Optimisation of changes of the operation quality of the transportation system in the fuzzy quality states space

M Pająk¹  L Muślewski² and B Landowski²

¹Department of Thermal Technology, Faculty of Mechanical Engineering, University of Technology and Humanities, ul. Stsieckiego 54, 26-600 Radom, Poland
²Machine Maintenance Department, Faculty of Mechanical Engineering, University of Science and Technolog, Al. Prof. S.Kaliskiego 7, 85-796 Bydgoszcz, Poland

E-mail: m.pajak@uthrad.pl

Abstract. The main objective of the management and control of the transportation system operation is to achieve the highest quality of its operation tasks execution. However, because of the system complexity the accurate determination of the system operation quality is very complicated. To optimize the efficiency of the activities performed to increase the operation quality, it was expressed in the quality states space. In the space the subspaces of the inadvisable, advisable, limited, acceptable and desired quality of operation were defined and the momentary quality of the system operation was expressed in form of the point. Taking into account the subjective character of the survey results and their linguistic inaccuracy the space was transformed into the fuzzy quality states space. Subsequently, the distance between the fuzzy set of the momentary system operation quality and the border of the desired quality subspace was defined. This way, for the quality states not belonging to the desired quality subspace, the minimal changes of the system features required to move this state to the subspace were calculated. The presented in the paper method allows optimizing the efficiency of the activities performed to increase the operation quality of the transportation system.

1. Introduction

The object of presented studies is a complex transportation system. The state of the system is determined by the unique set of its cardinal features. The momentary values of the cardinal features uniquely identify the system state. For each system feature \( x_i \), the range of its possible values \( X_i \) can be defined as a set of values, which the feature can have. The range of the possible values is limited by its minimum value \( x_{i\text{min}} \) and its maximum value \( x_{i\text{max}} \). Inside the range, depends on chosen criteria, we can distinguish boundary minimum and maximum values (\( x_{i\text{brmin}} \) and \( x_{i\text{brmax}} \)) which describe the range of acceptable values.

Subset of the acceptable values, which is limited by the boundary minimum value \( x_{i\text{brmin}} \) and boundary maximum value \( x_{i\text{brmax}} \) is called boundary values range. Subset of the acceptable values, which is limited by the suboptimum minimum value \( x_{i\text{isomin}} \) and suboptimum maximum value \( x_{i\text{isomax}} \) is called suboptimum values range. Among the suboptimum values it is possible to distinguish the optimum value \( x_{iop} \). Defining presented values the following ranges are formulated (1-5)

\[
X_{ip} = [x_{i\text{min}}, x_{i\text{max}}]
\]
where: $x_{\text{imin}}$ - the minimum value of the feature no. $i$, $x_{\text{ibrmin}}$ - the boundary minimum value of the feature no. $i$, $x_{\text{ibrmax}}$ - the boundary maximum value of the feature no. $i$, $x_{\text{iSOmin}}$ - the suboptimum minimum value of the feature no. $i$, $x_{\text{iSOmax}}$ - the suboptimum maximum value of the feature no. $i$, $X_{\text{iUA}}$ - the range of the unacceptable values of the feature no. $i$, $X_{\text{iSO}}$ - the range of the suboptimum values of the feature no. $i$, $X_{\text{iA}}$ - the range of the acceptable values of the feature no. $i$, $X_{\text{iB}}$ - the range of the boundary values of the feature no. $i$.

The cardinal features of the system define the $n$-dimensional space which is called the features space of the system. If we interpret points of the features space of the system as the system states then characteristic ranges of the system features (1 - 5) determine $n$-dimensional subspaces of the system states in a features space. The ranges of unacceptable values of the system features determine the subspace of unacceptable system states $S_{\text{UA}}$. The ranges of acceptable values of the system features determine the subspace of acceptable system states $S_{\text{A}}$, whereas the ranges of suboptimum values determine the subspace of suboptimum system states $S_{\text{SO}}$. The subspaces of the system states in a features space are constructed as the Cartesian product [1], which is an intersection of cylindrical extensions of enumerated ranges of the system features.

2. Quality states space

If a set of the cardinal features includes the ones describing the system operation quality, then it formulates a space which consists of the points representing the system quality states. Such a space is called the quality state space of the system and the features are the dimensions of this space [2, 3]. The conditions for the system operation appropriate quality are defined for each feature. A condition is possible to be unequivocally identified if it is fulfilled or not by a specified feature [4].

The fixed minimum boundary value divide the domain of the feature into the range of values corresponding to undesirable quality of the system operation and the range of values corresponding to desired quality of the system operation. Internally, the range of values corresponding to the desired quality of the system operation is divided into the ranges of values corresponding to the limited quality of the system operation, acceptable quality of the system operation and desired quality of the system operation. These ranges are defined by the boundary, suboptimum and maximum values of the system feature. Partitioning of a feature domain is presented in figure 1 and described by the formulas (6-11)

![Figure 1. The domain of the feature - the dimension of the space of the system quality states](image)

$$X_{ip} = [x_{\text{imin}}, x_{\text{imax}}]$$ (6)
An exemplary position of the subspaces of the system operation quality states for two independent features is presented in figure 2.
Figure 2. The subspaces of the system quality states expressed in $R^2$ space of two independent features: $S_{COQ}$ - the subspace of the system critical operation quality; $S_{LOQ}$ - the subspace of the system limited operation quality; $S_{AOQ}$ - the subspace of the system acceptable operation quality; $S_{DOQ}$ - the subspace of the system desired operation quality.

3. Fuzzy quality states space

It is possible to distinguish two types of system features measurable and immeasurable ones. As far as immeasurable features are concerned it is not possible to measure their values because of technical difficulties or because of a lack of researcher knowledge. In order to determine the approximate value of immeasurable features a range of variability can be assigned. The range of variability is divided homogenously into $m$ parts described by $m$ values [5]. These values correspond to intensity of appearance of the approximated feature. Thanks to the range of variability implementation it is possible to express the intensity of the feature between $0$ and $m$ values.

In case of measurable features their momentary values are assigned on basis of the measurements and are specified with the measuring device precision. So they are inaccurate because of the observation errors [6]. Therefore it is impossible to precisely determine them. When the measurable feature value is not measured directly but calculated on the basis of the indirect measurements, additional error of the calculation method should be taken into consideration. In case of immeasurable features, their momentary values are expressed in the discrete scale and therefore are also determined approximately.

The inaccuracy of the features values was modelled in a form of fuzzy sets. This type of approach is successfully applied in wide range of research [7, 8]. In case of measurements comprising zones of insensitivity the tolerance interval was modelled as a fuzzy set of $\Pi$ type. In case of other measurements they were modelled as a $\Lambda$ type fuzzy set where the modal value was equal to the measured value. The inaccuracy of the immeasurable features values was also modelled in form of the $\Lambda$ type fuzzy set but in this case the modal value of the set was equal to the discrete grade of the scale describing the feature intensity and the support was as wide as a double distant between discrete values of the intensity assessment scale.

The fuzzification of the momentary values of the features causes the fuzzy modelling of their characteristic values and ranges. During the carried out studies [9] it was proposed to model the fuzzy maximum value in a form of the $\Gamma$ type fuzzy set and the fuzzy minimum value in a form of $L$ type fuzzy set while the fuzzy boundary values and the suboptimum minimum values in a form of $\Lambda$ type fuzzy sets.

Accordingly, the range of values corresponding to inadvisable quality of the system operation was modelled in form of $L$ type fuzzy set, the ranges of values corresponding to the advisable quality and desired quality of the system operation were modelled in form of the $\Gamma$ type fuzzy sets, the ranges of the
values corresponding to limited quality and acceptable quality of the system operation were modelled in form of \( \Pi \) type fuzzy sets.

The obtained feature domain partitioning is presented in the figure 3.

**Figure 3.** Fuzzy characteristic values and ranges of the feature which describes the quality state of the system

Expression of the momentary and characteristic values of the system features in a form of the fuzzy sets introduce into the quality states space the additional dimension in which the values of the membership functions of the sets are depicted. So, the quality states space \( R^n \) is transformed into the \( R^{n+1} \) space [10]. In this space the state of the system is expressed in a form of the multidimensional fuzzy set created as a result of the t-norm relation executed on cylindrical extensions of flat fuzzy sets of the momentary values of the system features [11].

In the fuzzy quality states space the subspaces of the system quality states are defined as multidimensional fuzzy sets. The multidimensional fuzzy set of the desired quality of the system operation is created as a result of the \( MIN \) relation executed on cylindrical extensions of the flat fuzzy sets of values corresponding to desired quality of the system operation of each feature (16)

\[
S_{DOQ}^{FS}(x_1, x_2, ..., x_p) = MIN(ce(X_{1DOQ}^{FS}), ce(X_{2DOQ}^{FS}), ..., ce(X_{nDOQ}^{FS}))
\]

where: \( S_{DOQ}^{FS} \) - the multidimensional fuzzy set of the desired quality of the system operation, \( x_i \) - \( i \)-th feature of the system and \( i = 1, ..., n \), \( ce(X_{iDOQ}^{FS}) \) - the cylindrical extension of the flat fuzzy set of the values corresponding to desired quality of the system operation of the \( i \)-th feature described by the formula (17).

\[
ce(X_{iDOQ}^{FS}) = \sum_{(x_1,x_2,...,x_n) \in \mathbb{X}^n} X_{iDOQ}^{FS}(x_1, x_2, ..., x_n)
\]

The multidimensional fuzzy set of the system critical operation quality is created as a result of the \( MAX \) relation executed on results of the \( MIN \) relation executed on a cylindrical extensions of flat fuzzy sets of the values corresponding to the inadvisable quality of the system operation of specified system feature and the cylindrical extensions of the flat fuzzy sets of the possible values of the remaining system features (18)

\[
S_{COQ}^{FS}(x_1, x_2, ..., x_p) = MAX(MIN \left( ce(X_{1ADOQ}^{FS}), ce(X_{2DOQ}^{FS}), ..., ce(X_{nDOQ}^{FS}) \right),
...
MIN \left( ce(X_{kADOQ}^{FS}), ce(X_{1P}), ..., ce(X_{k-1P}), ce(X_{k+1P}) ..., ce(X_{nP}) \right),
...
MIN \left( ce(X_{nADOQ}^{FS}), ce(X_{1P}), ..., ce(X_{n-1P}) \right)
\]
where: $S_{LOQ}^{FS}$ - the multidimensional fuzzy set of the system critical operation quality, $x_i$ - $i$-th feature of the system and $i = 1,...,n$, $ce(X_{i}^{FS})$ - the cylindrical extension of the flat fuzzy set of the possible values of the $i$-th system feature, $ce(X_{iADOQ}^{FS})$ - the cylindrical extension of the flat fuzzy set of the values corresponding to the inadvisable quality of the system operation of the $i$-th system feature.

The multidimensional fuzzy set of the system limited operation quality is created as a result of the $MAX$ relation executed on the results of the $MIN$ relation executed on the cylindrical extensions of the flat fuzzy set of the values corresponding to the limited quality of the system operation of the specified feature and the cylindrical extensions of the flat fuzzy sets of the values corresponding to the advisable quality of the system operation of the remaining features (19).

$$S_{ADOQ}^{FS}(x_1,x_2,...,x_n) = MAX(MIN(ce(X_{1ADOQ}^{FS}), ce(X_{2ADOQ}^{FS}),..., ce(X_{nADOQ}^{FS}))),$$

$$MIN(ce(X_{1ADOQ}^{FS}), ce(X_{2ADOQ}^{FS}),..., ce(X_{(i-1)ADOQ}^{FS}), ce(X_{(i+1)ADOQ}^{FS}),..., ce(X_{nADOQ}^{FS}))),$$

$$MIN(ce(X_{(i-1)ADOQ}^{FS}), ce(X_{(i+1)ADOQ}^{FS})))$$

where: $S_{ADOQ}^{FS}$ - the multidimensional fuzzy set of the system limited operation quality, $x_i$ - $i$-th feature of the system and $i = 1,...,n$, $ce(X_{iADOQ}^{FS})$ - the cylindrical extension of the flat fuzzy set of the values corresponding to the advisable quality of the system operation of the $i$-th system feature, $ce(X_{iADOQ}^{FS})$ - the cylindrical extension of the flat fuzzy set of the values corresponding to the limited quality of the system operation of the $i$-th system feature.

The multidimensional fuzzy set of the system acceptable operation quality is created as a result of the $MAX$ relation executed on the results of the $MIN$ relation executed on the cylindrical extensions of the flat fuzzy set of the values corresponding to the acceptable quality of the system operation of the specified feature and the cylindrical extensions of the flat fuzzy sets of the values corresponding to the advisable quality of the system operation of the remaining features (20).

$$S_{ADOQ}^{FS}(x_1,x_2,...,x_n) = MAX(MIN(ce(X_{1ADOQ}^{FS}), ce(X_{2ADOQ}^{FS}),..., ce(X_{nADOQ}^{FS}))),$$

$$MIN(ce(X_{1ADOQ}^{FS}), ce(X_{2ADOQ}^{FS}),..., ce(X_{(i-1)ADOQ}^{FS}), ce(X_{(i+1)ADOQ}^{FS}),..., ce(X_{nADOQ}^{FS}))),$$

$$MIN(ce(X_{(i-1)ADOQ}^{FS}), ce(X_{(i+1)ADOQ}^{FS})))$$

where: $S_{ADOQ}^{FS}$ - the multidimensional fuzzy set of the system acceptable operation quality, $x_i$ - $i$-th feature of the system and $i = 1,...,n$, $ce(X_{iADOQ}^{FS})$ - the cylindrical extension of the flat fuzzy set of the values corresponding to the advisable quality of the system operation of the $i$-th system feature, $ce(X_{iADOQ}^{FS})$ - the cylindrical extension of the flat fuzzy set of the values corresponding to the acceptable quality of the system operation of the $i$-th system feature.

4. The analysis of the operation quality of the selected transportation system

The object of the research is a real, complex transportation system executing passenger transport in 400 000 city. This system is of HME type (human-machine-environment). The system operation quality is assessed on the base of changes of its features values. The features describe the operators activity, the technical objects operation and the influence of the environment.

The main objective of the system is safe and effective from the economics point of view transport execution in the specified area, in defined amount and in defined time using the accessible technical objects. The level of the system operation quality is under the direct influence of its subsystems and the environment impact on these subsystems [12].
The assessment of the system quality (the quality features identification) was accomplished as a result of the operation research executed on real city transportation system and analysis of vehicle cards. The research were performed over eighty elementary subsystems consisted of drivers in different age, on different education level and differently experienced, sixteen types of buses different from the production year, millage and equipment point of view and the environment in which the transportation tasks were executed. The research were carried out ones a quarter and consisted in evaluative assessment of each quality feature under the variable influence of environmental factors. As a result eighteen quality features of the system were identified. Therefore the system operation quality function was formulated in the following form:

\[ Z_x(t) = f(x_1, \ldots, x_{18}) \]  

where: \( Z_x(t) \) - the system operation quality function, \( x_i \) - the value of the \( i \)-th feature of the system, \( i = 1,2,\ldots,18 \).

In each questionnaire the value of each feature and the value of the operation quality function were determined. In order to select the most important features from the operation quality point of view the fuzzy curves charts method was implemented [13]. According to the method for the specified values of each feature the cross-sections by the surface determined by the concerned quality function are defined. To analyse the real data the values of the features for the cross-sections were fuzzified. Thanks to it the problems of non-uniform and non-continuous overlapping of the surface by the collected values were avoided. The membership of each value to each cross-section is calculated according to Gauss function (22). The stochastic nature of real data is commonly taken into consideration using the Gauss function properties [14, 15]

\[ \mu(x_i^*) = \exp\left(-\left(\frac{x_i^* - x_i}{b}\right)^2\right) \]  

where: \( \mu(x_i^*) \) - the value of the membership function to cross-section defined for \( x_i^* \) value, \( x_i^* \) - the value of the feature no \( i \) specified for the concerned cross-section, \( b \) - the factor defining the width of the membership function.

For each cross-section the weighted mean value was calculated by the formula (23)

\[ Z_{\mu}(x_i) = \frac{\sum_{k=1}^{nwp} \mu(x_i) \cdot Z(wp_k)}{\sum_{k=1}^{nwp} \mu(x_i)} \]  

where: \( nwp \) - no of data set, \( wp \) - data set (the value of each feature and the value of the operation quality function defined during the survey).

Obtained values of the cross-sections formulate the curve. The difference between minimum and maximum value of the curve is the measure of the dependency between the operation quality function and the analysed feature.

Using software made by the authors the analysis of the features importance from the operation quality point of view was performed. During the studies the factor defining the width of the membership function was equal to 20\%, number of cross-sections was equal to 10 and the dispersion of the fuzzy means was calculated as a mean square value. As a threshold of the features importance value 1.0 of the dispersion was used.

Analysing the dispersion of the fuzzy means (table 1) the set of the six most important features from the system operation quality point of view were selected (table 2). For each of them the interpretation of the domain range was proposed:

- \( x_1 \) - the assessment of the result of the mistake made by the driver, where: [0 - fatality disaster, 1 - accident, 2 - collision, 3 - failure of the bus with course change, 4 - failure of the bus without course change, 5 - no driver mistake]
- $x_2$ - the millage of the driver [km]
- $x_{12}$ – the transport tasks execution coefficient expressed as the amount of the tasks executed according to the schedule divided by the amount of the planned tasks in total [%]
- $x_{15}$ - the difference between the value 20°C and the distance between temperature in a vehicle and the thermal comfort zone (15°C - 25°C)
- $x_{16}$ - the road surface state [ice, snow, water, contaminations (oil, sand etc.), damages], where: [0 - means that all enumerated elements are present, 5 - means that no one of the enumerated elements are present]
- $x_{17}$ – the visibility on the road [m]

Table 1. The analysed features of the transportation system.

| Feature name                              | Feature symbol | Fuzzy means dispersion |
|-------------------------------------------|----------------|------------------------|
| Mistakes made by the drivers             | $x_1$          | 18.2170                |
| Transport tasks execution coefficient    | $x_{12}$       | 13.8900                |
| The millage of the driver                | $x_2$          | 2.6903                 |
| The road surface state                   | $x_{16}$       | 1.4179                 |
| Visibility on road                       | $x_{17}$       | 1.1123                 |
| The thermal comfort (drivers and passengers) | $x_{15}$       | 1.0356                 |
| Drivers education                        | $x_3$          | 0.4167                 |
| Costs of vehicles operation and maintenance | $x_8$          | 0.1713                 |
| State of the vehicles tyres              | $x_6$          | 0.1614                 |
| Contaminations emission                  | $x_{13}$       | 0.0395                 |
| Percentage of existing bus stop bays     | $x_{18}$       | 0.0266                 |
| Monitoring and communication equipment existence | $x_7$          | 0.0233                 |
| Noise emission                           | $x_{14}$       | 0.0228                 |
| Ergonomics of bus                        | $x_9$          | 0.0219                 |
| Capacity of bus                          | $x_{10}$       | 0.0141                 |
| Operation monitoring equipment existence | $x_{11}$       | 0.0093                 |
| Safety systems existence                  | $x_5$          | 0.0030                 |
| Airbag existence                         | $x_4$          | 0.0011                 |

In order to determine the values of the selected features the operation research was also performed. As a result the characteristic values, characteristic ranges and the subspaces of the operation quality states were identified. The determined characteristic values of the features are presented in table 2. The fuzzy zones were defined as a 10% of the possible values range of each feature.

Table 2. The most important features from the operation quality point of view and theirs characteristic values.

| Feature symbol | Min value | Min boundary value | Max boundary value | Min suboptimum value | Max value |
|----------------|-----------|--------------------|--------------------|----------------------|----------|
| $x_1$          | 0         | 2                  | 3                  | 4                    | 5        |
| $x_2$          | 0         | 30000              | 60000              | 200000               | 500000   |
| $x_{12}$       | 0         | 40                 | 50                 | 80                   | 100      |
| $x_{15}$       | 0         | 8                  | 10                 | 16                   | 20       |
| $x_{16}$       | 0         | 2                  | 3                  | 4                    | 5        |
| $x_{17}$       | 0         | 50                 | 70                 | 200                  | 1000     |

Thanks to the characteristic ranges identification it was possible to express the quality of the transportation system operation in the analytic form. As an example the real quality state
$s_8(x_1=4,x_2=300000,x_{12}=60,x_{15}=8,x_{16}=4,x_{17}=500)$ of the system was considered. It was stated that the state belongs to the subspace of the limited operation quality. In order to move this state to the subspace of the desired operation quality it is necessary to change the transport tasks execution coefficient form value 60 to at least 70 (optimum 80) and to change the thermal comfort feature value from 8 to at least 14 (optimum 16). Simultaneously, when for processes of the changes of the features values the cost functions are defined then the result of the analysis will be expressed as the expenditures.

5. Summary
The described in the paper theoretical method and its implementation in case of the real transportation system can be summarized in a form of the following list:

- The quality state of the transportation system can be described by the values of its cardinal features.
- For each feature the characteristic values and ranges can be distinguished.
- The cardinal features construct the quality state space of the system in which the subspaces of the quality states are formulated by the characteristic values and ranges of the features.
- The inaccuracy of the features values was modelled in a form of fuzzy sets what implies the flat fuzzy set implementation to express characteristic values and ranges.
- The fuzzy modelling of the characteristic values and ranges of the feature causes the transformation of the quality state space into the fuzzy quality states space.
- In the fuzzy quality states space the subspaces of the critical, limited, accepted and desired quality of the system operation are expressed in the form of multidimensional fuzzy sets.
- In case of a real transportation system it is necessary to select the set of its cardinal features what can be accomplished by the fuzzy curves charts method implementation.
- In case of the transportation system under consideration six features are selected form the set of eighteen as a result of the fuzzy curves charts method implementation.
- Thanks to the characteristic ranges identification for all cardinal features it was possible to express the quality of the considered transportation system operation in the analytic form.
- In case of exemplary quality state of the considered transportation system the changes of the features values required to obtain the desired operation quality state were determined.
- Defining costs functions for the activities which change the cardinal features values the result of the analysis is expressed in the financial form.

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