Fuzzy Assessment of Manufacturability Design for Machining

Abstract
The article attempts to assess the manufacturability design taking into account the assessment due to the processing, assembly process and organization of production. The evaluation was conducted by the fuzzy inference methods. An assessment was presented for machining based on the proposed fuzzy inference database.

1. INTRODUCTION TO APPLICATION METHODS FOR FUZZY SETS

Knowledge representation in the fuzzy rule-based system is enhanced by the use of linguistic variables and the language of their values, which are defined by context-dependent fuzzy sets, which determine the importance of a gradual membership function (Zadeh, 1965). On the other hand, fuzzy set inference methods, such as generalized Modus Ponens, generalized Modus Tollens, etc., form the basis for approximate inference (Zadeh, 1975). Therefore, fuzzy logic provides a unique framework for inference computational systems based on rules. This idea suggests the presence of two clearly different concepts in the inference methods of fuzzy sets: knowledge and reasoning. This clear separation of knowledge and reasoning (knowledge base) and processing structure is a key aspect of knowledge-based systems, so from this point of view fuzzy set inference methods can be considered a kind of knowledge-based system. The methods of inference of fuzzy sets in which two input variables (\(x_1\) and \(x_2\)) and a single output variable (\(s\)) are involved, for example, sets of terms are related as follows: \{small, medium, large\}, \{short, medium, long\} and \{bad, medium, good\}. 
The following base rule consists of five linguistic rules:

- R1W IF X1 is small and X2 is short, THEN Y is bad,
- R2W IF X1 is small and X2 is medium, then Y is bad,
- R3W IF X1 is medium and X2 is short, THEN Y is medium,
- R4W IF X1 is large and X2 is medium, THEN Y is medium,
- R5W IF X1 is large and X2 is long and Y is good.

The above method of inference can be represented by the decision table shown in Table 1.

| x2    | x1      |
|-------|---------|
| short | small   |
| medium| bad     |
| long  | good    |

The Mamdani method (Fernández & Herrera, 2012) processing structure of fuzzy set inference consists of the following five elements – Fig. 1:

- Input scaling that transforms parameter values – enter variables from its domain to the one in which the input fuzzy partitions are defined,
- A fuzzy interface that transforms explicit input into fuzzy values that serve as input to the fuzzy inference process,
- An inference engine that extracts data from blurry input data into several resulting fuzzy sets according to the information stored in the knowledge base,
Defuzzification interface that converts fuzzy sets received from the inference process into a clear value,

- Output scaling that converts defragmented value from the output domain of fuzzy areas to output variables, creating a global result of the fuzzy set inference method.

**Defuzzification** (sharpening) is an action to provide the predicted value of a parameter. The center of gravity method consists in determining the value of \( y^* \), which is the center of gravity of the area under the curve \( \mu_{\text{wyn}}(y) \).

\[
y^* = \frac{\int y \cdot \mu_{\text{wyn}}(y)dy}{\int \mu_{\text{wyn}}(y)dy}
\]

The project reference model is of the type: multiple entries – multiple outputs (multiple input-multiple output MIMO).

## 2. FUZZY ASSESSMENT OF MANUFACTURABILITY

### 2.1. General description of the variables

A set of linguistic variables \( V_i = \{V_1, ..., V_n\} \), and \( \in N - \{0\} \) is given, defining input and output criteria of technology. The linguistic variable \( V_i \) is described by the quadrangle \([L_i, T_i(L_i), \Omega_i, M_i]\) where:

- \( L_i = \{L_{i1}, ..., L_{in}\} \), and \( \in N - \{0\} \) is a set of linguistic variable names,
- \( T_i(L_i) = \{T_{i1}(L_{i1}), ..., T_{im}(L_{in})\} \), and \( \in N - \{0\} \) is a set of countable determinations of linguistic variables,
- \( t_{ij} = \{t_{i1}, t_{i2}, ..., t_{im}\}, i, j \in N - \{0\}, t_{ij} \in T_i(L_i) \) is a set of linguistic values of linguistic variables,
- \( \Omega_i = \{\Omega_{i1}, ..., \Omega_{in}\}, i \in N - \{0\} \) is a set of linguistic ranges of \( V_i \) variables,
- \( M_i = \{M_{i1}, ..., M_{in}\}, i \in N - \{0\} \) is a set of semantic rules,
- \( m_{ij} = \{m_{i1}, m_{i2}, ..., m_{im}\}, i, j \in N - \{0\}, m_{ij} \in M_i \) is a range of variation of the linguistic value \( t_{ij} \) with an assessment of belonging from 0 to 1.

### 2.2. Procedure – list of variables

The fuzzy method course of action results from project management schemes adopted according to PMI – according to AIAG (Kuo, Huang & Zhang, 2001). Assessment of machining processability and subsequent assembly process assessment, correspond to the prototyping phase during product design and development (Lalaoui & El Afia, 2018), and the assessment of the production organization technology corresponds to the pilot series and preserver phase during validation and then serial production (Favi, Germani & Mandolini, 2016).
In terms of manufacturability processing variables being indicators evaluating product design for the future feasibility of the machining technology (Deka & Behdad, 2019) and compliance with selected requirements – Fig. 2:

- $V_1$ – Technological Capabilities of the Machine Park/Accuracy,
- $V_2$ – CAD/CAM Software Capability,
- $V_3$ – Machining Capabilities of Available Tools,
- $V_4$ – Material meeting the project requirements,
- $V_5$ – Energy Consumption,
- $V_6$ – Waste Environmental Aspects.

![Fig. 2. Procedure – list of variables](image)

In terms of manufacturability assembly (Matuszek & Seneta, 2017) variables being indicators evaluating product design for the feasibility of installation in accordance with the principles assemblability and shortest installation time:

- $V_1$ – Access,
- $V_2$ – Maneuverability,
- $V_3$ – Orientation,
- $V_4$ – Maneuverability,
- $V_5$ – Assemblability,
- $V_6$ – Processes.

In terms of manufacturability organization of production variables being indicators evaluating product design in terms of organizational and technical capabilities, quality and maintenance (Matuszek, Seneta & Moczała, 2018):

- $V_1$ – Disassembly,
- $V_2$ – Reuse,
- $V_3$ – Standardization of components,
- $V_4$ – Target cost,
- $V_5$ – Mounting quality,
- $V_6$ – Number of special elements in maintenance.

Sets of $V_i$ variables can be modified and changed depending on the nature of the target process for which we design the product. This gives the fuzzy method a significant advantage in terms of flexibility. In the example presented, the set of variables $V_i$ was prepared for medium-sized plant and small-lot production.
3. EVALUATION OF MACHINING MANUFACTURABILITY

3.1. The manufacturability evaluation processing procedure

An example of the assessment of machinability of processing consists of three sub-stages of analysis for which linguistic variables are described in Table 2:

Tab. 2. Sub-stages of machining efficiency evaluation - linguistic variables Sub-step 1

| $V_i$ | $L_i$ | $T_i(L_i)$ | $t_{ij}$ | $\Omega_i$ | $M_i$ |
|-------|-------|------------|----------|------------|-------|
| $V_1$ | Technological Capabilities of the Machine Park/Accuracy | $T_1(L_1)$ | $t_{11}$ – unfulfilled<br>$t_{12}$ – deviates significantly<br>$t_{13}$ – deviates slightly<br>$t_{14}$ – fully meets | [0–4] | $M_1$ |
| $V_2$ | CAD/CAM Software Capability | $T_2(L_2)$ | $t_{21}$ – unfulfilled<br>$t_{22}$ – deviates significantly<br>$t_{23}$ – deviates slightly<br>$t_{24}$ – fully meets | [0–4] | $M_2$ |

Substage 2

| $V_3$ | Machining Capabilities of Available Tools | $T_3(L_3)$ | $t_{31}$ – unfulfilled<br>$t_{32}$ – deviates significantly<br>$t_{33}$ – deviates slightly<br>$t_{34}$ – fully meets | [0–4] | $M_3$ |
| $V_4$ | Material meeting the project requirements | $T_4(L_4)$ | $t_{41}$ – unfulfilled<br>$t_{42}$ – deviates significantly<br>$t_{43}$ – deviates slightly<br>$t_{44}$ – fully meets | [0–4] | $M_4$ |

Substage 3

| $V_5$ | Energy consumption | $T_5(L_5)$ | $t_{51}$ – unfulfilled<br>$t_{52}$ – deviates significantly<br>$t_{53}$ – deviates slightly<br>$t_{54}$ – fully meets | [0–10] | $M_5$ |
| $V_6$ | Waste Environmental Aspects | $T_6(L_6)$ | $t_{61}$ – unfulfilled<br>$t_{62}$ – deviates significantly<br>$t_{63}$ – deviates slightly<br>$t_{64}$ – fully meets | [0–10] | $M_6$ |
3.2. Machining Manyfacturability Assessment – sub-step 1

The processability of the workpiece (sample housing) is determined, assuming that it depends on two factors, which are:
- Technological Capabilities of the Machine Park/Accuracy,
- CAD/CAM Software Capability.

Tab. 3. Fuzzification of input variables

| Technological Possibilities Of The Machine Park/Accuracy | Rating |
|----------------------------------------------------------|--------|
| Fully fall within the capabilities of machines/accuracy  | 100    |
| It deviates slightly from the machine’s capabilities/accuracy | 60    |
| It deviates from the machine capabilities/accuracy significantly | 30    |
| Machine capabilities/accuracy not met completely         | 0      |

| CAD/CAM SOFTWARE CAPABILITY | Rating |
|----------------------------|--------|
| CAD/CAM capabilities not met | 0      |
| It deviates significantly from the CAD/CAM               | 30     |
| It deviates slightly from the CAD/CAM                    | 60     |
| Fully fits CAD/CAM capabilities                           | 100    |

Tab. 4. Fuzzy relations for the variable TECHNOLOGICAL POSSIBILITIES

| TECHNOLOGICAL POSSIBILITIES | Unfulfilled | It deviates significantly | It deviates slightly | Fully meets |
|-----------------------------|-------------|---------------------------|----------------------|-------------|
| 0                           | 1           | 0                         | 0                    | 0           |
| 30                          | 0           | 1                         | 0                    | 0           |
| 60                          | 0           | 0                         | 1                    | 0           |
| 100                         | 0           | 0                         | 0                    | 1           |

Fig. 3. Membership function graph for TECHNOLOGICAL POSSIBILITIES
The membership function for Technological Capabilities is described by the formulas:

\[
\mu_{\text{UNFULFILLED}}(x) = \begin{cases} 
\frac{30 - x}{30} & \text{for } 0 < x < 30 \\
0 & \text{for } 30 \leq x \leq 100 
\end{cases}
\]

\[
\mu_{\text{DEVIATES SIGNIFICANTLY}}(x) = \begin{cases} 
\frac{x}{30 - 0} & \text{for } 0 < x < 30 \\
\frac{60 - x}{60 - 30} & \text{for } 30 < x < 60 \\
0 & \text{for } 60 \leq x \leq 100 
\end{cases}
\]

\[
\mu_{\text{DEVIATES SLIGHTLY}}(x) = \begin{cases} 
0 & \text{for } x \leq 30 \\
\frac{x - 30}{60 - 30} & \text{for } 30 < x < 60 \\
\frac{100 - x}{100 - 60} & \text{for } 60 < x < 100 
\end{cases}
\]

\[
\mu_{\text{FULLY MEETS}}(x) = \begin{cases} 
0 & \text{for } x \leq 60 \\
\frac{x - 60}{100 - 60} & \text{for } 60 < x < 100 
\end{cases}
\]

Table 5. Fuzzy relations for the variable SOFTWARE CAPABILITY

| SOFTWARE CAPABILITY | Unfulfilled | It deviates significantly | It deviates slightly | Fully meets |
|---------------------|-------------|---------------------------|----------------------|-------------|
| 0                   | 1           | 0                         | 0                    | 0           |
| 30                  | 0           | 1                         | 0                    | 0           |
| 60                  | 0           | 0                         | 1                    | 0           |
| 100                 | 0           | 0                         | 0                    | 1           |

Fig. 4. Membership function graph for SOFTWARE CAPABILITY
The membership function for Software Capability is described by the formulas:

$$\mu_{UNFULFILLED}(x) = \begin{cases} 
\frac{30 - x}{30 - 0} & \text{for } 0 < x < 30 \\
0 & \text{for } 30 \leq x \leq 100 
\end{cases}$$

$$\mu_{DEVIADES SIGNIFICANTLY}(x) = \begin{cases} 
\frac{x}{30 - 0} & \text{for } 0 < x < 30 \\
\frac{60 - x}{60 - 30} & \text{for } 30 < x < 60 \\
0 & \text{for } 60 \leq x \leq 100 
\end{cases}$$

$$\mu_{DEVIADES SLIGHTLY}(x) = \begin{cases} 
0 & \text{for } x \leq 30 \\
\frac{x - 30}{60 - 30} & \text{for } 30 < x < 60 \\
\frac{100 - x}{100 - 60} & \text{for } 60 < x < 100 
\end{cases}$$

$$\mu_{FULLY MEETS}(x) = \begin{cases} 
0 & \text{for } x \leq 60 \\
\frac{x - 60}{100 - 60} & \text{for } 60 < x < 100 
\end{cases}$$

The course of fuzzification with the Mamdani rule, the basis of inference rules (tab. 6) was carried out for the selected workpiece according to expert assessments:

- Technological capabilities = 20,
- Software capability = 55,
- Rule 10 Technological capabilities – Deviates significantly and Software capability – Deviates significantly in min (0.67, 0.17) = 0.17,
- Rule 11 Technological possibilities – Deviates significantly and Software capability – Deviates slightly to a degree of min (0.67, 0.83) = 0.67,
- Rule 14 Technological possibilities Unfulfilled and also Software capability – Deviates significantly to a degree of min (0.33, 0.17) = 0.17,
- Rule 15 Technological possibilities Unfulfilled and Software capability – Deviates slightly to a degree of min (0.33, 0.83) = 0.33,
- **Inference processing for manufacturability – substep 1.**

From rules 10, 11, 14 and 15 – MAX, so we activate the rules: 11. Technology 1 takes the value for Technology Capabilities 20 and Software Capability 55.
Tab. 6. Base rules of inference manufacturability evaluation processing – Substage 1

|   | IF | TECHNOLOGICAL POSSIBILITIES | AND | SOFTWARE CAPABILITY | THAN | MANUFACTURABILITY |
|---|----|-----------------------------|-----|---------------------|------|-------------------|
| 1 |   | FULLY MEETS                 |     | UNFULFILLED         |      | MEDIUM            |
| 2 | IF | TECHNOLOGICAL POSSIBILITIES |     | SOFTWARE CAPABILITY |      | MEDIUM HIGH       |
|   |   | FULLY MEETS                 |     | DEVIATES SIGNIFICANTLY |    |                   |
| 3 | IF | TECHNOLOGICAL POSSIBILITIES |     | SOFTWARE CAPABILITY |      | MEDIUM            |
|   |   | FULLY MEETS                 |     | DEVIATES SLIGHTLY   |      |                   |
| 4 | IF | TECHNOLOGICAL POSSIBILITIES |     | SOFTWARE CAPABILITY FULLY MEETS | | MEDIUM HIGH |
|   |   | DEVIATES SLIGHTLY           |     | DEVIATES SIGNIFICANTLY |    |                   |
| 5 | IF | TECHNOLOGICAL POSSIBILITIES |     | SOFTWARE CAPABILITY  |      | MEDIUM LOW        |
|   |   | FULLY MEETS                 |     | UNFULFILLED         |      |                   |
| 6 | IF | TECHNOLOGICAL POSSIBILITIES |     | SOFTWARE CAPABILITY |      | MEDIUM            |
|   |   | DEVIATES SLIGHTLY           |     | DEVIATES SIGNIFICANTLY |    |                   |
| 7 | IF | TECHNOLOGICAL POSSIBILITIES |     | SOFTWARE CAPABILITY FULLY MEETS | | MEDIUM HIGH |
|   |   | DEVIATES SLIGHTLY           |     | DEVIATES SLIGHTLY   |      |                   |
| 8 | IF | TECHNOLOGICAL POSSIBILITIES |     | SOFTWARE CAPABILITY FULLY MEETS | | MEDIUM HIGH |
|   |   | DEVIATES SLIGHTLY           |     | DEVIATES SIGNIFICANTLY |    |                   |
| 9 | IF | TECHNOLOGICAL POSSIBILITIES |     | SOFTWARE CAPABILITY  |      | MEDIUM LOW        |
|   |   | DEVIATES SIGNIFICANTLY      |     | UNFULFILLED         |      |                   |
| 10| IF | TECHNOLOGICAL POSSIBILITIES|     | SOFTWARE CAPABILITY  |      | MEDIUM LOW        |
|   |   | DEVIATES SIGNIFICANTLY      |     | DEVIATES SIGNIFICANTLY |    |                   |
| 11| IF | TECHNOLOGICAL POSSIBILITIES|     | SOFTWARE CAPABILITY |      | MEDIUM LOW        |
|   |   | DEVIATES SIGNIFICANTLY      |     | DEVIATES SLIGHTLY   |      |                   |
| 12| IF | TECHNOLOGICAL POSSIBILITIES|     | SOFTWARE CAPABILITY FULLY MEETS | | MEDIUM          |
|   |   | DEVIATES SIGNIFICANTLY      |     | DEVIATES SIGNIFICANTLY |    |                   |
| 13| IF | TECHNOLOGICAL POSSIBILITIES|     | SOFTWARE CAPABILITY  |      | MEDIUM LOW        |
|   |   | UNFULFILLED                 |     | UNFULFILLED         |      |                   |
| 14| IF | TECHNOLOGICAL POSSIBILITIES|     | SOFTWARE CAPABILITY  |      | MEDIUM LOW        |
|   |   | UNFULFILLED                 |     | DEVIATES SIGNIFICANTLY |    |                   |
| 15| IF | TECHNOLOGICAL POSSIBILITIES|     | SOFTWARE CAPABILITY  |      | MEDIUM LOW        |
|   |   | UNFULFILLED                 |     | DEVIATES SLIGHTLY   |      |                   |
| 16| IF | TECHNOLOGICAL POSSIBILITIES|     | SOFTWARE CAPABILITY FULLY MEETS | | MEDIUM          |
|   |   | UNFULFILLED                 |     | DEVIATES SIGNIFICANTLY |    |                   |
For technology – the low average (range <0; 60>) takes the value of min (0.67; technology – medium) – the value lower 0.67 or the value of the function technology – medium – low (Fig. 5).

Therefore, after the defuzzification process, the assessment is:

\[
\begin{align*}
\{ y = \frac{x}{20} & \quad 0.67 = \frac{x}{20} & x = 20 \cdot 0.67 = 13.4 \\
y = \frac{60-x}{60-40} & \quad 0.67 = \frac{60-x}{20} & 60 - x = 20 \cdot 0.67 & \quad 60 - x = 13.4 & x = 46.6
\end{align*}
\]

\[
r = \frac{\int_{0}^{80} y \cdot \mu_{B}(y)\,dy}{\int_{0}^{80} \mu_{B}(y)\,dy}
\]

\[
r = \frac{\int_{0}^{13.4} y \cdot \frac{y^2}{20} \, dy + \int_{13.4}^{46.6} y \cdot 0.67 \, dy + \int_{46.6}^{60} y \cdot \frac{60 - y}{20} \, dy}{\int_{0}^{60} \mu_{B}(y)\,dy}
\]

\[
\int_{0}^{60} \mu_{B}(y)\,dy = P_1 \quad P_1 = \frac{(60 + 33.2) \cdot 0.67}{2} = 31.2
\]

\[
r = \frac{\frac{y^3}{60} + \frac{y^2}{3} + \frac{1}{20} \cdot \left(30y^2 - \frac{y^3}{3}\right)}{30.1} = 40.1 + 664 + 229.24 = 933.34
\]

\[
r = \frac{933.34}{31.2} = 29.91
\]

The value of the sample assessment of Machining Manufacturability Sub-step 1 is 29.9.
3. CONCLUSIONS

Attempt to assess manufacturability assessment takes into account the structure due to the machining, assembly process and organization of production. The assessment was carried out according to the fuzzy set inference methods. The manufacturability evaluation procedure is proposed in the steps, which start their ratings linguistic variables divided into sub-steps. An example of the evaluation due to machining on the basis of the proposed base of fuzzy inference can be extended for the assembly process steps and organization of production.

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