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Quantitative constructional attributes selection in construction series of types

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Analysis and modelling

ABSTRACT

Purpose: The main aim of research was to analyze the selection process of quantitative constructional attributes in construction series of types.
Design/methodology/approach: The quantitative constructional attributes selection process is based on constructional similarity theory.
Findings: The constructional similarity theory allows to select the quantitative constructional attributes.
Research limitations/implications: The final construction similarity is not complete because of adjusting the dimension values to preferred numbers, catalogue and standardized elements dimensions etc.
Practical implications: Presented method was applied to generate the constructions series of types with the use of quantitative constructional attributes selection process.
Originality/value: Described analysis presents the process of selecting the quantitative constructional attributes with computer aid.
Keywords: Constructional design; Engineering design; Similarity theory

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1. Introduction

The main purpose of applying the constructional similarity theory is to generate an ordered construction family such as series of types based on pattern construction.

In a market economy, construction is not limited only to develop single technical mean, but it should cover a wide range of construction needs for a particular class of technical means. For example the economic plans of production only lugs loaded by force P = 4 kN, bar or rod diameter d = M16 and pin hole diameter D = 16 mm (Fig. 1) will not be bought. However, if an ordered construction family will be created in the form of lug series of types, for a set of needs identified by the unified characteristic attributes of range values: P = 0.9-8 kN, d = M5-M30 mm, D = 5-30 mm, it will result in a greater chance of obtaining an order, better adapt to the needs of the client, and thus able to stay on the market. So it is reasonable to develop methods of construction, which base on one design. It creates a reasonable range of constructions, characterized by constant construction shape and variable dimensions values.

On this basis, the quality – quantity problem is reduced to a quantitative problem, i.e. for which characteristic attributes cch_{ic}^{u} one can select the optimal dimensions values $w_{il}^{e_j}(j=1,jz)$. This assignment, in the generation process of constructions ordered families, is called γ assignment [3,9].

$$cch_{ic}^{u} \rightarrow w_{il}^{e_j}(j=1,jz) \tag{1}$$

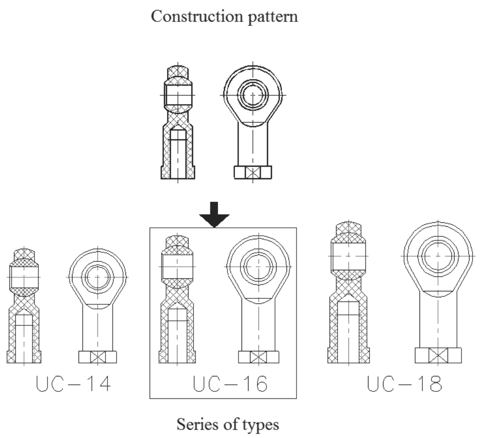

Fig. 1. Lug series of types

In the construction ordered family generation process, with construction similarity method use, the following steps are distinguished below:

1. selection, verification and pattern construction modification,
2. unifying process of construction ordered families parameters,
3. construction drafting with opened dimensions set,
4. generation of parameters and dimensions similarity conditions,
5. calculation and verification of series of types dimensions values,
6. parametric construction drafting.

2. Pattern construction

The pattern construction (ks_0) is the construction which is practically verified in terms of action (CAD simulation) and optimized (especially by CAE stress analysis), checked in reference to manufacturing process (CAM simulation) and the result has been experimentally verified (prototype verification). The construction can be a pattern one if the product based on that construction meets the criteria from experimental verification. Because of calculation of dimensions values by constructional similarity method it is recommended to select the pattern construction from middle range of ordered parameters values [6,11].

The Varian Analysis used in advanced graphical program I-Deas is the special tool to generate the new pattern construction for new ordered construction family [10]. In this stage the Finite Element Method is applied. Here it is extended to:

- sensitivity analysis – the dimension values, significant in reference to stress states, strain and mass, are selected,
- parametric analysis - for given range of important dimensions values the optimal values are determined [8], in reference to maintain the permissible stress, strain and to minimize the mass.

3. Unification and construction drafting with opened dimensions set

Because of drafting formalization, the quantitative attributes were distinguished from the characteristic attributes collection CCH_c^u. The quantitative attributes are called the construction family parameters $Pa_a^u;(a=1,az)$. The parameters matrix pa_{ia}^u sets the ***independent variables*** during the quantitative attributes values of the elements $x_{ia}^u = pa_{ia}^u$ designation process. The constructional attributes of the element selection process is made in reference to a single need po_i^u which is represented by a row of a parameters matrix.

The quantitative construction attributes are selected in reference to parameters value (geometrical and material dimension values) each of the element e_j, $y_{ml}^{e_j}(m=i,iz;l=1,lv_j)$. The space of needs is described by unified parameters values, which are limited and ordered parameters values taken as valid for a limited time. The tools, which aid the unified parameters generation, are: forecasting, adjust parameters values to the preferred numbers, adjust parameters values to cooperating technical means parameters [3,14]. The example of hydraulic actuator unified parameters is shown in Figure 2, as independent variables of γ assignment.

The γ assignment precedes β assignment, which involves the decomposition of typical design solutions by creating common constructional shapes of elements with dimensions sets. In the set of dimensions, variable dimensions take the alpha - numerical marks, for example the element MTG dimensions are: TG1 - TG15 (Fig. 2).

4. Constructional similarity conditions

The method of dimensions values selection is based on physical similarity theory [1,9]. The physical models were build in a proper scale and tested to simulate complex physical phenomena. Based on that step the new technical means constructions were developed, for example the airplane model (in a proper scale) tested in aerodynamic tunnel helped to modify the constructional shape and dimension values of analyzed real-scale airplane.

In the constructions ordered family generation process with the constructional similarity use, the model corresponds to pattern construction $ks_0\{y_{ol}^{e_j};(l=1,lv_j)(j=1,jz)\}$ with pattern parameters $\overline{X}_0\{x_{0a};(a=1,az)\}$.

They are the base for creation of constructions which are geometrically similar $ks_i\{y_{il}^{e_j};(l=1,lv_j)(j=1,jz)\}\in RK_n$ in reference to properly unified parameters $\overline{X}_i^u\{x_{ia}^u;(i=1,iz)(a=1,az)\}$, so the coupling and transformation relations are identical (Fig. 3).

The two main relations between attributes of pattern construction ks_0 and new construction ks_i were defined:

- parameter similarity:

$$\varphi_a^u = \frac{x_{ia}^u}{x_{0a}} \tag{2}$$

- dimension similarity:

$$\varphi_l^{e_j} = \frac{y_{il}^{e_j}}{y_{01}^{e_j}} \tag{3}$$

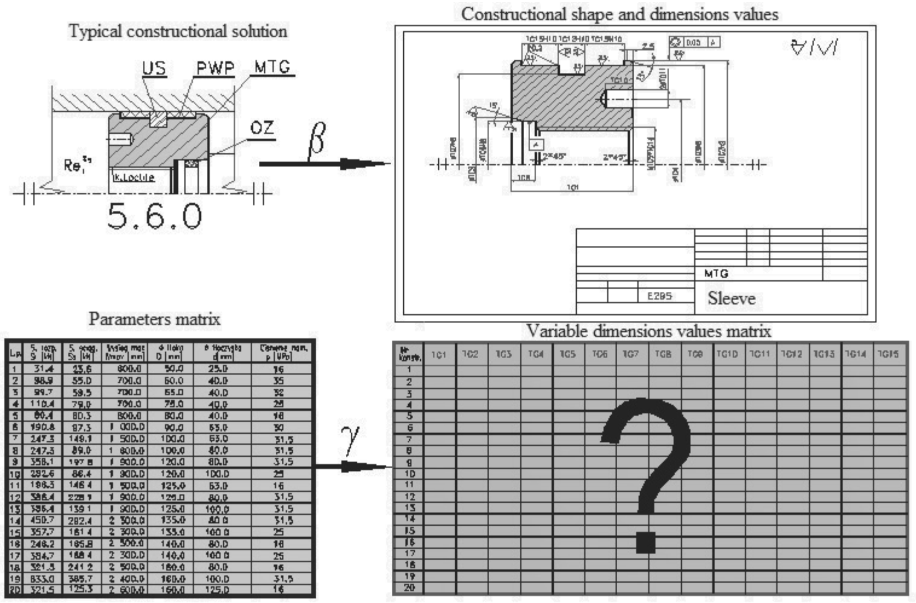

Fig. 2. The β and γ assignment

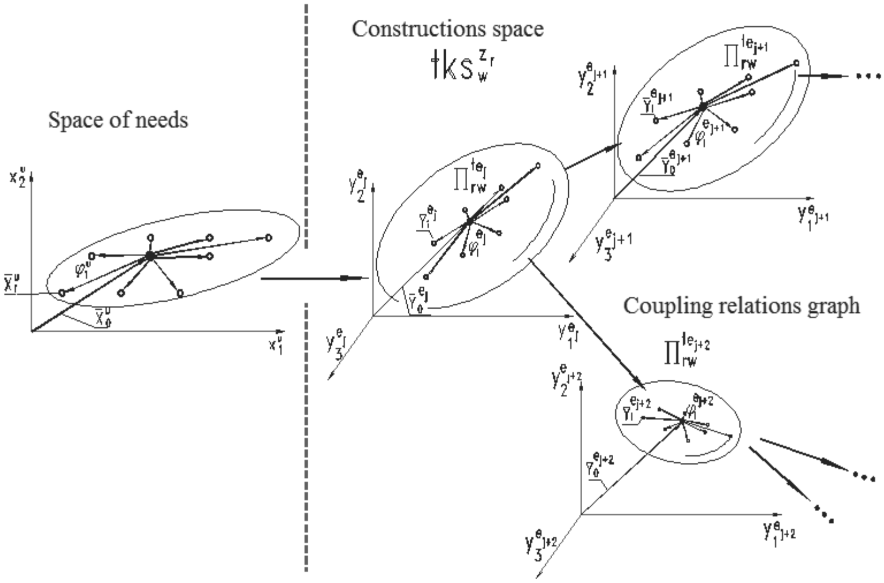

Fig. 3. Quantitative constructional attributes selection model based on constructional similarity

Following the constructional similarity theory assumption, the coupling and transformation relations (Fig. 4a) of the new construction have to be the same as pattern construction, so the construction collection is optimally diffused. The phenomenological models and physical relationships, described by mathematical equations (Fig. 4b), are assigned to isomorphic coupling and transformation relations which are distinguished in a system structure.

That functions are the basis for constructional attributes selection $y_{il}^{te_j}(l=1,lv_{is}) = f_p(x_{ia}^u)$.

The ***constructional similarity conditions*** are created preserving the identity of the states: physical, stereomechanical and simple described by mathematical functions for each family relationship system structure.

Constructional similarity numbers are determined as a function of the dimensions similarity φ_l for assumed similarity numbers: force φ_F, torque φ_{Mo}^u, area φ_A, volume φ_V, strength indicator φ_W, mass moment of inertia φ_J. The constructional similarity numbers relate to quantitative constructional attributes where the constructional shape is constant. An example of assumed cross-section area similarity, eg. square which side length is 1, where the similarity of the side is equal to φ_l:

$$A = 1^2, \quad \varphi_A = \left(\frac{l_i}{l_0}\right)^2 = \varphi_l^2 \tag{4}$$

Equation (4) also applies to other sections: rectangle, ellipse, etc., assuming a uniform growth of all cross dimensions, so it meets full dimensions similarity. The condition of cross-sectional area similarity means that if the shaft diameter will increase twice $\varphi_1 = 2$, the cross section area will be four times greater $\varphi_A = 4$. Generally the following relationships can be distinguished in Table 1.

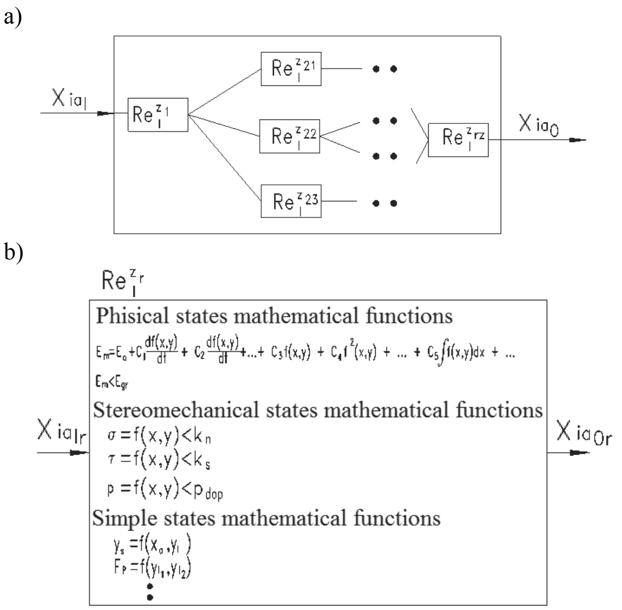

Fig. 4. Mathematical description of future technical mean

The base stereomechanical state, which must stay the same in the new construction as in pattern one, is the stress identity $\varphi_\sigma = 1$. Considering the simple tensile state caused by static force F (excluding weight), the stresses are equal to:

$$\sigma = \frac{F}{A} \le \sigma_{dop} \tag{5}$$

The stress similarity number in series of types (modular series) is:

$$\varphi_\sigma = \frac{\sigma_i}{\sigma_0} = \frac{F_i \cdot A_o}{F_0 \cdot A_i} = \frac{\varphi_F}{\varphi_A} = \frac{\varphi_F}{\varphi_l^2} = 1 \tag{6}$$

After transformation:

$$\varphi_F = \varphi_l^2 \tag{7}$$

Parameters values and quantitative constructional attributes values of elements, based on constructional similarity conditions, can be calculated by equations:

- unified parameters values:

$$x_{ia} = x_{0a} \cdot (\varphi_{i1}^{u})^i \tag{8}$$

- dimensions values:

$$y_{il}^{e_j} = y_{01}^{e_j} \cdot (\varphi_{il}^{e_j})^i \tag{9}$$

where:
x_{0a} - a-value of pattern parameter,
y_{01} - l-value of pattern construction dimension,
exponent of the number which describe the distance to pattern construction (takes the values i=..-2, -1, 0, 1, 2…, where i=0 corresponds to pattern construction).

The parameters and dimensions values can be calculated in the analytic way, as described above, or in graphical way (monograms with logarithmic axes).

5. Example

The quantitative constructional attributes selection process will be presented on the example of hydraulic prop series of types.

5.1. Pattern construction

The pattern construction is the base for series of types generation process. Because of that it has to be optimized and practically verified. This construction must fulfill the criteria which comes from: Technical Purposefulness Rights, Manufacturing Capabilities Rights and Economical Rights [4,5]. As mentioned before, the final product has to be verified experimentally. The pattern construction of hydraulic prop must fulfill following criteria:

- maximum construction density,
- minimum number of elements,
- assembly simplicity.

The two-stage, two-piston hydraulic prop construction was chosen (Fig. 5).

5.2. Parameters unification

The hydraulic prop is characterized by parameters:

- working load,
- maximum overhang.

This parameters have to be unified. The unification process is defined as the criterion limitation and organization of the characteristic attributes values forming one values set applied to particular family structure [2,13]. The unified characteristic attributes values, which are the result of this process, are presented in Table 2.

Table 1.
Basic dependences between similarity numbers

Similarity number of	Designation	Similarity number
Rotational speed Angular velocity	φ_n, φ_ω	φ_l^{-1}
Linear velocity From static forces: Elongation Stress, surface pressure	φ_v, φ_ε, φ_σ, φ_p	$\varphi_l^0 = 1$ (const.)
Elastic elongation, spring stiffness From gravity force: Elongation Stress, surface pressure	$\varphi_{\Delta l}$, φ_c, φ_ε, φ_σ, φ_p	φ_l^1
Static forces Surface area	φ_F φ_A	φ_l^2
Volume Weight Torque Axial and polar section modulus	φ_V φ_G, φ_{Ms}, φ_{Wx}, φ_{W0}	φ_l^3
Area moment of inertia	φ_{Ix}, φ_{I0}	φ_l^4
Mass moment of inertia	φ_{Jx}	φ_l^5

Table 2.
Unified parameters values

I stage piston diam.[mm]	**250**	**315**	**400**	**500**	**630**
II stage piston diam.[mm]	200	250	315	400	500
Working load [kN]	1005.31	1570.80	2493.80	4021.24	6283.19
Max. overhang [mm]	2000	2500	3150	4000	5000

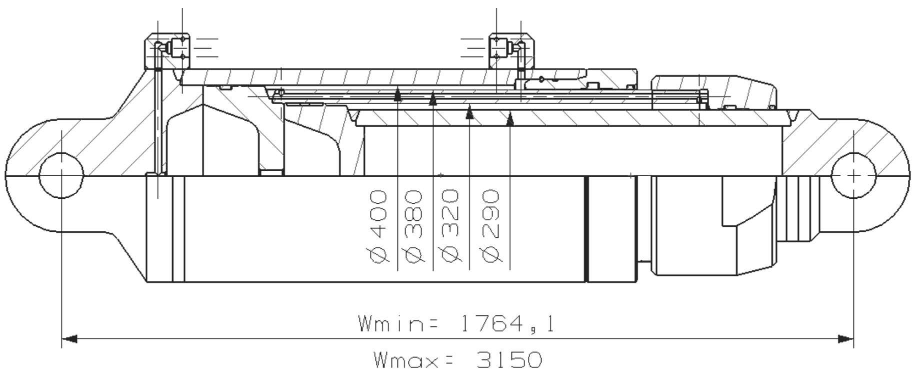

Fig. 5. Hydraulic prop construction

The working load depends directly on piston diameter of second stage and on hydraulic pressure.

$$Q = p \cdot \frac{\pi D^2}{4} \tag{10}$$

where:
D - second stage piston diameter [mm],
p - hydraulic pressure [MPa].

The maximum overhanging value depends on pipes length, glands and pistons dimensions etc. To calculate the lengths of the pipes, which allow to achieve the desired overhang, the following set of equations was defined:

$$\begin{cases} S1 = M11 + R1 + D12 + M2 + D21 + D22 + M3 + M4 \\ S2 = S1 + L1 + L2 \\ R1 = M12 + T11 + L1 + D11 \\ R2 = T13 + T21 + L2 \\ R2 = R1 - M12 - T11 - T12 + D12 + M2 + D21 \end{cases} \tag{11}$$

The above equations solution allows to estimate the length of the pipe, R1:

$$R1 = \frac{1}{3}(S2 - M11 + 2M12 - 2M2 - M3 - M4 - 2D12 + D11 - 2D21 - D22 + 2T11 + T12 + T13 + T21) \quad (12)$$

The other pipes lengths:

$$R2 = R1 - M12 - T11 - T12 + D12 + M2 + D21 \quad (13)$$

$$R3 = R2 - T13 - T21 - T22 + D22 + M3 \quad (14)$$

The minimum overhang:

$$S1 = M11 + R1 + D12 + M2 + D21 + D22 + M3 + M4 \quad (15)$$

Now it is possible to calculate the geometrical attributes of elements to achieve planned overhang.

5.3. Hydraulic prop constructional similarity conditions

The construction relations are distinguished and then the constructional similarity conditions were defined.

The relations are:

- R1 - hydraulic pressure to force transformation.
- R2 - hydraulic pressure to force transformation which produces stress in bottom of prop.
- R3 - hydraulic pressure to force transformation which produces stress in cylinder walls.

This relations are described below.

- R1 - hydraulic pressure to force transformation.

Similarity condition comes from physical similarity. It describes the relation between the working load and the circle area and comes from the equation:

$$p = \frac{4F}{\pi D^2} \quad (16)$$

where:
p - hydraulic pressure [MPa],
F - actuator force [N],
D - piston diameter [mm].

So the constructional similarity condition (constant pressure):

$$\varphi_p = \frac{\sigma_i}{\sigma_0} = \frac{F_i \cdot A_0}{F_0 \cdot A_i} = \frac{\varphi_F}{\varphi_A} = \frac{\varphi_F}{\varphi_r^2} = 1 \quad (17)$$

The relation between piston diameter and force is square:

$$\varphi_F = \varphi_l^2 \quad (18)$$

where:
f_l - dimension similarity number,
f_F - parameter (force) similarity number.

- R2 - hydraulic pressure to force transformation which produces stress in bottom of prop.

The bottom thickness is calculated as follows [7]:

$$\sigma_{max} = \frac{3p}{4h^2} R^2 \quad (19)$$

$$h = 0{,}433 \cdot d \sqrt{\frac{p}{k}} \quad (20)$$

where:
p - hydraulic pressure [MPa],
D - bottom inner diameter [mm],
R - bottom radius [mm].

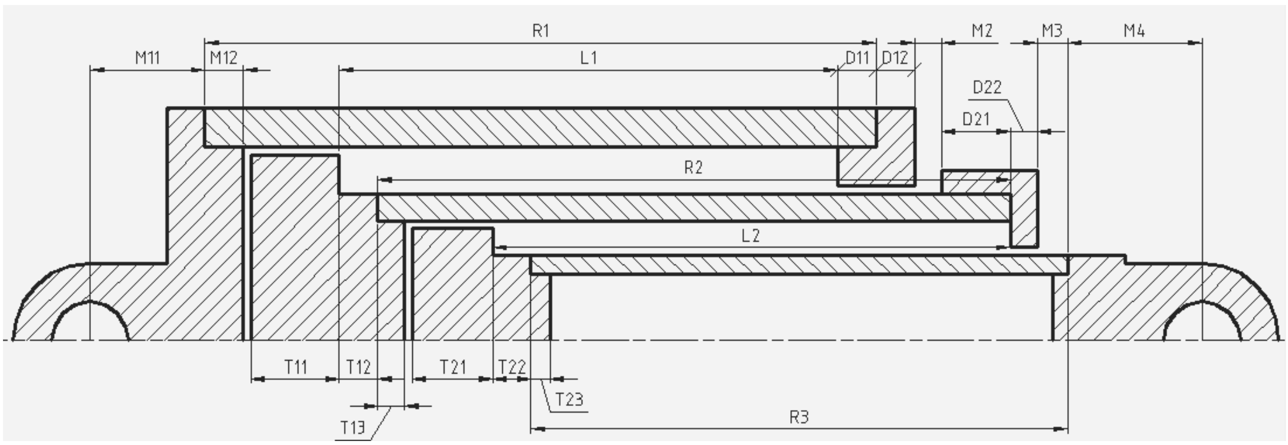

Fig. 6. Quantitative constructional attributes selection model based on constructional similarity

The constructional similarity condition:

$$\varphi_\sigma = \frac{\sigma_i}{\sigma_0} = \frac{p_i \cdot R_i^2 \cdot h_0^2}{h_i^2 \cdot p_0 \cdot R_0^2} = \frac{\varphi_p \cdot \varphi_R^2}{\varphi_h^2} = \frac{\varphi_R^2}{\varphi_l^2} = 1 \quad (21)$$

Finally:

$$\varphi_R = \varphi_l^2 \quad (22)$$

- R3 - hydraulic pressure to force transformation which produces stress in cylinder walls.

Stress condition:

$$\sigma = \frac{P}{F} + \frac{Py_{\max}}{W} = \frac{PW + Py_{\max}F}{FW} \quad (23)$$

where:
F - cross-sections area of each of the pipes [mm^2],
W - section modulus of each of the pipes cross-sections [mm^3],
P - axis, working load [N],
y_{max} - maximum inflection value [mm].

The constructional similarity condition:

$$\varphi_\sigma = \frac{\sigma_i}{\sigma_0} = \frac{(P_iW_i + P_iy_{\max i}F_i)F_0W_0}{F_iW_i(P_0W_0 + P_0y_{\max 0}F_0)} =$$
$$= \frac{(P_0\varphi_pW_0\varphi_l^3 + P_0\varphi_py_{\max o}\varphi_l F_0\varphi_l^2)F_0W_0}{F_0\varphi_l^2W_0\varphi_l^3(P_0W_0 + P_0y_{\max 0}F_0)} =$$
$$= \frac{P_0\varphi_p\varphi_l^3F_0W_0\,(W_0 + y_{\max 0}F_0)}{F_0P_0\varphi_l^5W_0\,(W_0 + y_{\max 0}F_0)} = \frac{\varphi_p}{\varphi_l^2} \quad (24)$$

After simplification:

$$\varphi_P = \varphi_l^2 \quad (25)$$

The similarity conditions for peripheral stress was defined analogically. The radial stress is equal to hydraulic pressure. Above equations show that the relation between parameters and geometrical attributes is square.

5.4. Stress analysis

The FEM stress analysis was performed with the Nastran solver use [12,15]. The hydraulic prop lug was tested. The analysis showed the stress accumulation in the lug at the milled side surfaces (Fig. 7a). To avoid that the constructional shape was modified (Fig. 7b).

The pipes were verified with FEM analysis too. The stress values in elements are shown on Figs. 8-11.

It may be noted that in the whole series of types the material stress is very similar.

a) b)

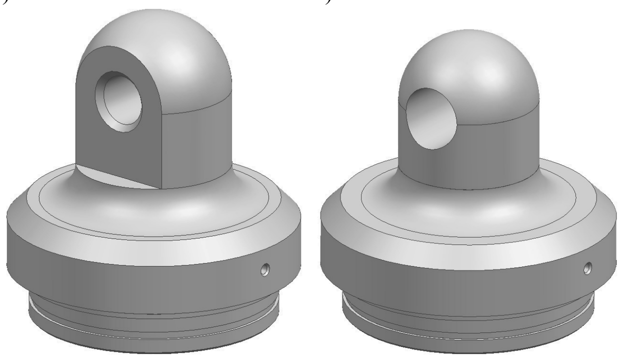

Fig. 7. The lug: a) before analysis, b) after analysis

5.5. Series of types

Basing on pattern construction and defined constructional similarity conditions the dimension values of elements were calculated. The pattern construction 3D model was made in advanced graphical program NX. The relations between elements dimensions and parameters were defined. The relational graph generated in NX program is shown on Figure 12. The hydraulic prop 3D model was modified basing on a matrix containing dimensions values of every size of the elements. The complete hydraulic props series of types is a final result of the presented procedure (Fig. 13).

6. Conclusions

The theory of constructional similarity bases on the theory of physical similarity. The pattern construction is a model in the theory of constructional similarity. The essence of this paper is to present the selection of new designed technical means constructional attributes to obtain the identical states: physical, stereomechanical or simple like in the pattern construction. The process was verified on hydraulic prop series of types. The research allows to present conclusions described below.

The differences between verification results of analytic and Finite Element Method are small. The stresses from analytic one are the sum of bending and compression. In the FEM analysis the pipes are fully fixed because of welding them to other parts. Taking into account the above factors it can be concluded that the finite element method provides more reliable results.

The stresses in the whole series of types differ very little. This means that the criterion of structural similarity theories, which point at preservation of identical stress states, is met. Slight variations due to adjusting of the dimension values to: a range of normal numbers, to the dimensions of standardized and catalogue elements, etc. are observed.

The use of computer aided design facilitated the process of generating a patter construction, analysis and stress verification of elements and complete series of types generation.

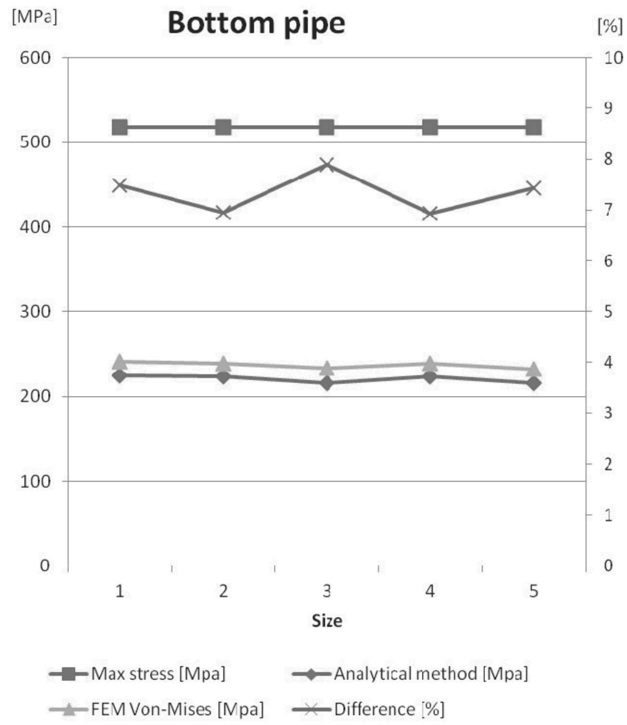

Fig. 8. Stress values in bottom pipe

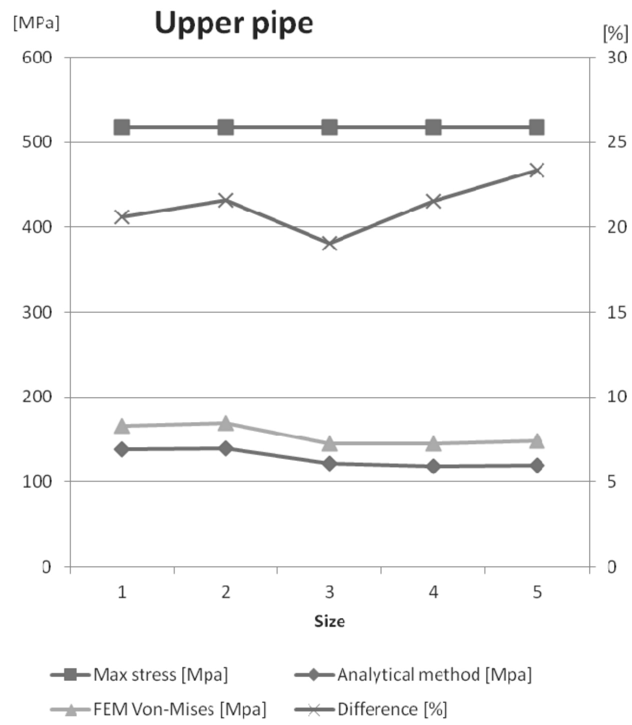

Fig. 10. Stress values in upper pipe

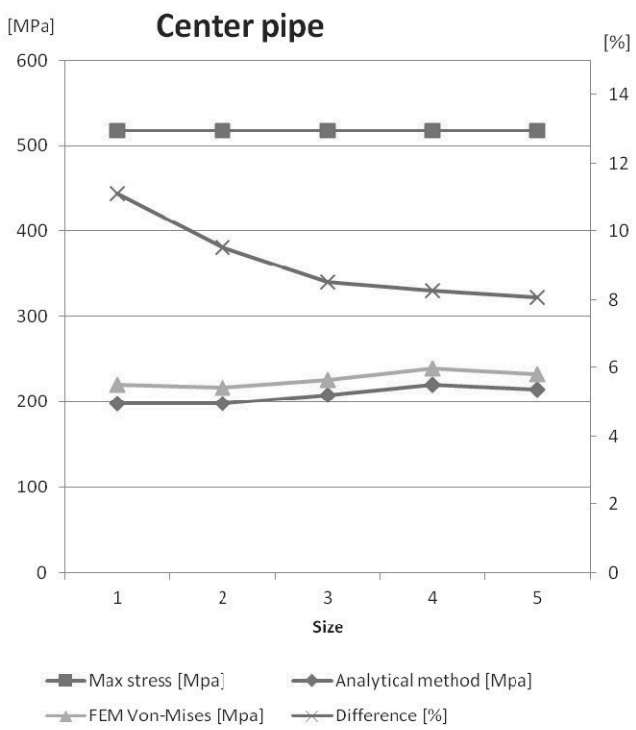

Fig. 9. Stress values in center pipe

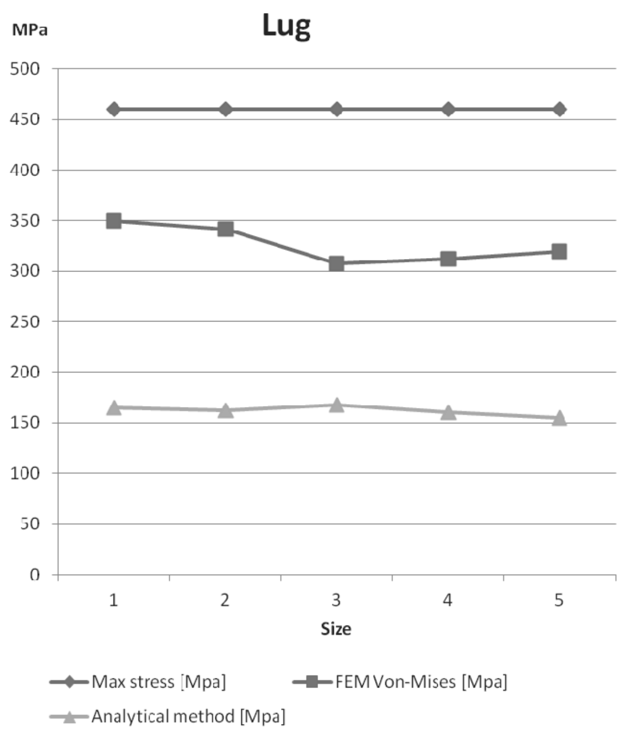

Fig. 11. Stress values in lug

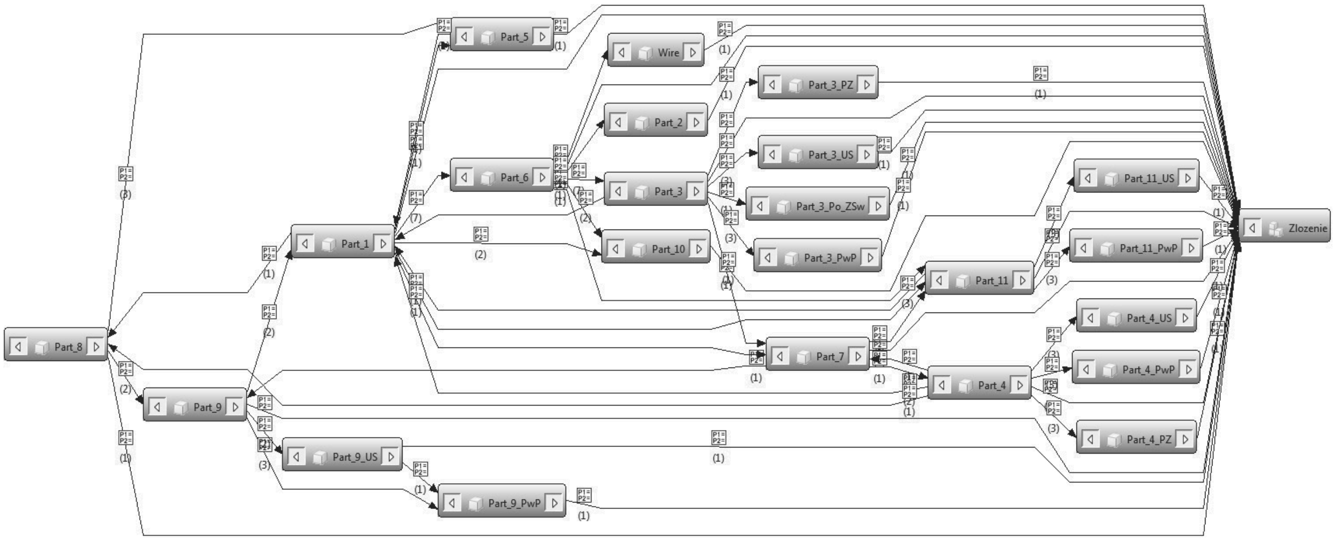

Fig. 12. Hydraulic prop relations graph

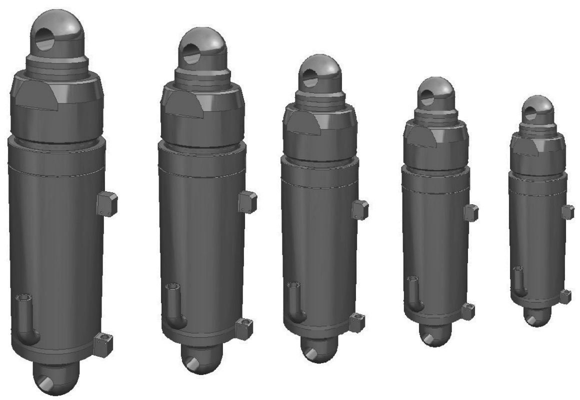

Fig. 13. Hydraulic props series of types

Acknowledgements

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