm of feature changes for selected features describing the system was developed [5]. Simulation module, on the basis of input data, generates quality change of particular features describing the tested system operation quality, in successive time intervals, and it also determines values of metric describing its operation quality [4].

Models of feature changes for features describing the operation subsystem operation quality were accepted. Next, there were conducted simulation experiments which involved changing values of reaction of selected input parameters (features), with regard to external factors, to the quality of its operation [7].

VI. The Concept of the Quality Control of Transport Systems

The methodology described in this paper makes it possible to make an assessment of operation quality for complex operation systems, including the considered transport ones. An outsized quality vector whose particular components are values of features determined for time \(t\) can express this assessment. This vector is called Outsized Quality Vector (OQV). In such a case the point of reference for assessment (placement of OQV vector end), can be comparison of the examined system quality state with previous or successive assessment times or comparing it with the so called Criterion Quality Vector CQV, which is determined on the basis of maximum or desirable values of the same features.

It has been assumed that the system operation quality assessment can be made in many ways, using different metrics. In this work, it has been accepted that the assessment will be express by a random process defined by dependence (8). It should be emphasized that in real cases each of the features, in the distinguished \(p\)-element set, is different, differently measured, with different assessment scale and different significance. Therefore, to make the research result reading clear, it is necessary to establish the same assessment scale for each feature and, if necessary, perform their recoding so that the highest values for each of them will be values reflecting the desired level of the system operation quality [1].

Interpretation of the obtained results can be the basis for taking actions aiming at increase and maintenance of a given level of the system operation quality. However, it is indispensable to develop a method which will enable, on the basis of the performed evaluation, its quality control, in times \(t\). Generally, control involves affecting the controlled object, by means of input signals, in such a way that its output signals can reach the desired value. Quality control is a method and system operation used for satisfying quality demands through giving the process or product appropriate characteristics or features.

It has been accepted that for a set of \(p\)-elements, on whose basis evaluation of a given system operation quality is performed, an identical, qualitative evaluation scale is set. This range was divided into three sections: favorable range, limited range, unfavorable range.

These ranges are established separately for each of the distinguished attributes, and their affinity is determined by their influence on the system operation quality, expressed by the values of assessments obtained in result of the carried out research, in given time \(t\). In extreme cases, it can happen that the assessment will be of two-state character, that is, when only the maximum value of a given feature will correspond to the favorable qualitative range, whereas, it will not be possible to distinguish the range of its limited quality operation.

Let us assume that for each of the features distinguished from a \(p\)-element set, there is a possibility of its variability division into three subsets. In connection with this, there can
be determined, of possible quality states, for given time t. It must be remembered that the system operation quality is a collective feature and the above considerations concern assignment of particular feature values to each quality range. Thus, analogically, there can be distinguished three quality areas (favorable, limited and unfavorable) that are qualitative operation states of the system, determined on the basis of quality evaluation of all features accepted for the resultant model.

Due to a general quality assessment of the system operation and a different influence of each of the features, it is necessary to carry out research and classify particular quality states to one of the three ranges of features. In a geometrical interpretation, there should be determined two planes that will run between the quality boundary states determining, in this way, three operation quality areas of the examined system. The discussed issues can be included to science called threshold logic. In fact, it is necessary to determine two such threshold planes that will divide the area of quality states into areas: favorable, limited and unfavorable for the system operation quality. For this purpose, there must be determined two threshold functions for a p-th element set of features \( f(x_1, x_2, \ldots, x_p) \) and \( f'(x_1, x_2, \ldots, x_p) \), where crossing them will mean a significant change in the system operation quality. Change of the area for a limited or unfavorable will be a signal forcing to make a decision on the actions to be taken in order to provide the object with the desired quality level. An exemplary graphic interpretation of quality state areas for two quality areas has been demonstrated in fig.3.

![Fig.3. Graphic interpretation of quality states determined on the basis of three features](image1)

It should be noted, though, that in practice, the number of features accepted for the system operation quality will be higher, thus, the number of quality states will increase, as well. Also, it must be defined which transitions between states are feasible and for this purpose a transition probability matrix should be built. On the basis of this matrix it is possible to identify a graph of quality states with determined areas of its operation quality. An exemplary graph of the system quality states is shown in fig.4.

![Fig.4. Exemplary graph of states with separated quality states](image2)

It should be emphasized that in order to provide the proper level of the system operation quality it is essential to make an analysis of transitions between boundary states (crossing the boundary planes) and to take up appropriate actions for control (decision) aiming at reaching the system state considered as the favorable state of its operation quality.

### VII. SUMMARY

This paper presents general, theoretical grounds of the theory of the systems and the theory of quality. The conception presented in the paper and the model built to evaluate the operation quality of complex transport systems are applicable both for evaluating the operation quality of the same system at various time moments, of two different systems at the same time moment and also of different systems at various time moments, provided that the valuing evaluation is performed on the basis of the same criteria and features which are set to describe the investigation objects.

The elaborated method may be a universal tool in the processes of providing diagnosis, prognosis and especially in optimizing and rational controlling complex operation and maintenance systems, by evaluating their states, which are set based on the changes of the values of the significant features, describing the system.

Currently, there is being conducted research aiming at determination of the system time of stay in particular quality states and finding probability of transition into a particular state. The author hopes that it will be possible by using semi-Markov processes and will be a solution to the decision making problem in the process of quality control of transport systems.

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