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Relative manufacturing costs in series of types with partial similarity

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Analysis and modelling

ABSTRACT

Purpose: The main aim of research was to analyse the relative manufacturing costs estimation process based on the similarity theory.
Design/methodology/approach: The manufacturing costs were calculated with similarity theory use, where the exponents were assigned to operations and cutting processes.
Findings: Many of construction series of types are similar partially. Because of that it is important to develop methods of manufacturing costs of series of types based on partial similarity. The cutting processes exponents use gives more accurate results than operation exponents.
Research limitations/implications: The calculation process preparation stage is more time consuming with exponents assigned to cutting processes than to operations.
Practical implications: Presented method was applied to sleeve series of types manufacturing cost estimation process.
Originality/value: Described analysis presents the manufacturing costs estimation method of partially similar series of types where exponents are assigned to cutting processes.
Keywords: Constructional design; Engineering design; Similarity theory

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1. Introduction

The product price is one of the key criteria while customer makes product search. For this reason, the manufacturer of a new technical mean must offer a product at a competitive price to meet customer requirements. Therefore the manufacturing costs estimation is extremely important stage in the constructional - designing process. Studies show that the decisions made at this stage are the key to the product cost [1,2]. For this reason it is important to develop tools to support the process of costs estimation, especially in the processes of designing the construction series of types. Many of construction series of types are similar partially. The new methods has to take into consideration that fact. In this paper the manufacturing costs estimation method results accuracy was analysed. There were used two methods: costs similarity with exponents assigned to operations and exponents assigned to cutting processes. The final costs values were compared.

2. Relative manufacturing costs

Relative costs are that calculated in reference to model construction based on identical calculation model A^{e_j}. They allow to take into consideration the variable (direct) costs - which depends on constructional attributes while omit the indirect costs, i.e. general factory costs, social costs etc. They describe the relation between manufacturing cost of one of the element size to manufacturing costs of the model construction [3].

$$rk_i^{e_j} = \frac{\text{new constr. manuf. costs}}{\text{model constr. manuf. costs}} = \frac{ko_i^{e_j}}{ko_0^{e_j}} = f\left(\varphi_{il}^{e_j}\right) \qquad (1)$$

where:

$rk_i^{e_j}$ - manufacturing costs similarity number (for identical construction with model construction $rk_i^{e_j} = 1$)

φ_{il} - dimension similarity number.

This makes possible to estimate the value without calculating specific values in a given currency. For this reason, the cost of production is not dependent on market prices of materials, services, etc.

There are three groups of relative manufacturing costs [3]:

- the relative manufacturing costs of geometrically similar elements (complete or partial similarity),
- the relative manufacturing costs of technologically similar elements,
- the relative manufacturing costs of geometrically similar parts manufactured by different machining processes.

In the first case there are manufacturing costs of elements based on the constructional similarity theory. That elements are characterized by constant shape and variable dimensions values. Technologically similar elements are manufactured using the same process steps and variable parameters. The relative manufacturing costs of geometrically similar parts manufactured by different technologies makes it easier to compare the cost of manufacturing the same item by different technologies and selecting the most advantageous from an economic point of view [4,5].

The manufacturing cost estimation models (calculation models) are the models of relations between constructional attributes and manufacturing costs.

One of the manufacturing costs determining method is the method which use cost similarity and it is the subject of the research presented in this paper.

3. Costs similarity

One of the manufacturing costs estimation method applied to series of types is the method based on the costs similarity. It starts from estimating the model element manufacturing costs $ko_o^{e_j}$. The relative costs of other series of types element $rk_i^{e_j};(i=1,iz)$ functionally depends on model element manufacturing costs (Fig. 1). The dimensions similarity number $\varphi_{il}^{e_j}$ is the independent variable [6, 7]:

$$rk_i^{e_j} = \sum_{op=1}^{opz}\left(a_{op}\cdot\prod_{l=1}^{lz_o}\varphi_{il}^{X_l}\right) \qquad (2)$$

where:

op - operation (0 - constant costs),

a_{op} - operation parameter based on costs which corresponds to model construction,

φ_{il} - dimensions similarity number assigned to operation $(l=1,lz_o)$,

x_l - exponent of dimension similarity number based on experiments in factory.

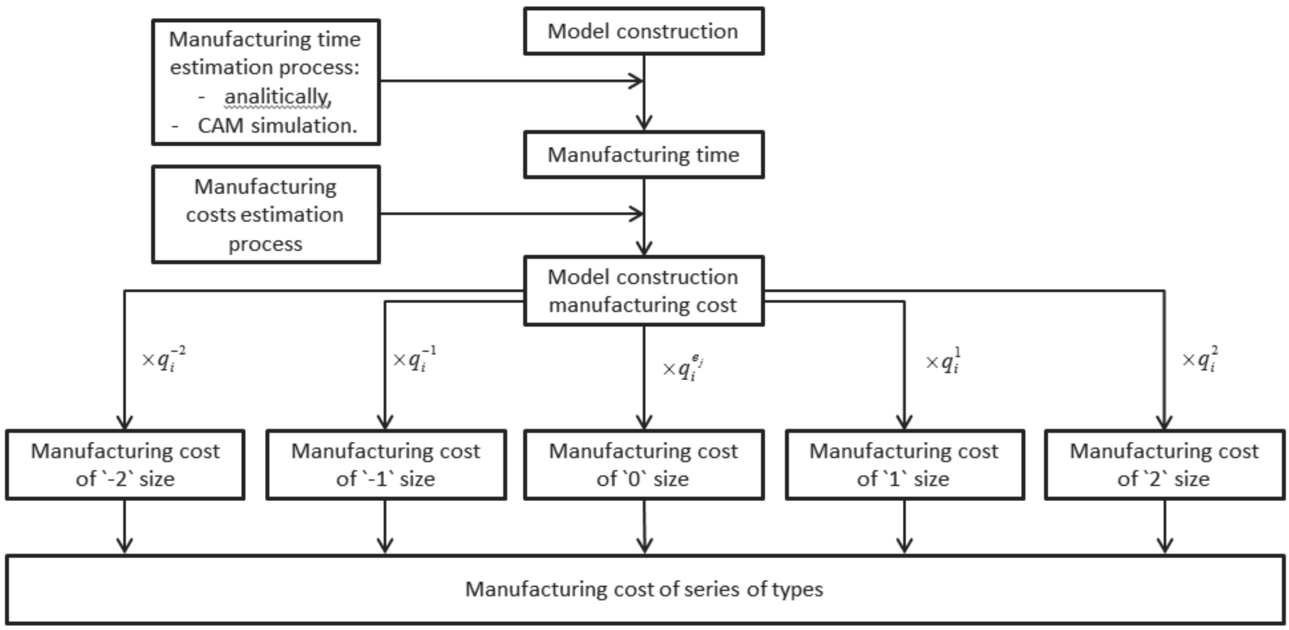

Fig. 1. Manufacturing costs estimation process based on similarity

4. Costs at complete similarity

Complete construction similarity assumes that every dimension of the element is multiplied or divided by the same similarity number.

4.1. Costs assigned to operations

When estimating the manufacturing cost by similarity method the cost components dependent on exponents are distinguished [2,8]. The equation which describes the manufacturing costs:

$$rk_i^{e_j} = a_3 \cdot \varphi_l^3 + a_2 \cdot \varphi_l^2 + a_1 \cdot \varphi_l^1 + \frac{a_o}{\varphi_s} \quad (3)$$

where:

$\varphi_s = \frac{s_i}{s_o}$,

s - number of elements.

The operations parameter values are defined in reference to the costs of operations corresponding to the model construction.

The exponent x_l is defined on the basis of approximation of the several elements construction costs, where the same operations are performed at the factory.

Constants a_3, a_2, a_1, a_0 are determined by the formulas:

$$a_3 = \frac{\sum \text{of model construction depend on } \varphi_l^3}{ko_0^{e_j}} \quad (4)$$

$$a_2 = \frac{\sum \text{of model construction depend on } \varphi_l^2}{ko_0^{e_j}} \quad (5)$$

$$a_1 = \frac{\sum \text{of model construction depend on } \varphi_l^1}{ko_0^{e_j}} \quad (6)$$

$$a_0 = \frac{\sum \text{of model construction depend on } \varphi_l^0}{ko_0^{e_j}} \quad (7)$$

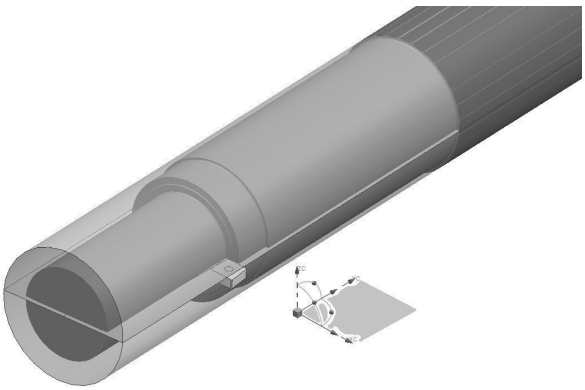

Fig. 2. The tool movement

The milling is the operation which costs similarity number is equal to third power of dimension similarity number. It is because during machining the tool moves along three axes. While turning the relation is square (Fig. 2), while drilling - linear. Table 1 includes exponents assigned to operations.

Table 1.
Operations exponents

Operation	Exponent
Material costs Milling	3
Turning Slotting	2
Drilling	1

This assignment allows to estimate the costs similarity number of every size of elements.

4.2. Costs assigned to operations cutting process

Assignment of exponents to the operation allows some simplification. Not every cutting process during turning is performed by moving the tool in two axes [9,10]. For example, when facing a shaft tool moves only perpendicularly to the axis of the element rotation and does not perform longitudinal movement (assuming processing in one pass). In this case, the exponent when turning is equal to one.

During milling of the splineway the milling cutter cuts in one pass: engage, move to the end of the groove, retract [11,12,13]. It can be assumed that in this way are performed splineways of every of the sizes. The splineway length is the only variable dimension. So the exponent will be equal to one. Table 2 includes exponents assigned to cutting processes.

Table 2.
Cutting processes exponents

Cutting processes	Exponent
Material costs Pocket milling	3
Planar milling Rough outer turning Rough inner turning Slotting	2
Splineway milling Shaft facing Finish outer turning Finish inner turning Thread turning Grooving Drilling	1

5. Costs in partial similarity

In partial similarity the dimensions values of series of types elements are defined by different similarity number. The exponent of the operations which were described by third power in complete similarity now are equal to:

$$\varphi_K = \varphi_{CK1} \cdot \varphi_{CK2} \cdot \varphi_{CK3} \tag{8}$$

Analogically the similarity numbers defined by square equation:

$$\varphi_K = \varphi_{CK1} \cdot \varphi_{CK2} \tag{9}$$

The similarity numbers in first power stay the same. For example: if the piston diameter depends on series R10 $(\varphi_{R10} = 1.25)$ of preferred numbers except for its height which depends on series R20 $(\varphi_{R20} = 1.12)$ then costs similarity number of turning will be equal to:

$$\varphi_K = \varphi_{R10} \cdot \varphi_{R20} = \varphi_{R10} \cdot \varphi_{R10}^{0.5} = \varphi_{R10}^{1.5} \tag{10}$$

The costs similarity numbers of cutting processes can be determined as for operations (Table 3).

Table 3.
Operations exponents

Operation	Exponent
Material costs Pocket milling	$\varphi_K = \varphi_{CK1} \cdot \varphi_{CK2} \cdot \varphi_{CK3}$
Planar milling Rough outer turning Rough inner turning Slotting	$\varphi_K = \varphi_{CK1} \cdot \varphi_{CK2}$
Splineway milling Shaft facing Finish outer turning Finish inner turning Thread turning Grooving Drilling	$\varphi_K = \varphi_{CK1}$

6. Verification

The manufacturing costs estimation process was verified on the sleeve example. In the first step the costs were calculated with exponents assigned to operation. Then the cutting processes were distinguished. The obtained results were compared with CAM simulation which is the most accurate and gives most valuable outcome (Table 5) [14,15,16]. The CAM simulation was performed in Siemens NX advanced graphical program. This simulation gives the main machining time. Based on that the manufacturing costs were calculated.

The sleeve shape is presented on Fig. 3 and Fig. 4. The diameter values are assigned to R10 series and the length values - to R20 series (Table 4). Because of that the similarity is partial.

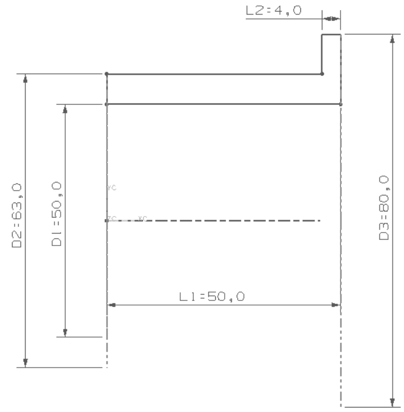

Fig. 3. Sleeve draft

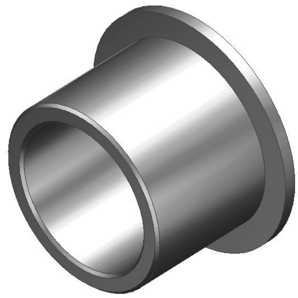

Fig. 4. Sleeve trimetric view

The technological operations during machining: turning and drilling. The turning similarity number is equal to:

$$\varphi_K = \varphi_{R10} \cdot \varphi_{R20} = \varphi_{R10} \cdot \varphi_{R10}^{0.5} = \varphi_{R10}^{1.5} \tag{11}$$

The drilling similarity number:

$$\varphi_K = \varphi_{R20} = \cdot \varphi_{R10}^{0.5} = \varphi_{R10}^{0.5} \tag{12}$$

The a_3, a_2, a_1, a_0 numbers were defined (Table 6).

Table 4.
Sleeve constructional attributes

	1	2	3	4	5	6	7	Series
	-3	-2	-1	0	1	2	3	
L1	36	40	45	50	56	63	71	R20
L2	2.8	3.2	3.6	4	4.5	5	5.6	R20
D1	25	32	40	50	63	80	100	R10
D2	32	40	50	63	80	100	125	R10
D3	40	50	63	80	100	125	160	R10

Table 5.
Manufacturing costs - CAM simulation

			1	2	3	4	5	6	7
			-3	-2	-1	0	1	2	3
Total costs [zł]			248.30	375.99	575.69	888.78	1456.24	2417.23	4312.99
Mass [kg]		In	0.41	0.71	1.29	2.20	3.81	6.63	12.12
		Out	0.10	0.16	0.28	0.51	0.93	1.56	2.80
Material costs [zł]			118.83	205.38	372.83	636.80	1104.23	1919.78	3507.90
Turning	Time [min]	Cycle	0.58	0.88	1.15	1.59	2.46	3.72	6.44
		Main	0.29	0.55	0.78	1.15	1.89	2.96	5.26
		Auxiliary	0.20	0.20	0.20	0.20	0.20	0.20	0.20
		Setup	25.00	25.00	25.00	25.00	25.00	25.00	25.00
		Machining	0.29	0.55	0.78	1.15	1.89	2.96	5.26
	Costs [zł]	Labour	28.64	39.24	48.74	63.88	94.51	138.63	233.90
		Amortization charges	7.23	13.60	19.30	28.40	46.79	73.29	130.50
		Energy	3.27	6.14	8.72	12.82	21.13	33.10	58.93
		Total machine costs	18.90	35.53	50.44	74.20	122.26	191.49	340.97
	Cutting operation cost [zł]	Facing	8.80	9.28	10.16	11.40	13.24	16.15	21.21
		Rough turning	8.76	10.91	12.32	14.21	21.43	27.02	53.20
		Finish turning	8.67	9.15	10.25	10.78	12.14	14.17	17.29
		Inner rough turning	0.00 (no cutting)	9.46	11.88	17.51	26.09	42.94	68.42
		Inner finish turning	7.88	8.67	8.93	9.33	9.90	10.74	11.79
		Total	81.64	122.25	152.72	201.31	299.58	441.14	746.78
Drilling	Time [min]	Cycle	0.45	0.46	0.48	0.49	0.51	0.53	0.55
		Main	0.19	0.19	0.21	0.21	0.23	0.25	0.27
		Auxiliary	0.20	0.20	0.20	0.20	0.20	0.20	0.20
		Setup	25.00	25.00	25.00	25.00	25.00	25.00	25.00
		Machining	0.19	0.19	0.21	0.21	0.23	0.25	0.27
	Costs [zł]	Labour	24.23	24.44	25.13	25.34	26.02	26.92	27.54
		Amortization charges	4.59	4.71	5.13	5.25	5.66	6.20	6.57
		Energy	2.07	2.13	2.31	2.37	2.56	2.80	2.97
		Total machine costs	11.99	12.31	13.39	13.72	14.80	16.20	17.17
	Cutting operation cost [zł]	Facing	47.84	48.37	50.14	50.67	52.44	56.32	58.31

Table 6.
Sleeve manufacturing costs - operations

Operation No.	Costs dependent on φ_1^3	Costs dependent on $\varphi_1^{1.5}$	Costs dependent on $\varphi_1^{0.5}$	Constant costs	Operations
1.	636.80	-	-	-	Material costs
2.	-	201.31	-	-	Turning
3.	-	-	50.67	-	Drilling
	636.80	201.31	50.67	0.00	888.78
	$a_3 = \frac{636.80}{888.78} = 0.73$	$a_2 = \frac{201.31}{888.78} = 0.23$	$a_1 = \frac{50.67}{888.78} = 0.06$	$a_0 = 0$	$\sum_{z=0.3} a_z = 1$

$$q_i^{e_i} = 0.73 \cdot q_1^3 + 0.23 \cdot q_1^{1.5} + 0.06 \cdot q_1^{0.5} + 0 \quad (13)$$

These are the costs of one hundred elements. The manufacturing costs of model element were defined with CAM simulation use. Costs of every element consist Table 7.

Table 7.
Manufacturing costs - operations

No.	i	Similarity number $q_i^{e_i}$	Manufacturing costs [zł]
1	-3	0.22	195.48
2	-2	0.35	310.54
3	-1	0.58	515.41
4	0	1.00	888.78
5	1	1.78	1581.74
6	2	3.25	2885.72
7	3	6.04	5364.83

In the second stage the cost of the same manufacturing process was calculated. Now the cutting processes and exponents corresponding to them were distinguished. The a_3, a_2, a_1, a_0 numbers were defined (Table 9). Costs values are shown in Table 8.

Finally the results obtained by three methods (costs similarity with operations and cutting processes exponents and with CAM simulation use) were compared (Table 10 and Fig. 5).

The differences between results obtained by similarity method with operations exponents and with CAM simulation use are greater (27.03%) than between cutting processes exponents and CAM (14.85%). This percent values are for smallest size. It can be seen that replacing the operations exponents by cutting processes exponents improved analysis accuracy. For biggest size that values are: 19.61% and 18.30%. In this case the improvement is very small - 1.31%.

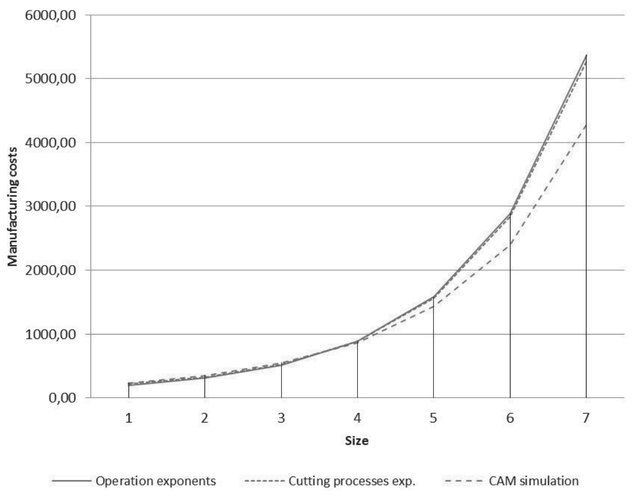

Fig. 5. Manufacturing costs

Table 8.
Manufacturing costs - cutting processes

No.	i	Similarity number $q_i^{e_i}$	Manufacturing costs [zł]
1	-3	0.24	216.19
2	-2	0.37	327.88
3	-1	0.59	526.33
4	0	1.00	888.78
5	1	1.76	1564.17
6	2	3.20	2840.89
7	3	5.94	5278.75

Table 9.
Sleeve manufacturing costs - cutting processes

No.	Costs dependent on φ_1^3	Costs dependent on $\varphi_1^{1.5}$	Costs dependent on φ_1^1	Costs dependent on $\varphi_1^{0.5}$	Constant costs	Cutting processes
1.	636.80	-		-	-	Material costs
2.			31.94			Facing
3.	-	50.69		-	-	Rough turning
4.				27.84		Finish turning
5.		72.67				Rough inner turning
6.				18.17		Finish inner turning
7.	-	-		50.67	-	Drilling
	636.80	123.36	31.94	96.67	0.00	888.78
	0.72	0.14	0.04	0.11	0.00	1.00

Table 10.
Manufacturing costs

No.	i	Operation exponents use [zł]	Cutting processes exponents use [zł]	CAM simulation use [zł]	Operation exponents - CAM [%]	Cutting operation exponents - CAM [%]
1	-3	189.61	216.19	248.30	-27.03	-14.85
2	-2	302.34	327.88	375.99	-21.08	-14.68
3	-1	503.94	526.33	575.69	-11.70	-9.38
4	0	872.76	888.78	888.78	0.00	0.00
5	1	1559.35	1564.17	1456.24	7.93	6.90
6	2	2854.43	2840.89	2417.23	16.23	14.91
7	3	5321.10	5278.75	4312.99	19.61	18.30

The use of cutting exponents instead of operation exponents in same cases may not be effective. For example if the shaft is machined in one operation - turning and this turning consist of many cutting operations (facing, turning, grooving, threading etc.) calculation with cutting exponents use will be much more time consuming than with only one exponent assigned to operation. If final improvement will be very small the simpler way (operation exponent use) will be more profitable. It must be always considered if the cutting operation exponents use is adequate to value of result improvement.

7. Conclusions

Technical means manufacturing costs estimation methods are very important in the market. It is very important to develop this kind of tools especially in reference to construction series of types. The manufacturing operations exponents, used in costs similarity method, were analyzed in this paper. The exponent values were calculated both by theoretical analyze and CAM simulation. The operations exponents were replaced by cutting processes exponents which gives better results accuracy. The calculation with cutting process exponent is more time consuming because it must be distinguished every cutting process. This is very important while calculating manufacturing costs of many elements. Sometimes significant increasing of analysis time may be not justified in reference to small accuracy improvement. It is always important to take into consideration the balance between time consumption and final results quality.

Developed tool can be very important in series of types manufacturing costs estimation process and will help to provide the economic profit of the company.

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