ASSESSMENT OF THE CONSTRUCTIONALITY OF THE STRUCTURE IN THE ASSEMBLY PROCESSES

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Resume
The paper presents the methodology of designing the production process of a new product from the point of view of the criterion of the assembly operations technology (Design for Assembly - DFA) in the automotive industry. The article describes methods and techniques used during the implementation of a new product into production. The impact of the methods on improving the assembly technology of a complex product is described. Suggestions for improving for unit and small series production are presented.

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Introduction
To evaluate the technology of the assembly and defined guidelines for shaping the design process due to PDM (Product Data Management - PDM), different methods may be used. In the automotive industry, widely recognised methods known as DFA were proposed and described for the first time by G. Boothroyd and P. Dewhurst in 1983. The DFA methods are constantly being refined due to technical progress. They allow a more efficient evaluation of the possibility of reducing the number of product components and estimating the costs of machining processes and assembly of the analysed product. By introducing the DFA methods into the design process, the new product design team can propose improved design solutions, which are characterized by better indicators, simpler construction and components, which directly affect the simplification of assembly operations.

The most popular methods of the DFA practice are Lucas DFA, Boothroyd and Dewhurst (B & D), Hitachi AEM. [1-3].

Development of machining technology (thanks to the automation and extension of the possibility of making objects of complex construction), in connection with a significant share of manual work in the assembly processes of finished products, has led to a change in the approach to the production of new products. There has been a development of methods of determining the production costs. The share of assembly costs in the production costs of products has greatly increased [4-6]. The design process of the new product is shown in Figure 1.

The design process should be determined from the point of view of different usability criteria. The assessment is based on marketing and conceptual preparation; documentation - construction, production and organization; implementation of the production process; distribution; conditions for the operation and decommissioning of the product.

Proposal to modify the methods to assess the manufacturability design

2.1 Input assumptions
As a part of the work, based on analysing and comparing existing methods and algorithms to improve the product’s technological efficiency, it was proposed to improve the abovementioned assessment methods.

The presented methods are focused on activities that reduce assembly times, which ultimately reduces the costs of assembly operations. An additional factor that reduces assembly times is the unification and standardization of product components, which can be
determined by an index of component unification. The unification of the product components allows, in turn, to rationalize production processes in the form of group processing applications. The proposed improvement of the above methods meets the development trends in the automotive industry consisting of continuous linear improvement of product design, use of components included in the assembly in many versions and brands of final products [7-8].

The presented methods of assessing manufacturability of the structure may also be used in the production of other products. As an example can be presented analysis of the structure’s efficiency on the single-stage gear transmission used to drive devices installed on means of transport example (Figure 1) [9-11].

2.2 Modified Boothroyd Dewhurst DFA and Lucas DFA methods

The final stage in the Boothroyd & Dewhurst DFA method is calculation for which it is necessary to know the sum of the number of operations, the total time of the operation, the total costs of the operation, the theoretical minimum number of parts and the $DFM_{\text{index}}$ [12-13].

In the Lucas DFA method, it is necessary to know the project performance indicator ($W_{\text{ep}} = DFMA_{\text{index}}$), manoeuvrability ($W_{\text{man}}$) and assemblability ($W_{\text{man}}$). Determination of the abovementioned quantities to determine the effects of rationalization takes place before and after the assessment of technology [14].

Similarly, for a more detailed analysis, the authors propose to define the technological indicators for both above-mentioned methods, with a view to harmonising the components of the product and the possibility of using the group processing and increasing serial production. The structure efficiency index after analysis for unified and standardised components is:

$$W_{\text{UNK}} = \left(\frac{C_{\text{UNK}}}{C_t}\right) \times 100\%$$

(1)

where: $W_{\text{UNK}}$ - the structure efficiency index for unified and standardised components

$C_{\text{UNK}}$ - the sum of unified and standardized assembly components,

$C_t$ - total components.

The structure efficiency index after the analysis of component structure, enabling group processing is:

$$W_{\text{OG}} = \left(\frac{C_{\text{OG}}}{C_t}\right) \times 100\%$$

(2)

where: $W_{\text{OG}}$ - the structure efficiency index of component structure enabling group processing

$C_{\text{OG}}$ - the sum of the components that can potentially be implemented using the group processing technologies in manufacturing processes,

$C_t$ - total components.

3 Examples

3.1 The Boothroyd and Dewhurst DFA method

According to the Boothroyd & Dewhurst DFA method for the gear prototype design (Figure 1), the assembly process was defined, the fragment of which is presented in Tables 1-3. The DFMA indicator before making the change is [15]:

$$DFMA_{\text{index}} = \frac{(t_s \cdot L_s)}{T_o}$$

(3)
For each assembled part and for each defined step of the assembly process, the following values were determined:

\[ L = \sum l_i,\ T = I_{\text{man}} + I_{\text{mon}} = \sum T_{\text{man}} + \sum T_{\text{mon}}, \]

where:

- \( l_i \) - i-th assembly operation,
- \( I_{\text{man}} \) - manipulation index for a given part of the product,
- \( I_{\text{mon}} \) - assembly index for a given part of the product,
- \( T_{\text{man}} \) - time manipulation index for the given product,
- \( T_{\text{mon}} \) - assembly time for a given component of the product.

For many parts, it can be assumed that:

\[ L = A \] and

\[ DFMA_{\text{index}} = \frac{(3-L)}{T}, \]

where:

- \( DFMA_{\text{index}} \) - the project performance indicator,
- \( A \) - number of parts necessary for functioning of the product (it was assumed in the study that \( L = A = C_t \)),
- \( t_a \) - assembly time of the basic ideal part (based on Boothoroyd; \( t_a = 3s \)),
- \( T_a \) - total assembly time of the product.

\[ DFMA_{\text{index}} = \frac{(3-L)}{T}, \]

Figure 2 Diagram of the gear unit being analysed

1 - body, 2 - cover, 3 - pinion, 4 - pinion cover I, 5 - pinion cover II, 6-7 - bearings pinion, 8 - pinion key, 9 - shaft, 10 - gear, 11 - gear key, 12 - shaft key, 13-14 - bearings shaft, 15 - shaft cover I, 16 - shaft cover II, 17 - pinion seal, 18 - shaft seal, 19 - spacer rings, 20-29 - body bolts, 30-39 - bolt washers to the body, 40-55 - cover bolts, 56-71 - bolt washers for covers, 72-76 - Monolith gasket, 77-78 - vent with cover gasket, 79-80 - oil gauge with gasket, 81 - oil plug, 82 - oil plug gasket, 83 - nameplate, 84-87 - rivet pin, 88-95 - sight glass screws, 96-103 - washers for sight glass screws, 104 - sight glass gasket, 105 - sight glass.
To improve the gear assembly technology, design of the proposed gear was changed (Figure 2). The change was adapted to the production conditions depending on the serial production. Limiting the scope of changes resulting from the serial production is forced by the costs of machining and assembly itself, which, with significant changes improving the technology of the structure, requires costly tooling (workshop aids) related to machining and assembly. Such changes are profitable in the conditions of mass production [16-18].

The gearbox dimensions result (Figure 2) from the ratio \( i = 1.95 \), the number of pinion teeth \( z_1 = 22 \); the gear wheel \( z_2 = 43 \); the module \( m_n = 3.00 \text{ mm} \), the tooth angle inclination \( \beta = 10^\circ \), the width of the teeth \( b = 15 \text{ mm} \).

For the mass production, the material and form of the body were changed, from the welded structure to the cast structure with the division perpendicular to the axis of the shafts. This way, two bearing caps were eliminated, the remaining caps would be pressed in, thus eliminating washers and screws; the assembly of individual components was replaced for the assembly of assemblies that will only be mounted vertically using tooling. In unit and small-lot production similarly, it was proposed to change the body to a cast form, but the division of the body parallel to the shaft axis was kept. At the same time, the same construction form was used to assemble gears of different sizes (different transmitted powers) and different ratios, materials and forms of pinion and gear wheels were unified, ensuring constant unified inter-axle distances and unified different ratios at individual gear stages (from the same elements gears are also mounted in multi-stage gears); the diameters of bearing openings have been unified, - pinion units with mounted bearings, shaft with mounted gear wheel and bearings mounted on the shaft are mounted to the gear
After the changes for serial and mass production (Figure 3):

$$DFMA_{wpo} = \left(3 \cdot \frac{A}{T_{\text{ipz}}} \right) \times 100\% = (3 \cdot 32/683.19) \times 100\% = 14\%.$$  

Theoretical indicator (for the theoretical number of parts - 22, after inserting the push-fit connections and eliminating subsequent fasteners):

$$DFMA_{wpz} = \left(3 \cdot \frac{A}{T_{\text{ipz}}} \right) \times 100\% = (3 \cdot 22/683.19) \times 100\% = 10\%,$$  

where:

- $DFMA_{wpo}$ - indicator before the gear structure changes,
- $DFMA_{wpz}$ - indicator after changes made to the gear design,
- $S_{\text{ipz}}$ - number of A-type transmission components before changes,
- $S_{\text{ipz}}'$ - number of A-type transmission components before the changes,
- $T_{\text{ipz}}$ - gearbox assembly time before structural changes,
- $T_{\text{ipz}}'$ - gearbox assembly time after the structural changes.

According to calculations, it can be stated that the

Table 1 Results of the technology analysis by the Boothroyd & Dewhurst method of the gearbox

| no. | description | initial assumption of the process | repetitions of activities | thickness (t mm) | size (s mm) | rotation alpha (°) | rotation beta (°) |
|-----|-------------|----------------------------------|---------------------------|-----------------|-------------|-------------------|-----------------|
| 1   | main housing no.1 | pick up                         | 1                         | 120             | 309         | 360               | 360             |
| 2   | bearing no.6 | press to main housing no.1 | 1                         | 17              | 72          | 180               | 0               |
| 3   | bearing no.13 | press to main housing no.1 | 1                         | 20              | 90          | 180               | 0               |
| 4   | main shaft no.3 | press to bearing no.6 | 1                         | 37              | 194         | 360               | 0               |
| 5   | slow-speed shaft no.9 | pick up                         | 1                         | 28              | 216        | 360               | 360             |
| 8   | spacer no. 19 | assembly on shaft subassy | 1                         | 4               | 60          | 180               | 0               |
| 9   | preheat gear no.9 | preheat gear no.9 to 180 deg. | 1                         |                 |             |                   |                 |
| 10  | shaft subassy | press to bearing no.14 | 1                         | 136             | 216        | 360               | 360             |
| 11  | cover no.2 | pick up                         | 1                         | 25              | 288         | 360               | 360             |
| 12  | bearing no.7 | press to cover no.16 | 1                         | 17              | 72          | 180               | 0               |
| 13  | bearing no.14 | press to cover no.15 | 1                         | 20              | 90          | 180               | 0               |
| 18  | spring washer z8.2 | assem with screw | 10                        | 4               | 14          | 180               | 0               |
| 19  | screw with washer | tighten cover no.2 to main housing | 10                        | 4               | 4           | 20                | 360             |
| 20  | cover no.5 | pick up                         | 1                         | 16              | 100         | 360               | 360             |
| 21  | screw m8x20 | pick up                         | 4                         | 4               | 20          | 360               | 0               |
| 22  | spring washer z8.2 | assem with screw | 4                         | 4               | 14          | 180               | 0               |
| 23  | monolith seal | sealing                         | 1                         |                 |             |                   |                 |
| 24  | screw with washer | tighten cover 5 to main housing no.1 | 4                         | 4               | 14          | 180               | 0               |

| total number of parts/operations before changes | 113 |

After the changes for serial and mass production, after the change - 32 (theoretically 22), including unified elements - 23 (theoretically 13), including workpieces - 9, in group machining - 7 (theoretically also 9 and 7 respectively).
The formula describing functionality $W_{ep}$ is:

$$W_{ep} = \frac{L_{kA}}{L_{kA} + L_{kB}} = \frac{23}{23 + 82} = 0.22 \text{ (22%),}$$

(10)

where:

$L_{kA}$ - number of components A (fulfilling the functions of a product),
$L_{kB}$ - number of components B (characterised by a lack of product function e.g. rivets, washers).

Formula describing manoeuvring $W_{man}$ is:

$$W_{man} = \frac{I_{man}}{L_{kA}} = \frac{67.2}{23} = 2.92,$$

(11)

where:

$I_{man}$ - manoeuvring index,
$L_{kA}$ - number of components A.

Formula describing assemblability $W_{mon}$ is:

$$W_{mon} = \frac{(W_{m} + W_{d})}{L_{kA}} = \frac{284.2}{23} = 12.36,$$

(12)

results of the analysis for a cast iron gear body are better than the results of the analysis for a welded body gear.

The DFMA project performance index should be as low as possible before the change it is 46 % after changes depending on the production series 37 % and 14 % respectively.

3.2 Lucas DFA method

According to the Lucas DFA method, the same design of a single-stage gear prototype was analysed (Figure 1). For each assembled part and each defined step (Table 4 and 5) of the assembly process, the values of individual method indicators were determined. Results of the analysis for the assumed assembly process are presented in Tables 4 and 5. The table summarizes selected examples of operations assigning them an analysis of functionality ($W_{ep}$) (in the form of parts belonging to group A or B), manoeuvring ($W_{man}$), assemblability ($W_{mon}$) and additional operations. Data related to additional operations can be found in the Sec column [22].

The formula describing functionality $W_{ep}$ is:

$$W_{ep} = L_{kA} / L_{kA} + L_{kB} = 23(23+82) = 0.22 \text{ (22%),}$$

where:

$L_{kA}$ - number of components A (fulfilling the functions of a product),
$L_{kB}$ - number of components B (characterised by a lack of product function e.g. rivets, washers).

3.2 Lucas DFA method

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Based on the performed analysis, the number of parts of type A is 23 \((L_{kA})\), the number of type B is 62 \((L_{kB})\) for a piece and small series production.

Formulas describing functionality \(W_{ep}\) after the changes are:

\[
W_{ep} = \frac{L_{kA}}{L_{kA} + L_{kB}} = \frac{23}{23+62} = 0.27 \text{ (27 %)}.
\] (13)

Based on the new data, after the changes specified in Tables 4 and 5, the manoeuvring index \(I_{\text{man}}\) is:

\[
I_{\text{man}} = L_{mA} + L_{mB} + L_{mC} + L_{mD} = \frac{58}{10} = 5.8.
\] (14)

The formula for the manoeuvring factor \(W_{\text{man}}\) \((W_d = 0)\) after the changes is:

\[
W_{\text{man}} = \frac{I_{\text{man}}}{L_{kA}} = \frac{58}{23} = 2.52.
\] (15)

Description of calculations presented above is presented in Table 4 and 5. In the example presented, the developed structure (Figure 1) is non-technological from the point of view of the possibility of implementation into production in conditions of high-volume production.

In the applied assessment method, the project efficiency index was obtained at the level of \(W_{ep} = 22\%\) (authors of publications \([23-24]\) give a minimum value of 60\%) and \(W_{\text{man}} = 2.92\) and \(W_{\text{mon}} = 12.36\) (where both indicators should be less than 2.5).

To improve the technology of the gearbox structure, the same changes were made as in the previously described method. Below are the indicators for the case of the unit and small-lot production, as well as for mass-production.

### Table 3 Results of the technology analysis by the Boothroyd & Dewhurst method of the gearbox - Continue

| no. | description | initial assumption of the process | repetitions of activities | relative movement | another material | separation of parts needed? |
|-----|-------------|----------------------------------|--------------------------|-----------------|-----------------|----------------------|
| 1   | main housing no.1 | pick up | 1 | N | N | N
| 2   | bearing no.6   | press to main housing no.1 | 1 | Y | Y | Y
| 3   | bearing no.13  | press to main housing no.1 | 1 | Y | Y | Y
| 4   | main shaft no.3 | press to bearing no.6 | 1 | Y | N | Y
| 5   | slow-speed shaft no.9 | pick up | 1 | Y | Y | Y
| 6   | spacer no. 19  | assembly on shaft subassy | 1 | N | N | N
| 7   | preheat gear no.9 | preheat gear no.9 to 180 deg. | 1 | N | N | N
| 8   | shaft subassy  | press to bearing no.14 | 1 | Y | Y | Y
| 9   | cover no.2     | pick up | 1 | N | N | Y
| 10  | cover no.7     | press to cover no.16 | 1 | Y | Y | Y
| 11  | bearing no.14  | press to cover no.15 | 1 | Y | Y | Y
| 12  | bearing no.14  | press to cover no.16 | 1 | Y | Y | Y
| 13  | bearing no.14  | press to cover no.15 | 1 | Y | Y | Y
| 14  | bearing no.14  | press to cover no.16 | 1 | Y | Y | Y
| 15  | sprin washer s8.2 | assem with screw | 10 | N | N | N
| 16  | screw with washer | tighten cover no.2 to main housing | 10 | N | N | N
| 17  | cover no.5     | pick up | 1 | N | N | Y
| 18  | screw m8x20    | pick up | 4 | N | N | N
| 19  | spring washer s8.2 | assem with screw | 4 | N | N | N
| 20  | monolith seal  | sealing | 1 | N | Y | N
| 21  | screw with washer | tighten cover 5 to main housing no.1 | 4 | N | N | N

**total number of parts/operations before changes**: 113

**theoretical minimum number of parts/operations**

**for serial and mass production, after the change - 32 (theoretically 22)**

**for piece and small batch production, after the change - 85, including unified elements - 71**, including workpieces - 14, in group machining - 12
Based on the performed analysis, the number of parts of type A is 18 (\(L^2kA\)), the number of type B is 14 (\(L^2kB\)) for serial and mass production.

Formula, describing functionality \(W_{ep}\) after the changes, is:

\[
W_{ep} = \frac{L^2kA}{L^2kA + L^2kB} = \frac{18}{18 + 14} = 0.56 \ (56 \%) \ (18)
\]

Based on the new data after the changes specified in Tables 4 and 5, the manoeuvring index \(I_{man}\) is:

\[
I_{man} = L^2mA + L^2mB + L^2mC + L^2mD = 35.2, \ (19)
\]

The formula for the main activity ratio \(W_m\) after the changes are:

\[
W_m = L^2pa + L^2pb + L^2pc + L^2pd + L^2pe + L^2pf + Sec = 246.7 \ (16)
\]

where:
- \(L^2pa = 104\),
- \(L^2pb = 1.9\),
- \(L^2pc = 7.7\),
- \(L^2pd = 15\),
- \(L^2pe = 12\),
- \(L^2pf = 7\),
- \(Sec = 99\).

The formula for assemblability factor \(W_{mon}\) after the changes is:

\[
W_{mon} = \frac{W_m}{L^2kA} = \frac{246.7}{23} = 10.73 \ (17)
\]

Based on the performed analysis, the number of parts of type A is 18 (\(L^2ka\)), the number of type B is 14 (\(L^2kb\)) for serial and mass production.

Formula, describing functionality \(W_{ep}\) after the changes, is:

\[
W_{ep} = \frac{L^2ka}{L^2ka + L^2kb} = 18(18+14) = 0.56 \ (56 \%). \ (18)
\]

Based on the new data after the changes specified in Tables 4 and 5, the manoeuvring index \(I_{man}\) is:

\[
I_{man} = L^2ma + L^2mb + L^2mc + L^2md = 35.2, \ (19)
\]

where:
- \(L^2ma = 27\),
- \(L^2mb = 4.3\),
- \(L^2mc = 1.4\),
- \(L^2md = 3\).
According to calculations presented above, it can be stated that the analysis results for a cast iron gear body are better than the analysis results for a welded body gear. The \( W_{\text{mon}} \) project performance indicator should be as high as possible, before the change 22\%, after the change of 27\% and 56\%, respectively, according to the series production. The maneuvering and assemblability factors of \( W_{\text{man}} \) and \( W_{\text{mon}} \) should be as low as possible; before the change they are respectively 2.92 and 12.35, after the change they depend on the production series \( W_{\text{man}} = 2.52 \) and 1.96 and \( W_{\text{mon}} = 10.73 \) and 6.27.

The unification and batch processing ratios, for both methods before the redesigning, are as follows:

\[
W_{\text{unk}} = \frac{91}{91+105} = 0.46 \ (46 \%).
\]
After the redesign for the small lot production:

\[ W_{\text{small}} = \frac{71}{1} + 85 = 0.45 \ (45\%). \]  
(24)

After the redesign for the mass production:

\[ W_{\text{mass}} = \frac{23}{3} + 32 = 0.42 \ (42\%). \]  
(25)

In the case of the gearboxes from the unification index (machining) before redesigning is:

\[ W_{\text{uno}} = \frac{5}{5} + 14 = 0.26 \ (26\%). \]  
(26)

After the redesign for the small lot production:

\[ W_{\text{uno}} = \frac{12}{12} + 14 = 0.46 \ (46\%). \]  
(27)

After the redesign for the mass production: (including theoretically):

\[ W_{\text{uno}} = \frac{7}{2} + 7 = 0.78 \ (78\%). \]  
(28)

The presented results meet the assessment of the used production methods effectiveness in the production practice.

4 Conclusions and comments

The standard analysis of B&D and Lucas DFA is associated with a reduction in the number of parts that do not have a significant impact on the product’s functions or their change consisting in improvement in terms of the assembly method. This change may be associated with an increase in manufacturing costs. In modified methods by introducing indicators unification and possibilities of group processing, it is possible to improve the design more accurately. Original methods are oriented towards the mass production. Modified methods improve original ones giving the possibility of use in production with smaller series, as well. Analysis of unification and group machining indicators allow for the unification of components and thus saving investment in machines and shorter overall assembly time. Their use can contribute to design of products with higher efficiency and lower production costs.

Proposals for modification of methods allow the analysis of the obtained values of the assembly efficiency assessment parameters, which also causes:

- shortening of times, elimination of errors, reduction of process costs,
- considering, 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, the scope of external cooperation orders, etc.
- the use of methods for smaller series of manufactured products,
- stimulating a designer’s creativity.

These two methods cannot be compared directly due to the different way of calculations. The following conclusions can be drawn from analysis of comparison of results obtained by both methods.

The Boothroyd-Dewhurst method is more stringent and is aimed at reducing/simplifying the components of the project. At the same time, in the case of production not qualified for the high-volume production, the result of such an assessment may be a product with a small number of components, but a very complicated form and, therefore, a high cost of processing and quality and other in the field of production organisation.

The Lucas method assesses the above project in a more balanced way. It enables the assessment of technology from the point of view of value of several parameters. Differences in relation to the intended goal between the two methods are not large. Both methods, together with complex proposals, allow universalisation of the presented methods and their application to conditions of the unit and small-lot production.

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