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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1 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.

2 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

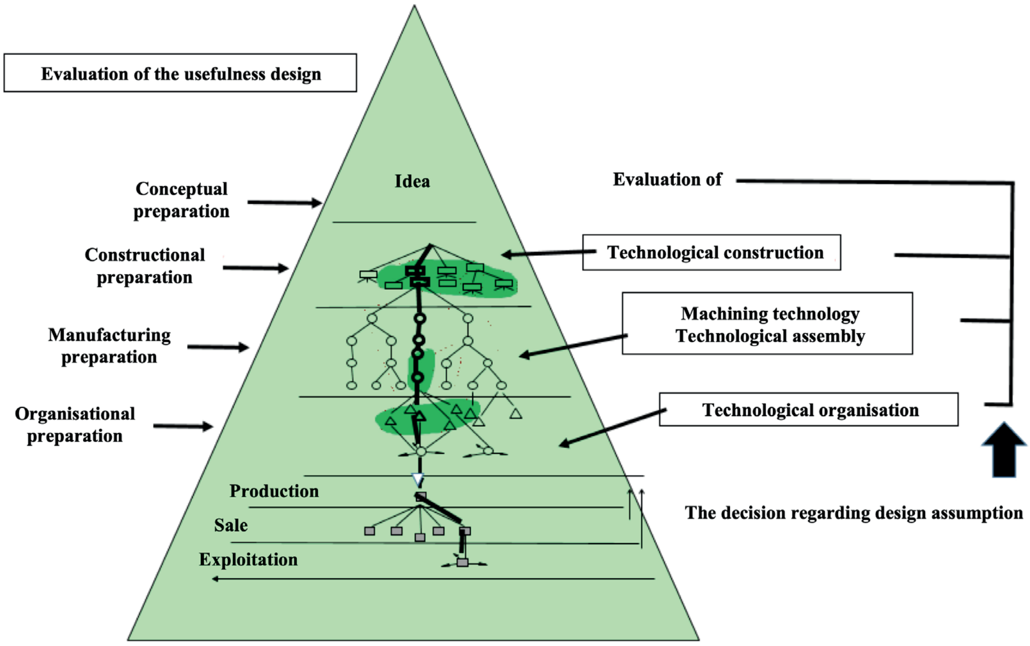

***Figure 1** The course of designing the production process of a new product [6]*

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 $DFMA_{index}$ [12-13].

In the Lucas DFA method, it is necessary to know the project performance indicator ($W_{ep} = DFMA_{index}$), manoeuvrability (W_{man}) and assemblability (W_{mon}). 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:

$$Wtk_{UNK} = (C_{UNK}/C_t).100\% \quad (1)$$

where: Wtk_{UNK} - the structure efficiency index for unified and standardised components

C_{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:

$$Wtk_{OG} = (C_{OG}/C_t).100\% \quad (2)$$

where: Wtk_{OG} - the structure efficiency index of component structure enabling group processing

C_{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]:

$$DFMA_{index} = (t_a \cdot L_o)/T_o, \quad (3)$$

for many parts, it can be assumed that: $L_o = A$ and where:
DFMAindex - the project performance indicator,
A - number of parts necessary for functioning of the product (it was assumed in the study that $L_o = A = C_t$),
t_a - assembly time of the basic ideal part (based on Boothoroyd; t_a = 3s),
T_o - total assembly time of the product).

$$DFMA_{index} = (3 \cdot L_o) / T_o, \tag{4}$$

where: L_o - the total number of operations to assembly ($L_o = A$),

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

$$L_o = \Sigma l_{oi}, \; T_o = I_{man} + I_{mon} = \Sigma T_{man} + \Sigma T_{mon}, \tag{5}$$

where: l_{oi} - i-th assembly operation,
I_{man} - manipulation index for a given part of the product,
I_{mon} - assembly index for a given part of the product,
T_{man} - time manipulation index for the given product,
T_{mon} - assembly time for a given component of the product.

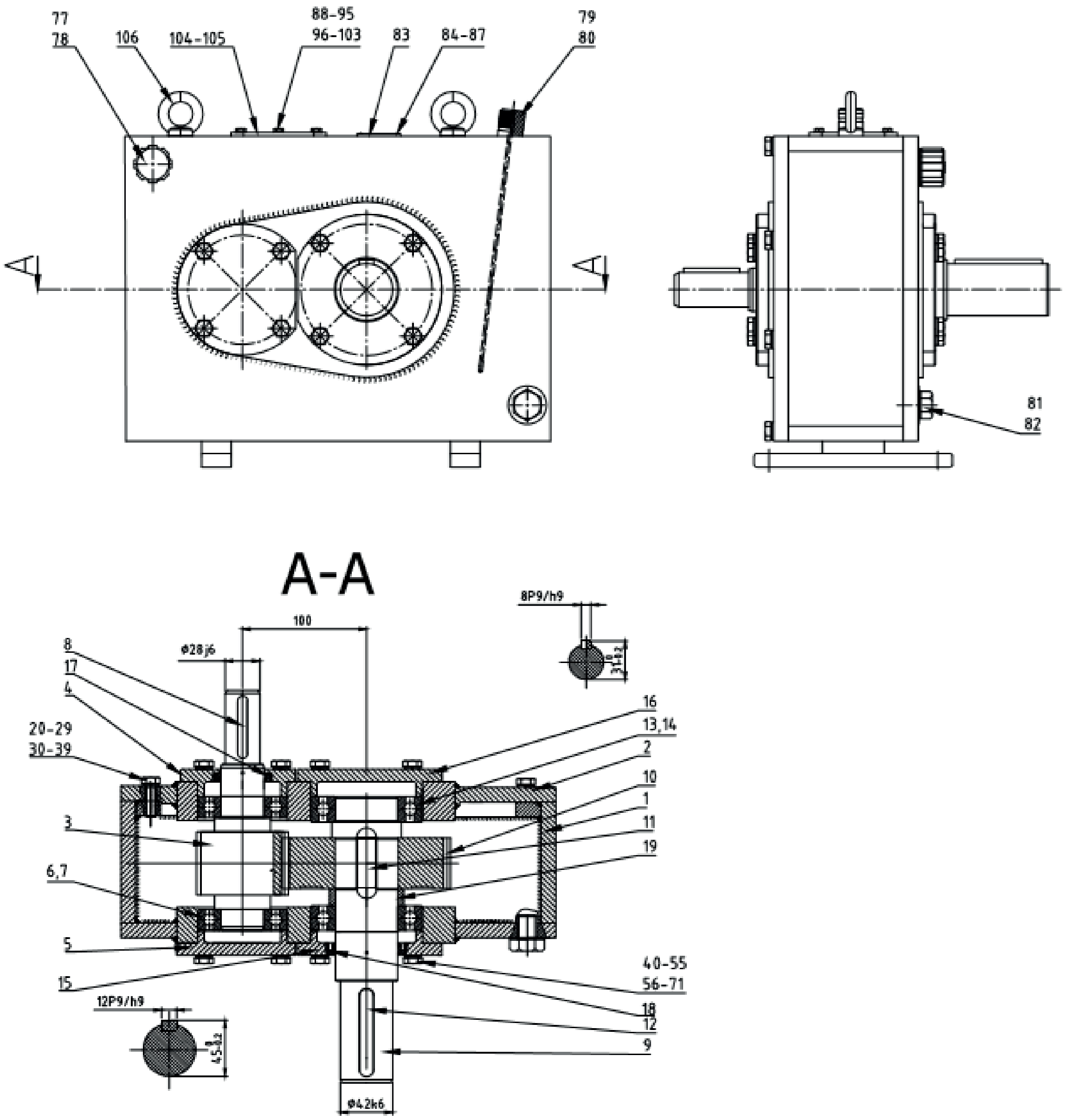

Figure 2 *Diagram of the gear unit being analysed*
1 - body, 2 - cover, 3 - pinion, 4 - pinion cover I, 5 - pinion cover II, 6- 7 - bearings pinion, 8 - pinion key, 9 - shaft, 10 - gear, 11 - gear key, 12 - shaft key, 13-14 - bearings shaft , 15 - shaft cover I, 16 - shaft cover II, 17 - pinion seal, 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

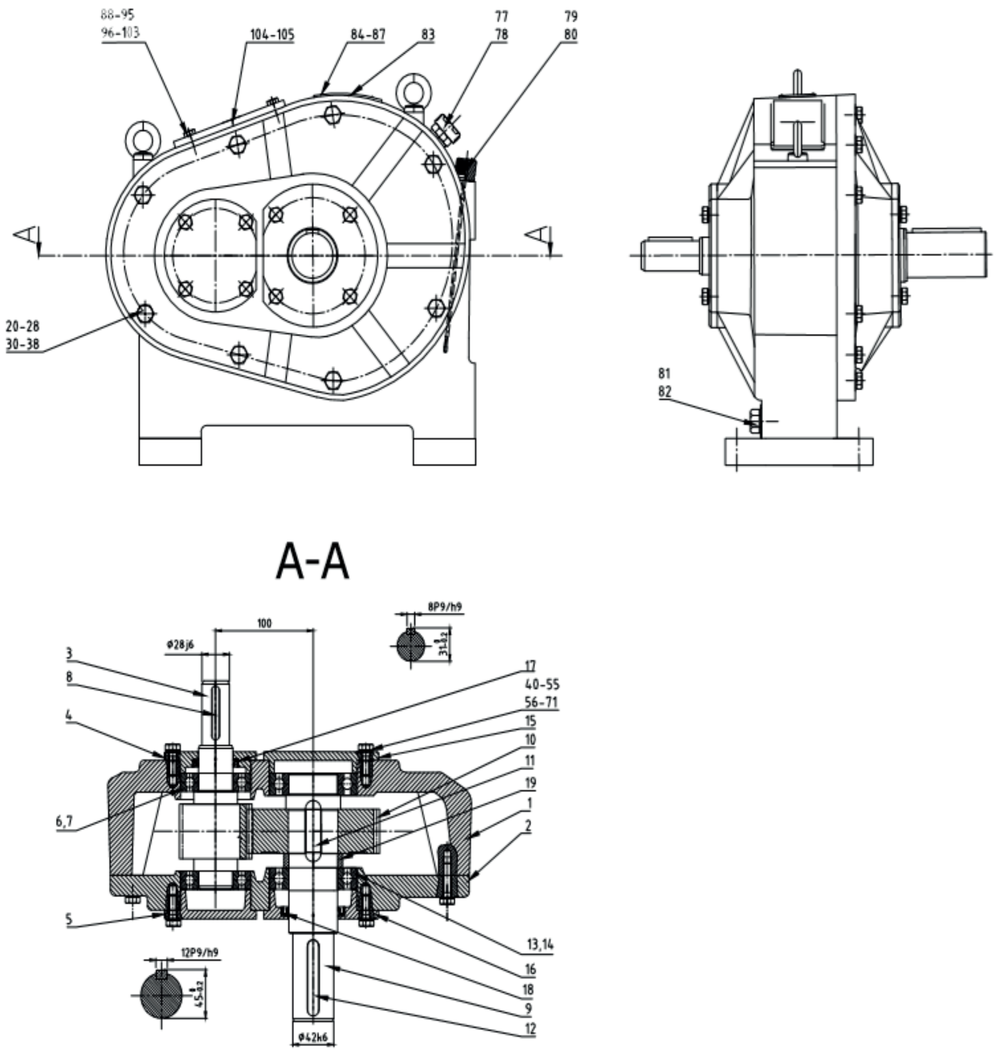

Figure 3 *Diagram of the gear unit analysed*
1 - body, 2 - cover, 3 - pinion, 4 - pinion cover I, 5 - pinion cover II, 6- 7 - bearings pinion, 8 - pinion key, 9 - shaft, 10 - gear, 11 - gear key, 12 - shaft key, 13-14 - bearings shaft , 15 - shaft cover I, 16 - shaft cover II, 17 - pinion seal, 18 - 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 mm, the tooth angle inclination β = 10°, the width of the teeth b = 15 m_n.

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

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

details of assembly and components			product data				
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	20	360	0
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				
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)							

body, washers, screws fastening covers to the body were unified, the whole series was unified gears, sight glasses and their fastening elements, workshop aids have been unified related to gear machining and assembly (e.g. bearing assembly, for sealing contact surfaces) [19-20].

Results of the technological analysis (for changes made for the mass production) are presented in Tables 1-3. In addition, the table provides data on transmission parts after a performance analysis for the conditions of the unit and small-lot production [21].

Based on the data set out in Tables 1-3, the following indicators of the gear structure design were obtained (the analyses assumed that $L_o = A = C_e$):

Indicator before the gear structure changes is (Figure 2):

$$DFMA_{wpz} = (3 \cdot A / T_{ipz}).100\% = \\ = (3 \cdot 105/683.19).100\% = 46\%. \quad (6)$$

Indicator after the changes for Unit and small-lot production:

$$DFMA_{wpo} = (3 \cdot A / T_{ipz}).100\% = \\ = (3 \cdot 85/683.19).100\% = 37\%. \quad (7)$$

After the changes for serial and mass production (Figure 3):

$$DFMA_{wpo} = (3 \cdot A / T_{ipz}) .100\% = \\ = (3 \cdot 32/683.19).100\% = 14\%. \quad (8)$$

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

$$DFMA_{wpo} = (3 \cdot / T_{ipo}).100\% = \\ = (3 \cdot 22/683.19).100\% = 10\%, \quad (9)$$

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

According to calculations, it can be stated that the

***Table 2** Results of the technology analysis by the Boothroyd & Dewhurst method of the gearbox -Continue*

details of assembly and components				manoeuvrability		assemblability		operation time index
no.	description	initial assumption of the process	repetitions of activities	code	time index	code	time index	
1	main housing no.1	pick up	1	30	1.95	00	1.5	3.45
2	bearing no.6	press to main housing no.1	1	00	1.13	31	5.0	6.13
3	bearing no.13	press to main housing no.1	1	00	1.13	31	5.0	6.13
4	main shaft no.3	press to bearing no.6	1	88	6.35	41	7.5	13.85
5	slow-speed shaft no.9	pick up	1	30	1.95			1.95
8	spacer no. 19	assembly on shaft subassy	1	00	1.13	01	2.5	3.63
9	preheat gear no.9	preheat gear no.9 to 180 deg.	1			99	12.0	12.00
10	shaft subassy	press to bearing no.14	1	30	1.95	51	9.0	10.95
11	cover no.2	pick up	1	30	1.95			1.95
12	bearing no.7	press to cover no.16	1	00	1.13	31	5.0	6.13
13	bearing no.14	press to cover no.15	1	00	1.13	31	5.0	6.13
18	spring washer z8.2	assem with screw	10	05	1.84	06	5.5	73.40
19	screw with washer	tighten cover no.2 to main housing	10	10	1.5	38	6.0	75.00
20	cover no.5	pick up	1	30	1.95			1.95
21	screw m8x20	pick up	4	10	1.5			6.00
22	spring washer z8.2	assem with screw	4	05	1.84	06	5.5	29.36
23	monolith seal	sealing	1			99	12.0	12.00
24	screw with washer	tighten cover 5 to main housing no.1	4	10	1.5	38	6.0	30.00
total number of parts/operations before changes			113	total operating time before changes				683.19
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)				for piece and small batch production, after the change - 85, including unified elements - 71, including workpieces - 14, in group machining - 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*), manouvering (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:

$$W_{ep} = L_{kA} \ / \ L_{kA} + L_{kB} = 23(23+82) = 0.22 \ (22\%), \tag{10}$$

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:

$$W_{man} = I_{man} / L_{kA} = 67.2/23 = 2.92, \tag{11}$$

where: I_{man} - manouvering index,
L_{kA} - number of components A.

Formula describing assemblability W_{mon} is:

$$W_{mon} = (W_m + W_d) / L_{kA} = 284.2/23 = 12.36, \tag{12}$$

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

details of assembly and components				theoretical minimum number of parts/operations			
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	Y	
2	bearing no.6	press to main housing no.1	1	Y	Y	Y	1
3	bearing no.13	press to main housing no.1	1	Y	Y	Y	1
4	main shaft no.3	press to bearing no.6	1	Y	N	Y	1
5	slow-speed shaft no.9	pick up	1	Y	N	Y	1
8	spacer no. 19	assembly on shaft subassy	1	N	N	N	0
9	preheat gear no.9	preheat gear no.9 to 180 deg.	1	N	N	N	0
10	shaft subassy	press to bearing no.14	1	Y	Y	Y	1
11	cover no.2	pick up	1	N	N	Y	1
12	bearing no.7	press to cover no.16	1	Y	Y	Y	1
13	bearing no.14	press to cover no.15	1	Y	Y	Y	1
18	spring washer z8.2	assem with screw	10	N	N	N	0
19	screw with washer	tighten cover no.2 to main housing	10	N	N	N	0
20	cover no.5	pick up	1	N	N	Y	1
21	screw m8x20	pick up	4	N	N	N	0
22	spring washer z8.2	assem with screw	4	N	N	N	0
23	monolith seal	sealing	1	N	Y	N	1
24	screw with washer	tighten cover 5 to main housing no.1	4	N	N	N	0
total number of parts/operations before changes			113	theoretical minimum number of parts/operations			22
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)				for piece and small batch production, after the change - 85, including unified elements - 71, including workpieces - 14, in group machining - 12			

where:
W_m - main activity indicator wherein, $W_m = L_{mA} + L_{mB} + L_{mC} + L_{mD} + L_{mE} + L_{mF}$,
W_d - indicator of additional activities, values making up the W_m and W_d parameters are specified in tables provided by the authors of the method,
L_{kA} - number of the type A parts.

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_{man} = 2.92 and W_{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.

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:

$$W_{ep} = L_{kA} \ / \ L_{kA} + L_{kB} = 23(23+62) = 0.27 \ (27\ \%). \quad (13)$$

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

$$I_{man} = L_{mA} + L_{mB} + L_{mC} + L_{mD} = 58, \quad (14)$$

where:
L_{mA} = 42,
L_{mB} = 7.7,
L_{mC} = 2.7,
L_{mD} = 5.6.

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

$$W_{man} = I_{man} \ / \ L_{kA} = 58/23 = 2.52. \quad (15)$$

***Table 4** Results of the gear assembly technology analysis*

details of assembly and components				handling analysis				
no.	step of assembly	description	functional analysis	A	B	C	D	Sum
1	pick up	body no.1	A	3	0	0	0	3
2	pressing to body	bearing no.6	A	1	0.4	0	0	1.4
3								
4	pressing to body	bearing no.13	A	1	0.4	0	0	1.4
5								
6	pressing to bearing no.6	pinion shaft no.3	A	1	0	0.1	0.2	1.3
8	pick up	main shaft no.9	A	1	0	0.1	0.2	1.3
9	assembly	wedge 11	B	1	0	0	0.2	1.2
10	assembly on shaft subassy	gear 7	B	1	0.4	0.1	0.2	1.7
11	assembly on shaft subassy	spacer sleeve 19	B	1	0	0	0	1
13								
18								
55	assembly on shaft subassy	prismatic wedge 12	B	1	0	0	0.2	1.2
56	assembly to the body	vent 77	A	1	0	0.1	0.2	1.3
57	assembly to the body							
58	assembly to the body	oil indicator 79	A	1	0	0.1	0.2	1.3
59								
60	assembly to the body	plug 81	A	1	0	0.1	0.2	1.3
61	assembly to the body	sealing ring 82	A	1	0	0.1	0.2	1.3
63	pick up and setup	nameplate	B	1	0.2	0.1	0.2	1.5
64	riveting	rivet	B	1.5	0.2	0	0	1.7
65								
66								
82								
83				48	11	2.7	5.6	67.2
84								
		22%		2.92				
		project efficiency ratio				maneuverability index		

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

$$W_m = L_{pA} + L_{pB} + L_{pC} + L_{pD} + L_{pE} + L_{pF} + Sec = 246.7 \quad (16)$$

where: $L_{pA} = 104$,
$L_{pB} = 1.9$,
$L_{pC} = 7.7$,
$L_{pD} = 15$,
$L_{pE} = 12$,
$L_{pF} = 7$,
$Sec = 99$.

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

$$W_{mon} = W_m \ / \ L_{kA} = 246.7/23 = 10.73 \quad (17)$$

Based on the performed analysis, the number of parts of type A is 18 (L_{kA}), the number of type B is 14 (L_{kB}) for serial and mass production.

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

$$W_{ep} = L_{kA} \ / \ L_{kA} + L_{kB} = 18(18+14) = 0.56 \ (56 \ \%). \quad (18)$$

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

$$I_{man} = L_{mA} + L_{mB} + L_{mC} + L_{mD} = 35.2, \quad (19)$$

where: $L_{mA} = 27$,
$L_{mB} = 4.3$,
$L_{mC} = 1.4$,
$L_{mD} = 3$.

Table 5 *Results of the gear assembly technology analysis - Continued*

no.		fitting analysis								
		A	B	C	D	E	F	sec.	sum	cumulative sum
1	pick up and place	1	0	0	0	0	0	0	1	1
2	pressing	1	0	0	0	0	0.7	0	1.7	2.7
3	baring position measure	1.3	0.1	0	1.5	0	0	1.5	4.4	7.1
4	pressing	1	0	0	0	0	0.7	0	1.7	8.8
5	baring position measure	1.3	0.1	0	1.5	0	0	1.5	4.4	13.2
6	pick up and hold down	1	0	0	0	0	0	0	1	14.2
8	pick up and place	1	0	0	0	0	0	0	1	18.6
9	assembly on shaft subassy	1	0	0	0	0.7	0	0	1.7	20.3
10	assembly on shaft subassy	2	0.1	0	0	0.7	0.7	0	3.5	23.8
11	assembly on shaft subassy	1	0.1	0	0	0	0	0	1.1	24.9
13										
18										
55	assembly on shaft subassy									
56	pick up and place	1	0	0	0	0.7	0	0	1.7	243.3
57	tightening	1	0	0	0	0	0	0	1	244.3
58	pick up and place	4	0.1	0	0	0	0	0	4.1	248.4
59	tightening	1	0	0	0	0	0	0	1	249.4
60	pick up and place	4	0.1	0	0	0	0	0	4.1	253.5
61	assembly on plug	1	0	0	0	0	0	0	1	254.5
63	pick up and place	1	0.1	0	0	0	0	0	1.1	255.6
64	pick up and place	2	0.1	0	0	0.7	0	0	2.8	262.5
65	riveting	2	0.1	0	0	0	0	0	2.1	264.6
66	additional rivets	4	0.1	0	0	0.7	0	0	4.8	269.4
82		2	0.1	0	0	0.7	0	12	14.8	284.2
83										284.2
84										284.2
		108	2.1	11	18	12	7	127		284.2
										284.2
	manouverity index				mounting index					12.36

The formula for the manoeuvring factor W_{man} after the changes is:

$$W_{man} = I_{man} / L_{kA} = 35.2/18 = 1.96. \quad (20)$$

The formula for the main activity ratio W_m after the changes is:

$$W_m = L_{pA} + L_{pB} + L_{pC} + L_{pD} + L_{pE} + L_{pF} + Sec = 112.8, \quad (21)$$

where:
$L_{pA} = 54$,
$L_{pB} = 1.4$,
$L_{pC} = 0$,
$L_{pD} = 7.5$,
$L_{pE} = 9.1$,
$L_{pF} = 6.3$,
$Sec = 35$.

The formula for the assemblability factor W_{mon} ($W_d = 0$) after the changes is:

$$W_{mon} = W_m / L_{kA} = 112.8/18 = 6.27. \quad (22)$$

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_{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_{man} and W_{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_{man} = 2.52 and 1.96 and W_{mon} = 10.73 and 6.27.

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

$$W_{unk} = 91/ 91+105 = 0.46 \ (46\ \%). \quad (23)$$

After the redesign for the small lot production:

W_{unk} = 71/ 71 + 85 = 0.45 (45 %). (24)

After the redesign for the mass production:

W_{unk} = 23/ 23+32 = 0.42 (42 %). (25)

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

W_{uno} = 5/5 + 14 = 0.26 (26 %). (26)

After the redesign for the small lot production:

W_{uno} = 12/12 + 14 = 0.46 (46 %). (27)

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

W_{uno} = 7/2 + 7 = 078 (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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