Application of Fuzzy Principles in Evaluating Quality of Manufacturing Process

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Abstract: The article deals with the possibility of using artificial intelligence elements in order to evaluate the quality of a manufacturing process. There are described selected indexes of a production process quality evaluation based on statistical process control (SPC), their interpretation and evaluation by means of fuzzy sets, which enable us to work with inaccurate, incomplete or vague information about a monitored and reviewed phenomenon. There are described possibilities of using program system Matlab and its toolboxes Simulink and Fuzzy Logic to evaluate quality of the manufacturing process based on fuzzy principles.

Key-Words: - SPC, quality, manufacturing, process, fuzzy, Matlab

1 Introduction

Companies are constantly under pressure not only to design new products faster, but also accelerate their production in today's competitive environment. Minimalization of time, which is necessary for the product introduction to the market is required as well as cost prediction and last but not least the increasing demands on product quality.

To evaluate the quality of the manufacturing process, statistical process control is used. It is a set of tools to maintain process stability and to improve its capability by reducing process variability. The theory of statistical process control is based on the existence of variation parameter in the production process which is influenced by a number of effects which make it impossible to produce completely two identical products. Is it possible to evaluate these effects and create conditions to make the process stable and to be able to assume the behavior of the process and ensure the required level of production quality [1].

Knowledge of process capability is a very important basis for professional decisions when planning quality by manufacturers allowing them to choose a suitable process for the production of certain products to predict the likelihood of non-conforming units, to plan preventive and corrective arrangements and evaluate their effectiveness, to assess the stability of processes, etc.

For the customer, who requires the process capability evaluation of the manufacturer, this information provides evidence that the product was produced under stable production conditions and that the prescribed quality criteria were met. In order to make an effective use of the knowledge about the manufacturing process, it is necessary that it is accessible to anyone who makes necessary decisions. One possibility is the application of fuzzy logic to obtain relevant information on the status of quality manufacturing process, as the industrial practice in the diagnosis of the real situation to a large extent provides just such an incomplete, inaccurate information, which makes great difficulties in using traditional methods of assessment and decision making.

2 The basic terms of quality control

The manufacturing process is the productive forces effect on each other to create a product.

Each product has a certain dimension which is highly important for it. This means that if the size is out of the tolerance limits, the product is classified as non-compliant, as a waste. As a result, companies have losses and therefore they put increased emphasis on compliance with these requirements.

A capable process is such a process where almost all the measurements fall inside the specification limits. But we assume that there are only random effects acting on the process.

This can be represented pictorially by the plot below[15]:

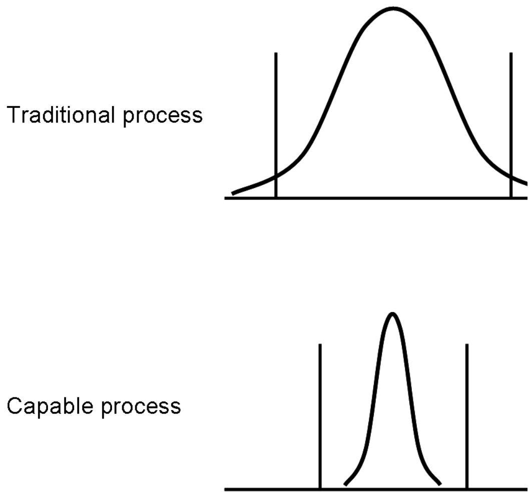

Fig. 1 Process Variation

This financial loss expresses a mathematical function called loss function. The Taguchi loss function is based on the assumption that all variation has a cost, even when the variation does not violate the data patterns defined by control charts. This concept is most useful where deviations from expectation are expected to be costly. Taguchi posited that all deviations from target values ultimately result in customer dissatisfaction. The Taguchi loss function enables organizations to calculate the financial consequence of process variability, making it useful in reaching design decisions. Mathematical expresion of this function is :

$$L = k(X - T)^2 \qquad (1)$$

where
k - loss coefficient
X - measured value
T - target value

In this case we assume required value *T* such as centre of tolerance limits. Mathematical expresion is :

$$T = \frac{USL + LSL}{2} \qquad (2)$$

Basic evaluation describing the quality level was provided by histograms, but the graphic representation was not fully appropriate to assess the achieved level of quality. It was therefore necessary that the level of quality attained was expressed by some number (indicator). Such indicators are capability indices. To evaluate the processes different indices were gradually developed.
According to the number of observed markers of their quality, they can be divided into:

- the indices for one character,
- indices for multiple characters simultaneously monitored the

and by a character of code quality:

- indices for measurable characters
  - o with normal distribution,
  - o with other distribution,
- indices of measurable characteristics (attributes).

Cp index (the process capability index) compares the required tolerance limits with natural tolerance limits of a process. It indicates what the process would be like if it were centered. It is assumed normal distribution.

$$C_p = \frac{USL - LSL}{6\sigma} \qquad (3)$$

where σ is the standard deviation of the process.

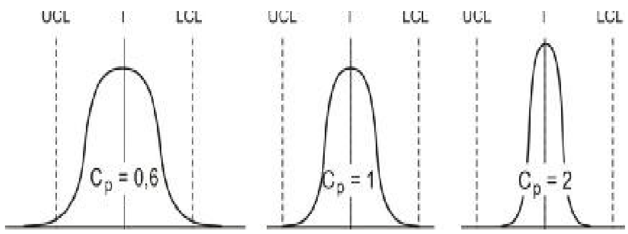

Fig. 2 Cp index values and behavior of the process

Cpk index is an indicator of current capability of the process. It responds to the deviation of the mean volume of the process from the centre of the tolerance interval, eventually from the target value of the reference indicator of quality. The Cpk index disadvantage is that if the desired target value isn't equal to the centre of the tolerance limits, the process does not capture the deviation from target values. The relationship is expressed as follows

$$C_{pk} = \min\left\{\frac{USL - \mu}{3\sigma}; \frac{\mu - LSL}{3\sigma}\right\} \qquad (4)$$

where σ is the arithmetic mean of the measured values. The following table presents the evaluation process in terms of comparison indices Cp and Cpk.

Table 1 *Cp and Cpk indices depends*

Cp = Cpk	the process is centered in tolerance interval
Cp > Cpk	the process is not ideally centered
Cpk = 0	the process is centered on one of tolerance limits
Cpk < 0	process is centered out of the tolerance limits

The index K indicates that if the required target process is not identical with the centre of the tolerance range than it captures the mean deviation from the desired value T, which is very important information [19]:

$$K = \frac{|T - \mu|}{\frac{USL - LSL}{2}} \qquad (5)$$

It may occur

K = 0 - the mean value of the process is identical to the desired target value

0 < K < 1 - mean the process is within tolerance limits

K > 1 - the mean value of the process is out of the tolerance limits.

3 Fuzzy sets

A fuzzy set in terms of algebraic structures represents ordered 3-tuple

$A = (X, M, \mu_A)$

where X, M, μ_A may be ordinary sets. X is a universe, which actually represents a domain of definition with particular relevance and dimension, i.e. the basis on which calculations are made. M is a range of values with the degrees of truth on the set M, to which the values from the set X are mapped. μ_A is a membership function , which expresses the relationship between the universe and a set of membership degrees (degrees of truth), so it is actually a set of ordered pairs always containing one element from X and one element from M .

The importance of fuzzy sets is represented by membership functions and there are used specific membership degrees. It is possible to create more membership functions, which represent concrete fuzzy sets. While binary logic is two-valued logic true or false, fuzzy logic variables may have a truth value that ranges in degree between 0 and 1. Fuzzy logic has been extended to handle the concept of partial truth, where the truth value may range between completely true and completely false. Geometry design, the type and number of membership functions is usually the most difficult part of the application of each fuzzy system. Regarding the number of linguistic values for one fuzzy variable is usually used 3 to 5. Although it is possible to define any shape of membership functions, only a limited number of types of membership functions is used. In contribution is taken to the next shape function :

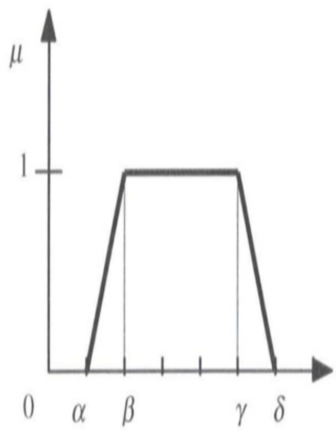

Fig. 3 Shapes of selected membership functions

The most important role in fuzzy logic is played by so called linguistic variable or also called language variable. Unlike a numerical variable, linguistic variable does not use numbers as values but verbal phrases. Thus, a linguistic variable represents a connection between verbal phrases and fuzzy sets.

In this paper are three variables interpreted by the verbal as: Unsufficient, Sufficient and Very good.

3.1 Steps of the Problem Solution

When solving the evaluation problem of the manufacturing process quality using fuzzy logic, we realize three basic steps

- fuzzification,
- fuzzy inference,
- defuzzification.

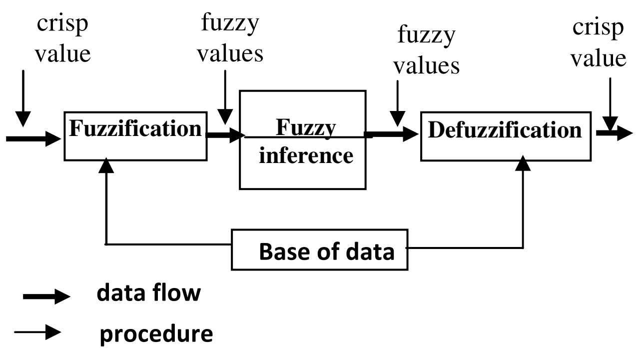

Fig. 4 Diagram of a fuzzy system

Fuzzification is the assignment process of the measure values of the input variables to fuzzy sets by means of the membership functions. Thus, to individual input variables the membership functions are assigned and the weight of the rule for each if-part of the rule (truth degree of the rule) is calculated. The principal application use of fuzzy sets consists in the fact that by their help we are able to interpret the meaning of vague linguistic statements, to quantify this statement and to formalize their relations [17].

Fuzzy inference defines the system behavior by means of the rules of <If> <Then> type at the language level. In these algorithms conditional sentences occur evaluating the condition of a related variable. For each rule it is necessary to determine its weight. The result depends to a certain extend on a correct determination of the defined rules importance. The weight of these rules can be changed during optimization. The result of this process is a linguistic variable. Composition connects all fuzzy sets of outputs into one set for each output. In such a case, a logical OR is used.

The aim of defuzzification is to express a crisp value of the given value from the resulting fuzzy set [5].

Defuzzification methods can be divided into:

- center of gravity methods – the calculation is more complicated but we consider the shape of the membership function
- maximum methods – the calculation is rather simple but we are not considering the shape of the function when calculating.

3.2 Design of membership function for selected indices

Capability, eventually the quality of manufacturing process is given by the numerical values of individual indices.

Table 2 gives numerical values of the Cp index with a corresponding interpretation of the achieved quality of the manufacturing process [2].

Table 2 Cp indices ranges

Cp	Evaluation
∞ - 1,33	**U**nsufficient
1 - 2,5	**S**ufficient
2 - 5	**V**ery **G**ood

Graphical interpretation is shown in the following figures for the Cp index.

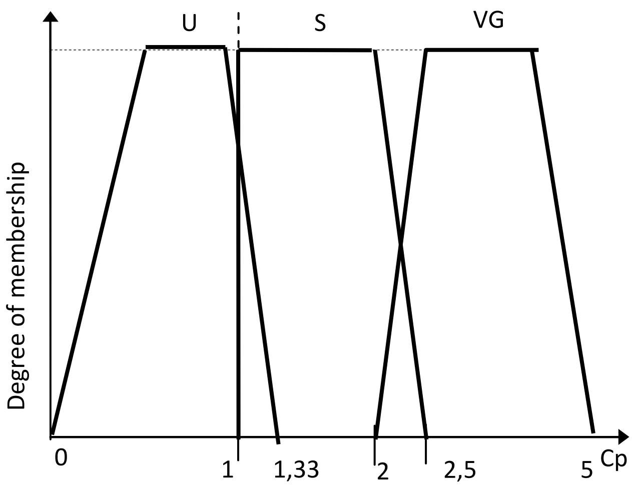

Fig. 5 Design of membership function for Cp index

Table 3 gives numerical values of Cpk index with corresponding interpretation of the achieved quality of manufacturing process.

Table 3 Cpk indices ranges

Cpk	Evaluation
0 - 1,55	**U**nsufficient
1,5-3	**S**ufficient
2,5 - 5	**V**ery **G**ood

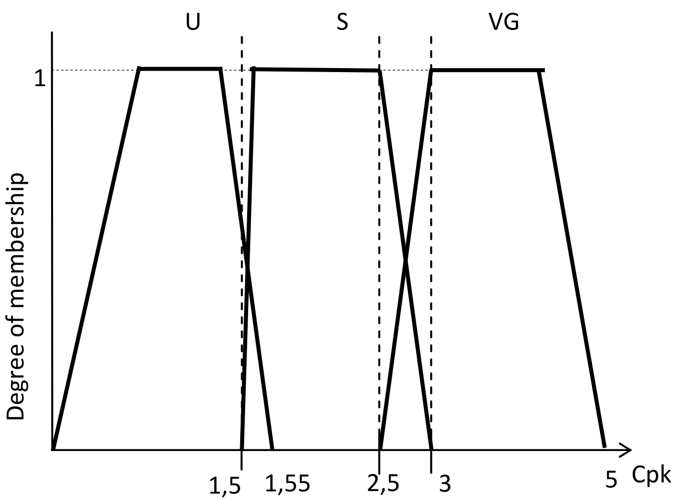

Fig. 6 Design of membership function for Cpk index

Index K expresses the measure of the manufacturing process setting accuracy.

Table 4 K indices range

K	Evaluation
0 - 0,3	**U**nsufficient
0,2 - 0,5	**S**ufficient
0,4 - 1	**V**ery **G**ood

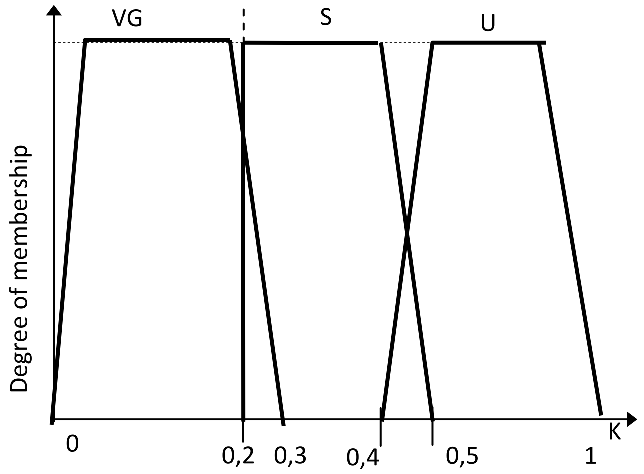

Fig. 7 Membership function for K index

With the evaluation of the achieved quality of a manufacturing process experts recommend to assess indices Cpk and K together [19]. It will represent the quality of the process setting *ProcSet*.

Table 5 Evaluation of K and Cpk indices

K \ Cpk	U	S	VG
Unsufficient	U	U[1]	S[2]
Sufficient	U[3]	S	VG[4]
Very **G**ood	S[5]	VG[6]	VG

Numbers with individual interpretations of conclusions represents the rules based on which were created:

1 If K = **U** and Cpk = **S** Then *ProcSet* **U**
2 If K = **U** and Cpk = **VG** Then *ProcSet* **S**
3 If K = **S** and Cpk = **U** Then *ProcSet* **U**
4 If K = **S** and Cpk = **VG** Then *ProcSet* **VG**
5 If K = **VG** and Cpk = **U** Then *ProcSet* **S**
6 If K = **VG** and Cpk = **S** Then *ProcSet* **VG**

Evaluation of the setting of the process with index Cp represent the process quality *PrQ*.

Table 6 The range of the process quality

PrQ	Process Quality
0 - 0,4	**U**nsufficient
0,3 - 0,8	**S**ufficient
0,7 - 1	**V**ery **G**ood

Membership functions for **process quality**.

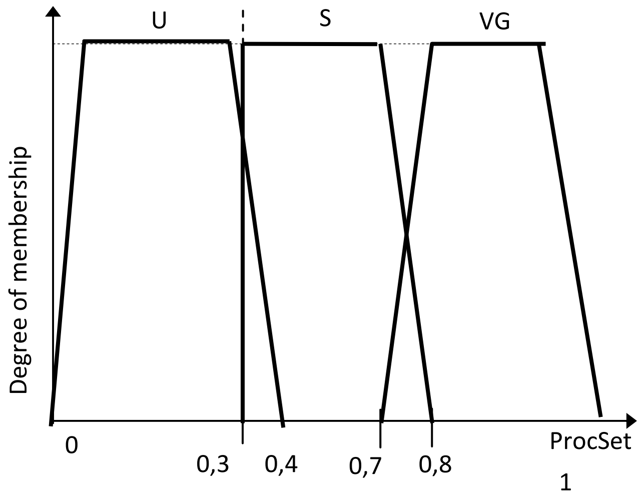

Fig. 8 Process quality

Individual rules and properties which are important from the view of which are important from the view of the manufacturing process quality evaluation were recorded in inference network [6]. This principal statement are interpreted as the network node. The rules were reformulated to production rules which represent transmission between individual states and which more or less affect the resulting quality of manufacturing process.
Inference network is graphical expression of knowledge basis and represents significant model expression of an expert.

4 Matlab

Short for Matrix Laboratory MATLAB® is a high-level technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numeric computation. Using the MATLAB product, we can solve technical computing problems faster than with traditional programming languages.

Key Features

- High-level language for technical computing
- Development environment for managing code, files, and data
- Interactive tools for iterative exploration, design, and problem solving
- Mathematical functions for linear algebra, statistics, Fourier analysis, filtering, optimization, and numerical integration
- 2-D and 3-D graphics functions for visualizing data

- Tools for building custom graphical user interfaces
- Functions for integrating MATLAB based algorithms with external applications and languages, such as C, C++, Fortran, Java, COM, and Microsoft Excel

4.1 Simulink

It is an interactive tool for modeling, simulating, and analyzing dynamic systems. It enables you to build graphical block diagrams, simulate dynamic systems, evaluate system performance, and refine your designs. Simulink integrates seamlessly with MATLAB, providing you with immediate access to an extensive range of analysis and design tools. Simulink is tightly integrated with Stateflow for modeling event-driven behavior. These benefits make Simulink the tool of choice for control system design, DSP design, communications system design, and other simulation applications.

4.2 Fuzzy Logic Toolbox

The Fuzzy Logic Toolbox is a collection of functions built on the MATLAB numeric computing environment.

It is a tool for solving problems with fuzzy logic. It provides tools for you to create and edit fuzzy inference systems within the framework of MATLAB, or if you prefer you can integrate your fuzzy systems into simulations with Simulink as well.

The Fuzzy Logic Toolbox allows you to do several things, but the most important thing it lets you do is create and edit fuzzy inference systems. You can create these systems by hand, using graphical tools or command-line functions, or you can generate them automatically using either clustering or adaptive neuro-fuzzy techniques.

The simulation tool of Simulink®, that runs alongside MATLAB, we can easily test our fuzzy system in a block diagram simulation environment.

5 Matlab and evaluation of manufacturing process quality

5.1 Description of Fuzzy Logic Toolbox

Fuzzy Inference System editor will be open first. In this setting are opened and edited input and output membership functions and set of fuzzy operators.

We can choose two types of models [19]:

Model of Sugeno : This model can be easily used especially to approximate nonlinear dependences. Working with them is comfortable, especially when we know the rules which also imply that we have done the state space decomposition for the number of cells characterized by fuzzy selected fuzzy sets.

Model of Mamdani

The default system has one input and one output and uses the Mamdani inference and an aggregation method. This editor also illustrates the three aspects of a fuzzy controller; fuzzification, inference, and defuzzification. To begin, let us define the membership functions.

The Membership Function Editor

The Membership Function Editor is the tool that lets you display and edit all of the membership functions associated with all of the input and output variables for the entire fuzzy inference system. The Membership Function Editor shares some features with the FIS Editor, as shown in the next figure.

In the graph of membership functions (Membership function plot) are displayed the membership functions with variables. We can work with these functions using the mouse to choose some membership function associated with a given value of the variable and move it as necessary in the chart from page to page.

This will affect the mathematical description of the variable values associated with a given membership function.

If-Then Rules

Fuzzy sets and fuzzy operators are the subjects and verbs of fuzzy logic. But in order to say anything useful we need to make complete sentences. Conditional statements, if-then rules, are the things that make fuzzy logic useful. A single fuzzy if-then rule assumes the form

if x is A then y is B

A and B are linguistic values defined by fuzzy sets on the ranges (universes of discourse) X and Y, respectively. The if-part of the rule "x is A" is called the *antecedent* or premise, while the then-part of the rule "y is B" is called the *consequent* or conclusion.

Insertion rules are very simple and intuitive. In the windows of input and output are contained names of linguistic values.

It is sufficient only click on a linguistic value of input and output and then using the buttons "Add rule" . The rule we have done.

We can also choose the kind of logical conjunction in the rule is (and, or - made by radio-button), the weight of rules (this value is always displayed at the end of the rule in parentheses - standard on setting the value one) or the negation of input or output in the rule.
Rules may be changed, deleted or even added the option using the button.

Rule Viewer Editor
This editor is used to graphically display the rules and for calculating the output parameters. Basically it is the full path to the fuzzy output process.
The individual lines represent the exact sequence of rules as they were defined in the "Rule Editor". Inserting the input parameters for calculation can be done again in two ways.
We can do it either in the editing line entitled "Input" or a graph. This is done by clicking the mouse on the vertical line that we move the mouse to set the desired level.
Then there is the calculation of the output variable and the graphical representation of the input values of input variables.
The red line on the left shows us input characterizing the resulting crisp value. Her motion we find that membership functions overlap and how will change output.

Surface Viewer Editor
It is designed for plotting 3D graph, where the axis "x" and "y" form the inputs and "z" axis is assigned an output variable.
It is very useful in case two or more inputs, which can get very mixed three-dimensional view of data, because we can influence which the input will answer to which axis (this is done using the pop-up menu).

5.2 Fuzzy Logic Toolbox and evaluate quality of manufacturing process

Based on the above possibilities of utilization Matlab, respectively the Fuzzy Logic toolbox we give possible approach of creating a system which based on fuzzy principles provide the user the final evaluation of the quality of the production process, if it knows some mentioned indices.
These indices are given for the so-called process control charts and are thus available. Knowing the impact of the various indices on the final quality is an important issue when deciding to vary, respectively maintaining the profile of the manufacturing process. These efforts are mainly based on target to meet customer requirements for overall quality.

5.3 Membership functions of capability indices

When you open FIS editor and the subsequent addition of other inputs (three inputs will be the number of indices) have been implemented membership functions based on the previous analysis in section 3.2. Individual graphs and linguistic marking of individual indexes are shown in the following figures.

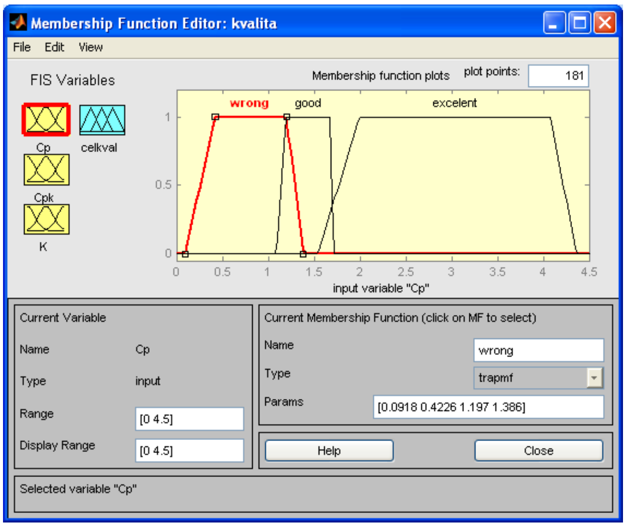

Fig. 9 Membership function for Cp

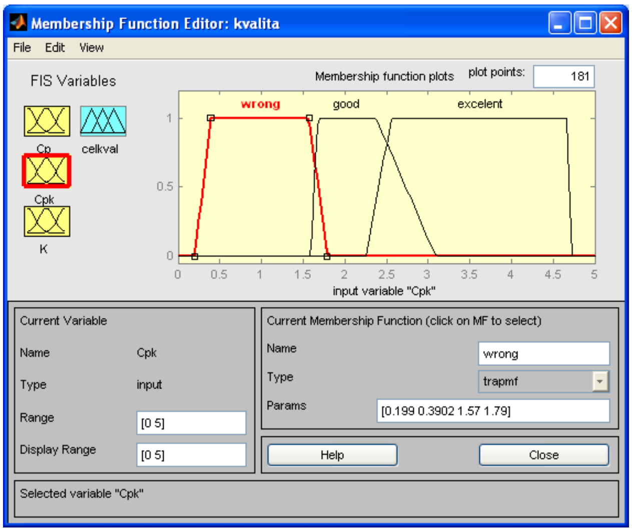

Fig. 10 Membership function for Cpk

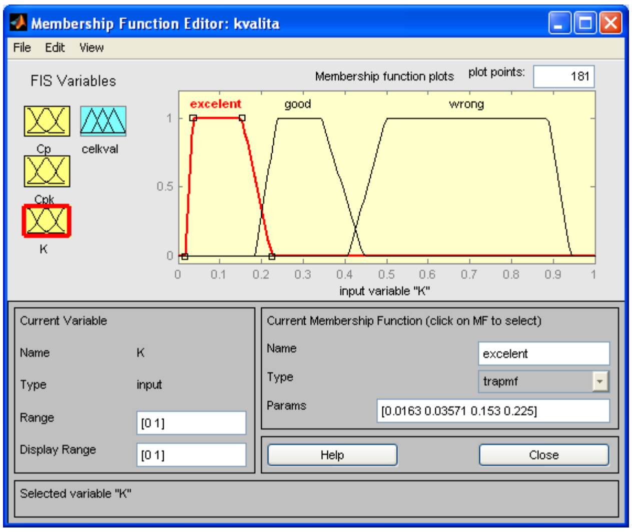

Fig. 11 Membership function for K

In order to assess the overall quality of the production process, for it has been proposed membership functions already mentioned in section 3.2. Next picture interprets the membership function for output - the overall quality.

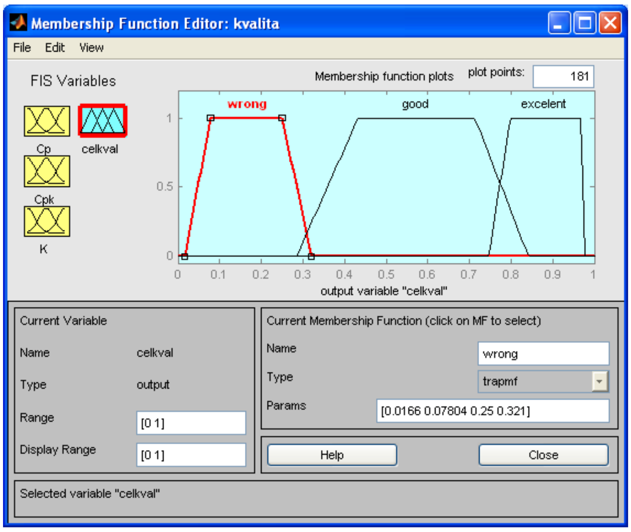

Fig. 12 Membership function for overall quality

Interaction of considered indices to the overall quality of the process represents an inference rules that were created in an Editor-in Rule. These rules were also intended the weight to differentiate the importance of their influence on the final quality of the production process. The creation of these rules in setting of Rule Editor are shown in Fig. 18.

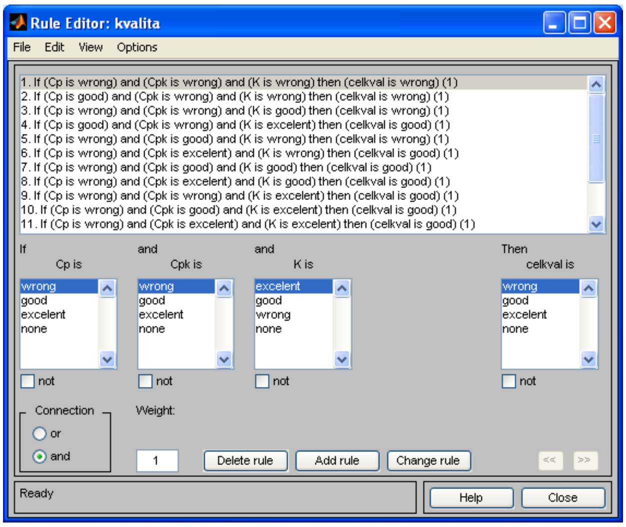

Fig 13 Creating rules of quality evaluation

Using the possibility of View → Rules we get the opportunity of graphic input and output. In this section, you can either enter directly the value of coefficients (the line labeled Input), or dragging the indicator (red vertical line) adjust the input variables. Visualization takes place now and we can see the overall result.

6 Creation of model

Nowadays we can find a lot of software programs which support statistical process control. They have a comfortable user setting with necessary tools and we can gain the results in a very short time. One of them is the software of FBE firm called SPC XL 2007. FBE - For Business Excellence is a reliable partner adapting vast experience of the world´s leading companies to specific conditions of the domestic markets. The software is based on spreadsheet MS Excel. The values are entered directly into spreadsheet. This format is also suitable for importing the data into Matlab setting by using its command xlsread (' filename '). The next picture presents a graphical interpretation the values of production process.

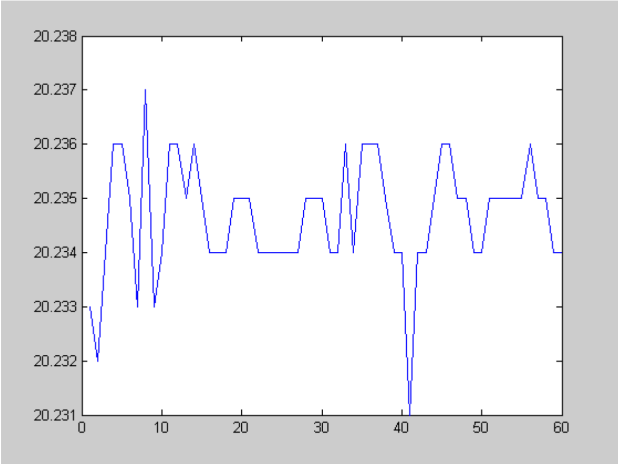

Fig 14 Values of production process

By loading the data into a workspace, respectively into a variable, we can direct calculate of individual characteristics according to the formulas (3), (4) and (5). These results will be entered into the proposed fuzzy regulator. We want to reach the automated transmission of data to the workspace of Matlab, so we create the code using M-file. For the calculation of the necessary characteristics we have to request from the user specifying Upper specification limit and Lower specification limit. These are known from the production documentation. The following figure shows the simulation scheme, established by the different blocks of Simulink.

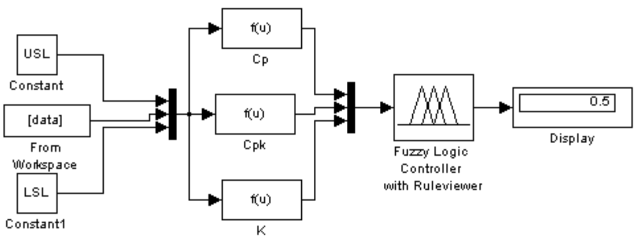

Fig 15 Scheme using Simulink

To calculate the values of individual characteristics, was used a block of User-Defined Functions and built-in mathematical functions of Matlab. As output block was chosen block Display to show the numeric value of the final quality of production process. Using a block of Simulink Fuzzy Logic Controller with Ruleviewer we can evaluate a final production process.. The next figure shows the result of simulation due Rule Viewer.

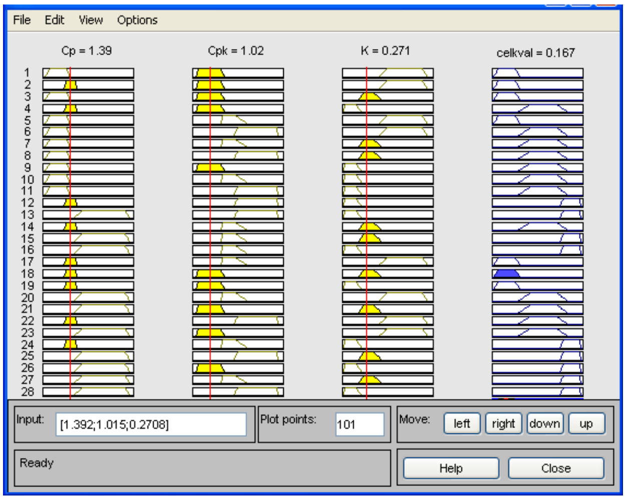

Fig 16 Creating rules of quality evaluation

Analysis of the individual characteristics of the input to the overall evaluation of manufacturing process it is obvious that the biggest change in this evaluation is caused by the coefficient *K*. It is given by the fact that in this contribution it is considered the required value of the centre of limits.. .

Using the resulting Rule viewer window, we can see the change of the coefficient K is reflected in the final quality. The best value of this coefficient is between 0 and 0.3, which gives the presumption of accuracy settings of the production process. Possible financial losses of non-compliance of this center are briefly described in Chapter 2 and the mathematical evaluation is represented by the equation (1). One of the strategies how to improve the process is to ensure the smallest deviations from the required value, i.e. from the center of the tolerance limits.

The value of the coefficient K indicates the distribution of tolerance limits as well. Thus it is this value closer to zero, the values are closer to the center of the tolerance field. Thus the value of the coefficient K can indirectly hint the possible financial losses.

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7 Conclusion

In this contribution are presented approaches using fuzzy logic principles to the field of quality assessment of production processes. Basic concepts were explained in various areas relating to the issues selected as tools for the implementation of fuzzy logic.

The aim of such an approach is to highlight the possibility of creating an expert system that would fulfill the role of intelligent advisor for the issue based on composed knowledge base and implement the knowledge of experts in this field. Knowledge and awareness of the importance of such an assessment of the manufacturing process gives companies a competitive edge in attracting and keeping the production of its plan. Since the proposed procedures allow the archiving of data as well, they can be used for long-term monitoring compliance with quality manufacturing process.

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