Assessment of the Design for Assembly processes using fuzzy logic

Józef Matuszek1*, Tomasz Seneta1 and Aleksander Moczała1

1 University of Bielsko-Biała, Faculty of Mechanical Engineering And Computer Science, Willowa 2, 43-309 Bielsko-Biała, Poland, jmatuszek@ath.bielsko.pl, tomasz.seneta@zf.com, amoczala@ath.bielsko.pl; e-mail@e-mail.com

* Correspondence: jmatuszek@ath.bielsko.pl; Tel.: +48-338279253

Featured Application: new method for assessing design for manufacturability based on fuzzy variables.

Abstract: The paper presents methodology for designing the production process of a new product from the point of view of the assembly operations technology criterion (Design for Assembly - DFA) in the conditions of high-volume production. Mentioned are DFA methods and techniques used in the implementation of a new product. Author presents a new method for assessing design for manufacturability based on fuzzy variables based on fuzzy variables. An example was given to illustrate the proposed course of action

Keywords: production process design, design for manufacturability, fuzzy logic.

1. Introduction

In today’s market conditions, the company introducing new products to the production, use different methods and techniques to rationalize actions that make up the concept of pre-production. The issue has a rich literature, different philosophies are presented there to rationalize the production process sequences, for example. Six Sigma, Lean, WCM, Target Costing [1,15,23].

In the conditions of high production volume, when implement new products, less attention is due to the ever-wider technological possibilities of contemporary workplaces, workshop aids, automation, the high performance achieved and relatively low costs, devoted to the processing of elements, components of final products. Hence reported in literature advanced evaluation methods of products design manufacturability tailored to evaluate the implementation of a new product in the conditions of high volume mass production and are directed to processes for assembly. This is due to the high proportion of manual work compared to machining, which is associated with high labour intensity and high costs of assembly processes.

In the production of individual and small-batch main attention is paid to the issue of the possibility to implement in the plant, the possibility of cooperative companies, as well as the determinants of the logistic flow of resources. Therefore, much attention is paid to the performance of the production cost target, taking into account investments in new production lines and positions, defined in terms of having to be carried out also other products and vision of the future production program[7,9,17].

2. Production preparation process

In the automotive industry, proposals for the use of design-oriented assessment methods for assembly. "Design for Assembly" - DFA, was described by G. Boothroyd and P. Dewhurst in the work "Design for Assembly, A Designers Handbook" in 1983. The concept of "Design for Assembly" can be defined in various ways, from the narrow meaning of "product design from the point of view of manufacturability criterion" to the broader term associated with "product and process design from the cost-effective criterion point of view and reliable manufacturing to ensure the state of customer
Many DFA methods are presented in the literature. The chronology of these methods and their brief characteristics are presented in Table 1 [16].

| Nr | Metoda                                      | Rok  | Odkrywcy                      | Opis                                                                 |
|----|--------------------------------------------|------|-------------------------------|----------------------------------------------------------------------|
| 1. | Lucas DFA                                 | 1980 | Redford A. H., Swift K. G.    | It is based on the assembly sequence diagram (SSM) that assess the assembly design. Producibility is estimated based on penalty points associated with the product installation problems. |
| 2. | Hitachi Assemblability Evaluation Method (AEM) | 1986 | Miyagawa S., Ohashi T.        | The method assesses the product's assemblability and the cost index to indicate project weaknesses. |
| 3. | Product Assemblability Merit Analysis Tool (PDM) | 1986 | Zorowski C. F.                | The method gives opinions on product and component assembly problems and oversize indicators in the project. |
| 4. | Boothroyd and Dewhurst                     | 1988 | Boothroyd G., Dewhurst P.     | The method is based on determining the costs associated with the manual or automatic assembly process and has three criteria to limit the number of components. |
| 5. | Integrated Design for Assembly Evaluation and Reasoning System | 1991 | Sturges R. H. Jr, Kilani M. I. | The method built based on solid modelling, explores the possibility of product assemblability. |
| 6. | Fuzzy Product Assemblability Merit Analysis Tool | 1993 | Jackson S. D., Sutton J. C., Zorowski C. F. | PDM developed with fuzzy logic. |
| 7. | DFA REV-ENGE                               | 1994 | Kim G. J., Bekey G. A.        | DFA method taking into account reverse engineering.                  |
| 8. | Constraints Network System                 | 1995 | Oh J. S., Grady P. O., Young R. D. F. | Method of interrelated constraints.                                  |
| 9. | Virtual Disassembly Evaluation             | 1998 | Srinivasan H.                 | Method taking into account virtual disassembly.                      |

The first and the second method are presented in the paper, due to the largest application in practice. Market conditions have forced companies to rationalize a comprehensive approach to the design and marketing of a new product [2,4,5,23]. The need for a broader look at the assessment of the technology of the structure, including this problem, take into account many other aspects, this way of design is illustrated in Fig. 1.
In the design process under the aforementioned philosophies have been used methods such as QFD (Quality Function Deployment) [1,10,13] use in processes of implement products customer requirements, FMEA (Failure Mode and Effect Analysis) [19] - related to the prediction and prevention of problems at the product design stage, DFX (Design for X) [23] - e.g. Design for Manufacturing (DFM) regarding the shaping of the design process of components and the product itself [6]. Decisions taken at the product design stage have a significant impact on production costs, efficiency and quality of production. Supporting methods such as modelling, simulation and animation of production processes and systems as well as stimulating innovation such as brainstorming, TRIZ is of great importance in carrying out these works.

3. Methods of assembly manufacturability assessment

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

3.1. Lucas DFA method

The method was developed in 1980 by Lucas and University of Hull research teams. The method is used for manual or automatic assembly analysis. The method includes aims to reduce the number of components of the final product, the use of shape the structure of components to facilitate assembly. In the Lucas DFA method, three indicators determine the measure of mounting difficulty.[21] The procedure is as follows. The prepared project is subjected to functional analysis, which determines whether individual components are needed and what their functions are - fig. 2.
A feasibility analysis is then made up consisting of manoeuvring analysis and assembly analysis. Data for analysis can be read for specific installation conditions from the tables. Formulas that describe the results of the analysis in the LUCAS DFA method are:

The project efficiency index based on functional analysis is determined by the formula

\[
W_{ep} = \frac{L_{KA}}{(L_{KA} + L_{KB})} \times 100\%
\]  

where: \(W_{ep}\) - project efficiency index, \(L_{KA}\) - number of A components (fulfill product functions), \(L_{KB}\) - number of B components (characterized by lack of fulfill product functions, e.g. rivets, washers).

Based on the analysis carried out in this way, it is possible to combine some separate components into one whole, thus reducing the number of individual components that make up the final product, change the design solutions that eliminate components that do not fulfill the function of the product. Then, an analysis is carried out consisting of an analysis of the displacement of the mounted components, their maneuvering and the method of assembly itself. [21] The maneuvering assessment of the assembled product components is determined on the basis of fig. 8.

The \(W_{man}\) maneuvering factor is given by the formula:

\[
W_{man} = \frac{I_{man}}{L_{KA}}
\]

\[
I_{man} = L_{pA} + L_{pB} + L_{pC} + L_{pD}
\]

where: \(W_{man}\) - maneuvering coefficient, \(I_{man}\) - maneuvering index, \(L_{pA}, L_{pB}, L_{pC}, L_{pD}\) - values read from tables related to the size and weight of parts, difficulty with maneuvering, assembly orientations.

The formula describing the results of the analysis of the \(W_{as}\) feasiblility factor according to the Lucas DFA method is:

\[
W_{as} = \frac{W_{m} + W_{ad}}{L_{KA}}
\]

\[
W_{m} = L_{mA} + L_{mB} + L_{mC} + L_{mD}
\]

\[
W_{ad} = L_{mE} + L_{mF} + S_{ec}
\]

where: \(W_{as}\) - assemblability coefficient, \(W_{m}\) - main activity indicator, \(L_{mA}, L_{mB}, L_{mC}, L_{mD}\) - values read from tables related to the insertion process, insertion direction and fold, access, \(W_{ad}\) - additional activities indicator, \(L_{mE}, L_{mF}, S_{ec}\) - values read from tables related to difficulty fit and resistance, additional activities [21].

3.2. The Boothroyd Dewhurst method

The method was developed in the late 1970s. by prof. Geoffrey Boothroyd at the University of Massachusetts in Amherst in cooperation with the University of Salford in UK. The method, like the previous one, aims to: reduce the number of components, eliminate rework, use self-positioning and self-embedding components, provide adequate access and unrestricted field of view, ensure ease of
assemble parts with looseness, minimizing the need for reorientation during assembly, eliminating parts, which cannot be installed incorrectly, maximizing symmetrical parts, if possible, or if not asymmetrical. The method assumes that the part is a permanent or non-permanent element of the assembly process. A subassembly is considered a part of it is added during assembly. Each part has two parameters - thickness and size (adhesives, fluxes, fillers, etc., used to connect parts are not considered parts) - Fig. 3. Thickness is the length of the shortest side of the smallest cuboid that surrounds the element. If the element has a cylindrical or regular polygonal shape, e.g. a section with five or more sides, the thickness is defined as the radius of the smallest cylinder that surrounds the element. The size is the length of the longest side of the smallest cuboid that can surround the part.

![Thickness and Size](image)

**Figure 3.** Determining the thickness and size of parts [5]

The next step is to assess the symmetry of the element and determine the number of degrees of rotation around both axes for proper orientation and alignment - Fig. 4 [5].

![Alpha and Beta Angles](image)

**Figure 4.** Determining alpha and beta angles [5]

BETA is the symmetry of the part relative to the insertion axis, i.e. the smallest rotation angle for correct insertion. ALFA is the symmetry of the part about the axis perpendicular to the insertion direction - the smallest angle between alternative insertion directions [5] (G. Boothroyd, 1983). After determining the thickness, size, BETA and ALFA angles, the method is shown in Fig. 5.

![Process Diagram](image)

**Figure 5.** Proceedings in the Boothroyd-Dewhurst for Assembly method

The indexes for handling time and insertion (assembly) time of individual elements are determined. A special table prepared by Boothroyd and Dewhurst serves this purpose. By specifying the time index of element manipulation, you can specify whether the manipulation can be performed: with one hand, one hand with an auxiliary handle, two hands, two hands with mechanical assistance. Knowing the assembly times, you can proceed to process analysis, e.g. whether the number of
assembled parts should be reduced, replace them other more complex. This method is used to analyze manual assembly, separate variants of the method are used to analyze automatic assembly. The final step is to calculate the sum of the number of operations, the total operation time, the total cost of the operation, the theoretical minimum number of parts and the DFMA index.

\[ L_0 = l_{o1} + l_{o2} + \ldots + l_{on} = \Sigma l_{oi} \]  
(5)

where: \( L_0 \) - number of operations, \( l_{oi} \) - assembly operation

\[ T_o = \Sigma t_{oi} = I_{ma} + I_{mo} \]  
(6)

where: \( T_o \) - the total operation time, \( t_{oi} \) - operation time, \( I_{ma} \) - time index manipulation operations, \( I_{mo} \) - time index assembly operations

\[ K_o = \Sigma k_{oi} = \Sigma l_{oi} \cdot k_{oi} \]  
(7)

where \( K_o \) -cost of the process; \( l_{oi} \) - an index (number) process operations; \( k_{oi} \) -average individual process treatment cost

\[ C_t = C_{pe} - C_{ae} \]  
(8)

where: \( C_t \) - the theoretical minimum number of elements; \( C_{pe} \) - number of elements before the elimination analysis; \( C_{ae} \) – the number of parts eliminated in the analysis of elimination

\[ \text{DFMA}_{\text{index}} = \left( \frac{l_o \cdot L_0}{T_o} \right) \]  
(9)

where: \( \text{DFMA}_{\text{index}} \) - DFMA index; \( A \) - the number of parts necessary for the functioning of the product for a large number of parts it can be assumed that: \( L_0 = A \) (the study assumes that \( L_0 = A = C_t \)); \( l_o \) - assembly time of basic ideal part (based on Boothoroyd \( t_o = 3s \)); \( T_o \) - the total assembly time of the product).

4. The project according to the new integrated DFA method based on fuzzy inference

4.1. Assumptions for the new DFA method

The justification for the emergence of a new fuzzy method for assessing the technology of the structure results from the observed lack of flexibility of the described methods of Boothroyd-Dewhurst and Lucas. These methods were created in the 1980s in the conditions of needs of the economy focused on serial and mass production. The current development of the economy and technology means that the modern economic system is characterized by a much greater need for flexibility in terms of production methods: high volume, low volume and unit. The need to create a more flexible method adaptable to the type of production is noticeable[3].

The design process should be determined from the point of view of various usability criteria - Fig. 6. The assessment should take into account many other various factors, sales, service, spare parts availability, production series, types of equipment, available assembly techniques, level of automation, cooperative services, possibilities of application commercial components, crew technical culture, etc. In small-lot and serial production conditions, the design process of new product production is based on simplified production documentation[9]. Due to the low production series, production data result from the project are rarely verified at the production stage, while the experience gained from this stage is used in the production projects of new products. In relation to mass production and mass production, particular attention from the point of view of cost criterion is paid to: the possibility to use unified and standardized elements included in the final product, the use of work stations and workshop aids for processing and assembly of various elements included in the products making up the program production and introduction of group machining processes, process phases, group operations for various elements [22]. The newly proposed method use fuzzy inference is characterized by such flexibility[11,20].
4.2. The course of the new DFA method

The product design analysis process is carried out by experts representing as experts: product design, machining process design, assembly process design, quality assurance, product cost analysis, OHS and environmental protection in accordance with Figures 7 and 8.

Figure 6. Modified design and development process for the production of a new product

Figure 7. Structural analysis of the structure's technology in the proposed method.
Experts determine to use method tables, e.g. Boothroyd or Lucas, in accordance with the order of the process for each component of the product design, make an assessment on a scale of 0 to 100. Then the process of the machining process and the assembly process are evaluated. The method was developed on the basis of the proposed General Scheme of Technology Assessment and consists of three stages: assessment of machining efficiency, assessment of assembly efficiency, assessment of production organization efficiency [14].

The assessment is related to the set of linguistic variables $V_i = \{V_1, ..., V_n\}$, and $i \in N - \{0\}$, defining the input and output criteria of technology. The linguistic variable $V_i$ is described by a quadrangle:

$$[L_i, T_i(L_i), \Omega_i, M_i]$$ (10)

where: $L_i = \{L_{i1}, ..., L_{in}\}$, $i \in N - \{0\}$ - set of linguistic variable names, $T_i(L_i) = \{T_i(L_{i1}), ..., T_i(L_{in})\}$, $i \in N - \{0\}$ - set of countable determinations of linguistic variables, $t_{ij} = \{t_{i1}, t_{i2}, ..., t_{im}\}$, $i, j \in N - \{0\}$ - set of linguistic values of linguistic variables, $\Omega_i = \{\Omega_1, ..., \Omega_n\}$, $i \in N - \{0\}$ - set of linguistic ranges of variables $V_i$, $M_i = \{M_1, ..., M_n\}$, $i \in N - \{0\}$ - set of semantic rules, $m_{ij} = \{m_{i1}, m_{i2}, ..., m_{im}\}$, $i, j \in N - \{0\}$, $m_{ij} \in M_i$ - range of variation in linguistic value $t_{ij}$ with an assessment of belonging from 0 to 1 [12].

The assessment of machining processability and subsequent assembly technology assessment correspond to the prototype stage during product design and development, and the assessment of production organization technology corresponds to the plot series and production series during validation and then serial production. The applied variables $V_1, V_2, V_3, V_4, V_5, V_6$ in the scope of machining technologies, assembly, production organization are shown in Fig. 8. The assessment, depends on the scope of information obtained, can be carried out for individual components of the product, groups of elements, its assemblies or also in a holistic way [12].

5. Example

5.1 Input assumptions
Based on the analyzes of the above methods of assessment the product’s producibility, an improved proprietary approach was proposed in the process of shaping the product’s productiveness. The illustration of the presented proposals is presented on the example of a single-stage gear in Fig 9. General purpose gearboxes are designed in the form of a series of types from the point of view of market demand, production costs and delivery time to the customer. The gearbox shown in Fig. 9 was designed in a traditional way (welded body, a large number of bolted joints, etc.).

![Figure 9. Diagram of the analyzed gearbox, 2- body, 5, 6, 7, 8- bearing caps, 10- shaft, 11-pinion, 12-tooth gear, 14- spacing rings, 17, 16- bearings, 18, 19, - seals, 21, 22, 23- keys, 25, 26-washers, screws.](image)

5.2 Fuzzy assessment of design for assembly technology

According to the order of evaluation (Fig. 7), experts assess the efficiency of the process for each stage of the process (on a scale of 0 to 100). To illustrate the course of the procedure, the assessment was carried out for sub-step 1 of the design for assembly efficiency assessment - Fig. 8. The remaining stages and assessments were used to compare the results of the proceedings. The example is presented for one group of elements mounted together - body and cover[8,20].

**Assessment of Design for Assembly Technology - sub-step 1**

The component’s technology, assuming that it depends on two factors, which are: access, assemblage has been set by experts for: "Access" = 20, "Number of workshop aids" = 55. The membership functions of linguistic variables for the given factors are given in Table 2 and 3, the bases of rules for them are presented in Table 4 and 5.

**Table 2. Membership functions in tabular form of linguistic variables for "Access"**

| DESCRIPTION - ACCESS                                      | Rate |
|-----------------------------------------------------------|------|
| The area is very difficult available, special care/tools/ techniques required to remove parts without damaging it | 0    |
| Limited surface/eyesight, extreme care required to take pictures without damage   | 30   |
The area has limited access, but some can be removed without damage 60
The area is easy to assemble, lots of hands/tools 100

Table 3. Membership functions in tabular form of linguistic variables for "Number of workshop aids"

| DESCRIPTION - NUMBER OF WORKSHOP AIDS | Rate |
|---------------------------------------|------|
| Unnecessary                           | 0    |
| Easy to grasp                         | 0    |
| Orientation tools in 1 axis           | 30   |
| Orientation tools in 2 axis           | 30   |
| Tools in both axes                    | 60   |
| Medium difficult tools                | 60   |
| Heavy nesting or tangling             | 60   |
| Requires a tool to capture            | 60   |
| Requires two people                   | 100  |
| Requires service equipment            | 100  |

Table 4. Rule base for "Access"

| ACCESS | Very hard | Limited | Moderately limited | Easy |
|--------|-----------|---------|--------------------|------|
| 0      | 1         | 0       | 0                  | 0    |
| 30     | 0         | 1       | 0                  | 0    |
| 60     | 0         | 0       | 1                  | 0    |
| 100    | 0         | 0       | 0                  | 1    |

Table 5. Rules database for "Number of workshop aids"

| NUMBER OF AIDS | Easy | Requires orientation | Heavy or tools | Two people or equipment |
|----------------|------|----------------------|----------------|-------------------------|
| 0              | 1    | 0                    | 0              | 0                       |
| 30             | 0    | 1                    | 0              | 0                       |
| 60             | 0    | 0                    | 1              | 0                       |
| 100            | 0    | 0                    | 0              | 1                       |

The "Access" factor is described by the formulas:

\[
\mu_{\text{VERY HARD}}(x) = \begin{cases} 
\frac{30-x}{30-0} & \text{dla } 0 < x < 30 \\
\frac{x}{30-0} & \text{dla } 30 \leq x \leq 100 \\
x = 0 & \text{dla } 60 \leq x \leq 100 
\end{cases}
\]  

\[ (11) \]

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

\[ (12) \]

\[
\mu_{\text{MODERATELY LIMITED}}(x) = \begin{cases} 
\frac{100-x}{100-60} & \text{dla } 0 < x \leq 30 \\
x = 0 & \text{dla } 60 \leq x < 100 \\
\frac{60-x}{60-30} & \text{dla } 30 < x < 60 \\
\frac{x}{60-30} & \text{dla } 60 \leq x \leq 100 
\end{cases}
\]  

\[ (13) \]

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

\[ (14) \]
Table 6. Fuzzy rules table for Design for Assembly Technology - sub-step 1.

|   | If                      | And                  | Then                    |
|---|-------------------------|----------------------|-------------------------|
| 1 | Easy access             | And                  | Numer of aids two people or equipment | DFA Technology 1 - medium-low |
| 2 | Easy access             | And                  | Heavy Numer of aids or tools | DFA Technology 1 - average |
| 3 | Easy access             | And                  | Maneuverability requires orientation | DFA Technology 1 - High |
| 4 | Easy access             | And                  | Easy Numer of aids      | DFA Technology 1 - High |
| 5 | Medium restricted access| And                  | Numer of aids two people or equipment | DFA Technology 1 - medium-low |
| 6 | Medium restricted access| And                  | Heavy Numer of aids or tools | DFA Technology 1 - medium-low |
| 7 | Medium restricted access| And                  | Maneuverability requires orientation | DFA Technology 1 - average |
| 8 | Medium restricted access| And                  | Easy Numer of aids      | DFA Technology 1 - average |
| 9 | Limited access          | And                  | Numer of aids two people or equipment | DFA Technology 1 - average |
|10 | Limited access          | And                  | Heavy Numer of aids or tools | DFA Technology 1 - medium-low |
|11 | Limited access          | And                  | Maneuverability requires orientation | DFA Technology 1 - average |
|12 | Limited access          | And                  | Easy Numer of aids      | DFA Technology 1 - average1 |
|13 | Access is very difficult| And                  | Numer of aids two people or equipment | DFA Technology 1 - Low |
|14 | Access is very difficult| And                  | Heavy Numer of aids or tools | DFA Technology 1 - Low |
|15 | Access is very difficult| And                  | Maneuverability requires orientation | DFA Technology 1 - medium-low |
|16 | Access is very difficult| And                  | Easy Numer of aids      | DFA Technology 1 - average |

For the body, for the values "Access" = 20 and "Maneuverability" = 55 on the basis of Fig. 9, according to the "min" inference rule described above, the following rules are active:
- Rule 14 Very Difficult Access and Maneuverability Heavy or Tools to a degree of min (0.33, 0.17) = 0.17 (medium technology)
- Rule 15 Very Difficult Access and Maneuverability Requires Minimal Orientation (0.33, 0.833) = 0.33 (medium technology)
- Rule 10 Limited Access and Maneuverability Heavy or Tools to a degree of min (0.67, 0.17) = 0.17 (low technology)
- Rule 11 Limited Access and Maneuverability Requires Min (0.67, 0.833) orientation = 0.67 (medium technology)

After taking into account rules 10, 11, 14 and 15, in Mamadani's inference there is a maximum operation as an operator of the aggregation of inference results obtained on the basis of individual rules, therefore rules 10 and 15 which have the same "medium-low" rating, we choose MAX so we activate rule 15.

Aggregation of rules for assembly technology in sub-step 1 is given in Fig. 10.
The next action is Defuzzyfication (sharpening) of the parameter value to provide the predicted factor value. The basis of action is the resulting membership function represented in a fuzzy form, while the inference should end with providing a specific numerical value, hence the need to sharpen. Various methods can be used to carry out this process: Center of gravity, Average maximum, First maximum, Last maximum. The centre of gravity method was selected:

\[
\left\{ \begin{array}{l}
  y = \frac{x}{20}; \\
  y = 0.17;
\end{array} \right.
\]
\[0.17 = \frac{x}{20}; \quad x = 20 \cdot 0.17 = 3.4 \tag{15}\]

\[
\left\{ \begin{array}{l}
  y = \frac{x}{20}; \\
  y = 0.33;
\end{array} \right.
\]
\[0.33 = \frac{x}{20}; \quad x = 20 \cdot 0.33 = 6.6 \tag{16}\]

\[
\left\{ \begin{array}{l}
  y = \frac{80-x}{20}; \\
  y = 0.67;
\end{array} \right.
\]
\[0.67 = \frac{80-x}{20}; \quad x = 80 - 13.4 = 66.6 \tag{17}\]

\[
\left\{ \begin{array}{l}
  y = \frac{x-20}{20}; \\
  y = 0.33;
\end{array} \right.
\]
\[0.33 = \frac{x-20}{20}; \quad x = 20 \cdot 0.33 + 20 = 26.6 \tag{18}\]

\[
\left\{ \begin{array}{l}
  y = \frac{x-20}{40-20}; \\
  y = 0.67;
\end{array} \right.
\]
\[0.67 = \frac{x-20}{20}; \quad x = 20 \cdot 0.67 + 20 = 33.4 \tag{19}\]

Deffuzified Center of Gravity value)

\[
r = \frac{r_1}{r_2} = \frac{\int_{b_1}^{b_0} y P_B(y) dy}{\int_{b_0}^{b_0} P_B(y) dy} = \frac{\int_{b_0}^{b_0} y 0.17 dy+\int_{b_1}^{b_0} 0.66 y \frac{x}{20} dy+\int_{b_1}^{b_0} 0.33 dy+\int_{b_1}^{b_0} 0.07 dy+\int_{b_0}^{b_0} 0.80 y \frac{x}{20} dy}{\int_{b_0}^{b_0} P_B(y) dy} \tag{20}\]

\[
r = \frac{\int_{b_0}^{b_0} y 0.17 dy+\int_{b_1}^{b_0} 0.66 y \frac{x}{20} dy+\int_{b_1}^{b_0} 0.33 dy+\int_{b_1}^{b_0} 0.07 dy+\int_{b_0}^{b_0} 0.80 y \frac{x}{20} dy}{\int_{b_0}^{b_0} P_B(y) dy} \tag{21}\]

gdzie:

\[
r_1 = \left[ \frac{y^3}{3} \right]_{0}^{12} + \left[ \frac{y^3}{3} \right]_{0}^{3.4} + \left[ \frac{y^3}{3} \right]_{6}^{26.6} + \left[ \frac{y^3}{3} \right]_{6}^{26.6} \cdot \left( \frac{y^2}{3} - 3y^2 \right) + \left[ \frac{y^3}{3} \right]_{33.4}^{66.6} + \left[ \frac{y^3}{3} \right]_{33.4}^{66.6} \cdot \left( \frac{40y^2}{3} - \frac{y^2}{3} \right) \right] \right|_{b_0}^{b_0} \tag{22}\]

\[
= 0.96 + 4.14 + 110.67 + 103.31 + 1106.67 + 319.02 = 1644.76 \tag{23}\]

\[
r_2 = \int_{b_0}^{b_0} P_B(y) dy = P_1 + P_2 + P_3 \tag{24}\]

\[
P_1 = (6.6 - 0) \cdot 0.17 = 1.1; \quad P_2 = (20 - 0) \cdot 0.33 = 6.6; \quad P_3 = \frac{[60+33.2] \cdot 0.67}{2} = 31.22 \tag{25}\]

\[
r_2 = \int_{b_0}^{b_0} P_B(y) dy = 1.1 + 6.6 + 31.22 = 38.9 \tag{26}\]

\[
r = \frac{1644.76}{38.9} = 42.2 \tag{27}\]
The technology assessment for the 1st stage assumes for the adopted access assessment - 20 and the number of workshop aids - 55 value ~ 40.

**Assessment of Design for Assembly Technology - sub-step 2**

The component's technology is determined, assuming that it depends on two factors, which are: orientation, manoeuvrability. The expert group made the following assessment: orientation - 10, manoeuvrability = 35.

Table 7. Membership functions in tabular form of linguistic variables for Orientation

| DESCRIPTION- ORIENTATION | Rate |
|--------------------------|------|
| Does not require orientation | 100  |
| Requires orientation in the assembly axis | 60   |
| Requires orientation perpendicular to the assembly axis | 30   |
| Requires orientation in the assembly axis and perpendicular to the assembly axis | 0    |

Table 8. Membership functions in tabular form of linguistic variables for Maneuverability

| DESCRIPTION - MANEUVERABILITY | Rate |
|-------------------------------|------|
| Easy to grasp (one hand) | 0    |
| Easy to grip (BH) | 0    |
| Change orientation (OH) | 30   |
| Change orientation (BH) | 30   |
| Slippery | 60 |
| Flexible or small | 60 |
| Heavy nesting or tangling | 60 |
| Requires a tool to capture | 60 |
| Requires two people | 100 |
| Requires service equipment | 100 |

Table 9. Rule base for Orientation

| ORIENTATION | 0 | 30 | 60 | 100 |
|-------------|---|----|----|-----|
| Both axis   | 1 | 0  | 0  | 0   |
| Perpendicular to axis | 0 | 1  | 0  | 0   |
| In the axis | 0 | 0  | 1  | 0   |
| None        | 0 | 0  | 0  | 1   |

Table 10. Rule base for manoeuvrability

| MANOEUVRABILITY | Easy | Requires orientation | Heavy or tools | Two people or equipment |
|-----------------|------|-----------------------|----------------|-------------------------|
| 0               | 1    | 0                     | 0              | 0                       |
| 30              | 0    | 1                     | 0              | 0                       |
Aggregation of rules for Assembly Technology 2 is shown in Figure 10.

![Graph showing aggregation of rules for Assembly Technology 2](image)

**Figure 11.** Aggregation of rules for Assembly Technology 2

Technology 2 takes the value for Orientation 10 and Maneuverability 35 the value 31.

**Assessment of Design fo Assembly Technology - sub-step 3**

The 3 component technology is determined, assuming that it depends on two factors, which are: Assemblability, Processes. The expert group made the following assessment: assemblability = 20, processes = 35.

**Table 11. Membership functions in tabular form of linguistic variables for Assemblability**

| DESCRIPTION-ASSEMBLABILITY                      | Rate |
|-----------------------------------------------|------|
| Difficult access and blind assembly           | 0    |
| Special equipment                             | 30   |
| Requires two hands                            | 60   |
| No difficulty                                 | 100  |

**Table 12. Membership functions in tabular form of linguistic variables for Processes**

| DESCRIPTION-PROCESSES   | Rate |
|-------------------------|------|
| Place part              | 100  |
| Snap-fit                | 100  |
| Light interference      | 60   |
| Pressed into            | 60   |
| Screw on by hand        | 60   |
| Hand tool screw         | 30   |
| Screw on with a power tool | 30 |
| Nitowanie               | 30   |
| Zaciskanie              | 30   |
| Soldering               | 0    |
Aggregation of rules for Design for Assembly Technology 3 presents Fig. 12

![ASSEMBLY MANUFACTURABILITY 3](image)

**Figure 12.** Aggregation of rules for Design for Assembly Technology 3

The technological assessment for the 3rd stage takes for the adopted assessment of Montability - 70 and Joining processes - 10 equal to - 36.

6. **Comparison of the use of methods on the example of a gear fragment - a drive shaft set**

In the study, the indicators of the assessment of the constructionality of the structure were determined for the sample product presented in Fig. 9. As a result of the analysis after the proposed changes, the new form of the gear structure change is illustrated in Fig. 13.

![Gearbox diagram](image)

**Figure 13.** Construction form of the gearbox after the changes have been made
7. Conclusions and comments

In standard technology analyzes according to B&D and Lucas DFA, it is associated with a reduction in the number of components that have no significant effect on the product’s functions or their change consisting in improvement in terms of assembly time and costs. In the traditional arrangement of the above mentioned the methods are oriented towards mass production. The proposed proprietary method based on the analysis of the obtained values of the parameters of the assessment of the efficiency of the entire process enables

- unification of components, application of group processing methods, standardization of machining and assembly operations, and thus saving of investment in machines and shorter overall assembly time, shortening of times, elimination of errors, reduction of process costs

- taking into account, in addition to assembly, many other various factors, e.g. availability of spare parts, production seriality, production conditions in the form of equipment types, available assembly techniques, level of automation, scope of external cooperation orders

- the method can be used for smaller series of manufactured products,

- assessment of technology in the form of given indicators and coefficients should be carried out by experts with extensive production experience,

- arousing designers’ creativity when designing new products, rationalizing works at the stage of improving and expanding the range of implemented production.

The presented method is universal. The use of fuzzy logic gives the opportunity to express incomplete and uncertain information in natural language, in a simple way for humans based on expert knowledge and empirical data. The method takes into account the analysis of the production process in a holistic way.

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