FINITE ELEMENT BASED OPTIMIZATION IN THE PROCESS OF SELECTING THE GEOMETRIC DESIGN FEATURES CONSTRUCTIONS

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Abstract: The article presents the capabilities of selected tools aiding the design and construction process in terms of optimization of the chosen design features. It lists and describes the application and possibilities of the construction form optimization process and the way of selecting optimal values of constructed dimensions or modified machine elements. The paper presents and describes stages of the geometric design features optimization using NX (Siemens) or TOSCA STRUCTURE software. It also defines the criteria for selecting optimal design features that are the basis for the assessment of the existing, as well as new construction solutions. The aim of the publication is to provide the Readers with the possibilities of construction optimization using the available on the market CAD/CAE software
Key words: topology optimization, parametric optimization, Finite Elements Method, design features, optimization criteria.

1. INTRODUCTION

Competitiveness on the dynamically changing market may only be retained by meeting the expectations of Clients. The accelerating technical development poses significant and difficult challenges for the designers and design engineers. They have little time to develop the technical measures adjusted to the demands of the Clients, taking into account the criteria resulting from the technical advisability as well as economic and technical feasibility (Cielniak, 2011; Dacko, 1994). In order to succeed in today's market economy, the design and construction process cannot be only limited to the development of just one construction of the technical measure (Brandt, 1994; Gendarz, 2013]. One should aim at creating sets of constructions encompassing the broad spectrum of demands for the particular class of technical measures (Dietrych, 1985). The best way to satisfy a wide range of needs with no increase in time and production costs is to use the ordered families of constructions, such as series of types and modular systems.

2. DESIGN FEATURES

According to the Silesian School methodology (Dietrych, 1985; Gendarz, 2009; Gendarz, 2013, Gendarz and Cielniak 2013; Gendarz and Chyra, 2009), a construction is an arrangement of structures (external and internal) and stages of the future technical means, described by means of the design features. A definition implies that clear identification of a construction in the design and construction process involves defining design features.
Design features CK (Gendarz, 2009) describe, according to the aforementioned definition of a construction, an arrangement of external structures – geometric features C_g, arrangement of internal structures – material-related features C_t and stages of the product– assembly-related features C_m.

$$CK = C_g \cup C_t \cup C_m \tag{1}$$

Geometric features C_g describe the external structure and macrostructure of the future technical means. They include the geometric construction form Π_g and geometric dimensions W_g.

$$C_g = \Pi_g \cup W_G \tag{2}$$

The geometric form Π_g, is a qualitative design feature, describing topology of a product. It mostly depends
on (Gendarz, 2009):

- specified system S_u,
- product parameters Pa,
- manufacturing technology Te.

Geometric dimensions W_g are quantitative design features, forming the arrangement of dimensions, according to the equivalence, completeness and non-contradiction principles. They depend on (Gendarz, 2009):

- technical means parameters Pa,
- identity of coupled dimensions.

Geometric form and geometric dimensions are the subjects of optimization in the process of selecting design features. This publication presents the selected methods of determining the optimal geometric form and optimal selection of dimension values.

Material-related features $\mathbf{C_t}$ describe the internal structure of the future technical means. They include the material-related construction form Π_t and material-related dimensions W_t.

$$C_t = \Pi_t \cup W_t \tag{3}$$

Material-related form Π_t is a qualitative design feature describing the microstructure of the product.

Material-related dimensions W_t are quantitative design features describing properties of the material that

is going to be used to manufacture particular elements of the technical means. A system of material-related dimensions is formed by (Gendarz, 2013):

- stereo mechanical properties,
- physical characteristics,
- chemical characteristics,
- alloying element percentages.

In engineering practice, any changes in material-related dimensions (stereomechanical, physical or chemical) entails changing the material used to manufacture the elements of a given technical means.

Assembly related features $\mathbf{C_m}$ describe stages of the future technical means and are assigned at the assembly process. Those are design features selected most commonly on the basis of the strength calculations. They involve the interoperating elements, whose manner of mutual coupling defines their proper joint action.

Determining both quantitative and qualitative design features is one of the most essential and complex stages of the design and construction process.

Application of the procedures aiding the selection of optimal design features, combined with the analysis of various construction options, is currently the only method to satisfy the increasing demands of Clients, and stay competitive on the market at the same time.

The process of broadly defined optimization is the key stage of every design and construction process and its importance and capabilities have increased remarkably in the last decade (Kutyłowski, 2001; Ostwald, 2005; Stadnicki, 2006).

3. OPTIMIZATION IN THE DESIGN AND CONSTRUCTION PROCESS

Optimization is a dynamically developing field of science that focuses on the methods of selecting the optimal solutions of any human activity (regarding technology, economy etc.), in accordance with the selected criteria. The subject of optimization in engineering has been described in detail in literature (Gendarz, 2013; Majid, 1981; Kutyłowski, 2001; Stadnicki, 2006). Optimization in the design and construction process particularly involves aspects related to the selection of design features or choosing the design solutions for the future technical means. The main idea of this selection process is mostly to identify the solution that is optimal in relation to the previously established set of criteria.

3.1. Criteria in the process of optimizing geometric design features

Optimization criteria are the baseline for the assessment of the design solutions. They are determined in the initial phase of the optimization process and may be changed in different stages of the design and construction process. The following optimization criteria groups have been established:

-performance criteria (operation-related), that define the operating reliability of technical means, its capability of operating in difficult conditions and under the load and results from the Rule of Technical Validity (Dietrych, 1985),

-criteria related to the minimum of manufacturing costs resulting from the Rules of Economy (Dietrych, 1985; Gendarz, 2009),

-criteria of the manufacturing process resulting from the Rule of Manufacturing Capabilities (Dietrych, 1985; Gendarz, 2009),

-dimension criteria, which are the consequence of the limitations regarding the possibilities of changes to the defined quantitative design features, resulting from the Rules of Construction Science (Gendarz, 2013),

-criteria related to the material stress, which means ensuring that maximum stresses are not exceeded,

-stiffness criteria, which means that the maximum deformation, displacement levels etc. are not exceeded,

-criteria related to minimum mass or capacity, which are the consequence of the trend aiming at the extended use of light elements.

The fundamental source of design features optimization criteria is the design intent, product validity, rules of construction science and specific Client's requirements (Dietrych, 1985; Gendarz and Cielniak 2013; Osinski and Wróbel, 1995).

4. STAGES OF THE FINITE ELEMENT BASED STRUCTURAL ANALYSIS

Generally speaking, FEM (Finite Element Method) is a discretization of a continuous domain of the simplified geometric model into a finite number of discrete sub-domains of regular shape. Each physical quantity (deformation, stress) derived as a continuous function is approximated with a known function (called shape function). These functions interpolate the nodal displacements in the finite element domain. They are also used to calculate stiffness matrix, deformation and stresses inside the elements. The mesh connecting subdomain nodes should map the topology of the analyzed model precisely enough to facilitate obtaining approximate results that do not diverge from the exact solutions by more than acceptable error. As a consequence of splitting the analyzed domain into finite elements (interaction between the elements happens via nodes), instead of the boundary-initial value problem described by the equation or the system of differential equations with defined boundary conditions and preset load condition, we obtain a system of general equations (Stadnicki, 2006; Rusiński, 1994):

$$[K] \cdot u = R \quad (4)$$

where: [K]- stiffness matrix, u- displacement vector, R- nodal force vector.

Knowing the nodal values (of displacement and force), on the basis of defined shape functions we can determine their values in any point of the analyzed domain (any point of the finite element). A detailed method of performing analyses using finite element method has been presented in literature positions, as listed below (Dacko, 1994; Stadnicki, 2006; Rusiński, 1994; Szmelter, 1979, Zagrajek et al., 2006).

Stages of the FEM-based structural analysis have been presented in Fig. 1.

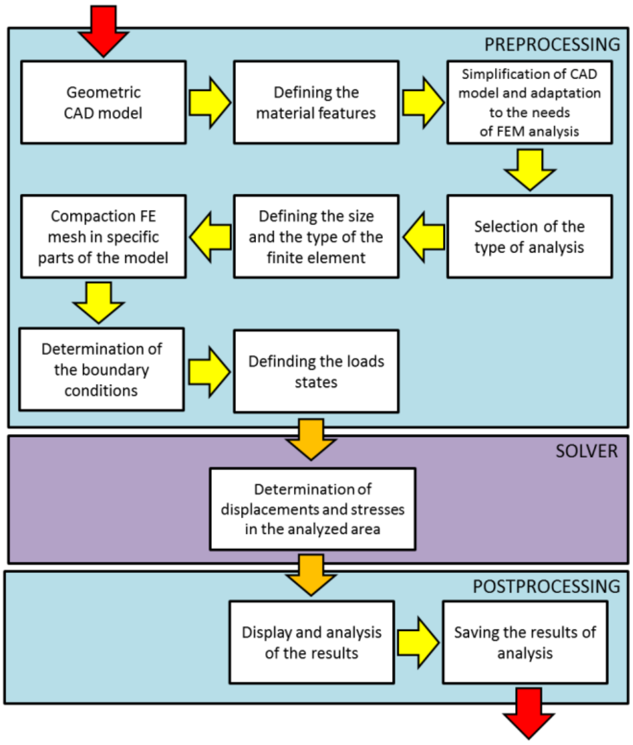

Fig. 1. Stages of the FEM-based structural analysis

The process of structural analysis using finite element method begins with preparing the geometric model of the element (or part of the element). Most commonly, the model is created using CAD software or using a CAE software module dedicated to model elements. Next step entails simplifying the model (Fig. 2a) by removing the irrelevant element parts such as holes that do not influence the analysis results, small radius round-offs, hole chamfering and selected edges. Simplification of a model aims at facilitating discretization of the analyzed domain, and at the same time – reduction of mesh cover errors and the amount of time needed for numerical calculations. The geometric model should also be prepared with regard to introducing boundary conditions and state (or states) of loading. If the analyzed construction is characterized by symmetry, the analysis process may be carried out only on the fragment of a model and the removed part may be replaced with the relevant node (Zagrajek et al., 2006). It will cause significant reduction of time needed for numerical calculations run by the computer program, which in turn significantly shortens the time needed for the analysis. Another preparatory phase is the selection of the analysis type and numerical algorithm responsible for the process of determining values of stresses and deformations in the verified of the element model. Very important, with regard to the accuracy of obtained results, is of the phase of the process is identifying the type and quantity of finite elements (Fig. 2b). Type of the used element depends on the number of factors, such as topology of the analyzed elements of constructions and type of the performed analysis. If the analyzed model is characterized by structure discontinuity in the form of notches or spots where stresses may be cumulated, it is necessary to condense the finite element mesh in those places. This process is intended to increase the accuracy of the obtained analysis results. The engineering software used to carry out numerical analyses using finite element method usually features a module for automatic condensation of the mesh in places of structure discontinuity (Zagrajek et al., 2006). However, it is necessary to verify the process of automatic mesh condensation every time due to the possibility of occurring unsuitable finite elements. Another stage of preprocessing is identifying the restraint and load conditions of the analyzed element (Fig. 2c).

Boundary conditions should correspond with the actual restraint and load conditions of the analyzed system. This applies especially to the direction and values of loading forces. Reflection of the actual restraint and load conditions affects to a large extent credibility of the obtained analysis results. After defining the restraint and load conditions one should start the numerical analysis (using the chosen FEM solver) aiming at determining the values of displacements, deformations and forces. Duration of the process depends on the calculation unit, degree of complexity of the analyzed geometric model, type and quantity of the applied finite elements and quantity of the defined load conditions. The user has the possibility of displaying results of the performed analysis in the form of the isohypse distribution of displacements plan (Fig. 3a), deformations, stresses (rys. 3b) and values of reaction forces.

Structural analysis of the construction using finite element method is a key tool of every engineer in the process of the selection and verification of design features.

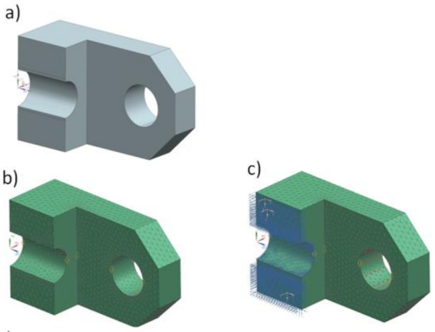

Fig. 2. Selected stages of preparing the model for FEM analysis in NX Advance Simulation module:
a) simplified geometric model, finite element model, finite element model with the defined restraint and load conditions

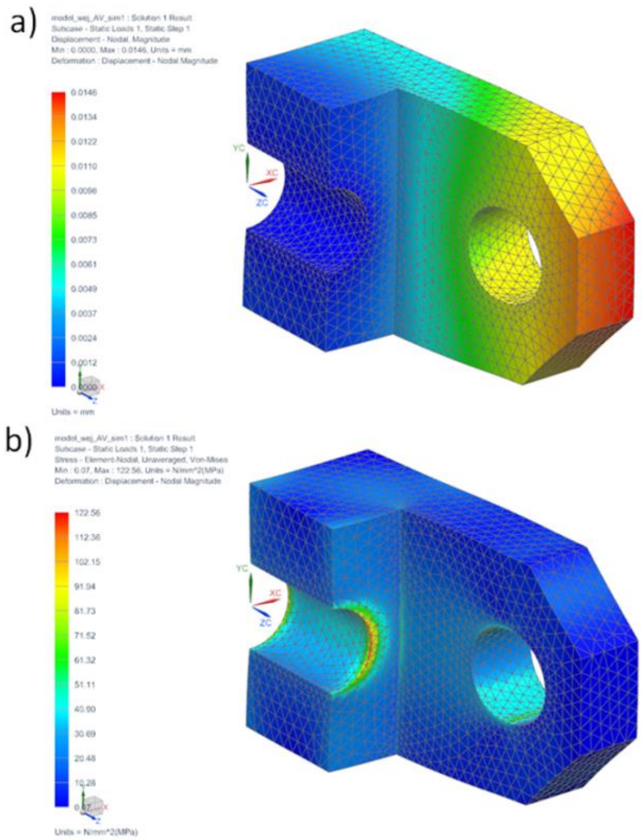

Fig. 3. Results of the FEM-based structural analysis:
a) isohypse distribution of displacements,
b) isohypse distribution of averaged stresses

5. OPTIMIZATION STAGES OF THE GEOMETRIC DESIGN FEATURES USING FEM

On the basis of the results of the analysis of deformation and stress conditions it is possible to perform the optimization of geometric features of the technical means elements. As process variables (decision variables) we take features characterizing the geometry of optimized structure and as criteria: not exceeding permissible stresses (according to the specified strength hypothesis), not exceeding permissible deformations and minimum mass of construction elements.

General motto of the construction form optimization: „where there are no stresses, there is no material". During the process of optimizing geometric form, the finite element mesh in the following iterations of the process is modified by removing (or moving) finite elements in directions leading to the improvement of the objective function (defined superior criterion) within the framework of adopted criteria (Łaczek, 2011; Stadnicki, 2006). The article presents two methods of optimizing the geometric design features: geometric form optimization (topology optimization) and dimension values (parametric optimization).

5.1. Topology optimization

Topology optimization defines a way of distributing material in the designer – or engineer-defined domain of the entry model in a way that allows the optimal topology of the model element for the preset load and restraint conditions. This process involves searching the maximum or minimum value of the objective function simultaneously fulfilling a certain number of specified conditions. Optimization process is carried out in the domain that does not change in time of the process and where domains with and without the material are created. The final effect of the process is the optimum distribution of material in the defined domain of the entry model (Kutyłowski, 2001). Finite elements are treated as single material points that need to be removed or whose nodes should be repositioned in the certain direction in a given step of the optimization process. A number of removed or repositioned finite elements depends on current process parameters. Division into finite elements is done once for the whole domain of the entry model. Two variables and updated in the process: density and Young module of finite elements. FEM-based optimization process is an iteration process, because the boundary value problem is solved a number of times and the material points (mass) are repositioned to the domains, where material strength is greater (Kutyłowski, 2001). The result of the process is a construction form created of finite element mesh that optimally satisfies the established criteria. Process of optimizing topology of the elements of technical means using FEM is shown in Fig. 4.

One of the initial stages of the process of topology optimization is defining a permissible domain through identifying the domain that is to undergo optimization process or fixed subdomains, most commonly resulting from the necessity to retain identity of coupled dimensions and technological criteria (Fig. 5a). A crucial stage of preparing optimization is defining geometric conditions (mostly resulting from the symmetrical geometry of the element). Those conditions directly influence the result and concurrence of the optimization process. In the next step, one should define the objective function of the process. In machine construction, optimization of the construction form is usually performed with regard to minimizing the capacity (mass), maximizing stiffness, maximizing material strength or searching for maximum frequency of natural vibration (Stadnicki, 2006).

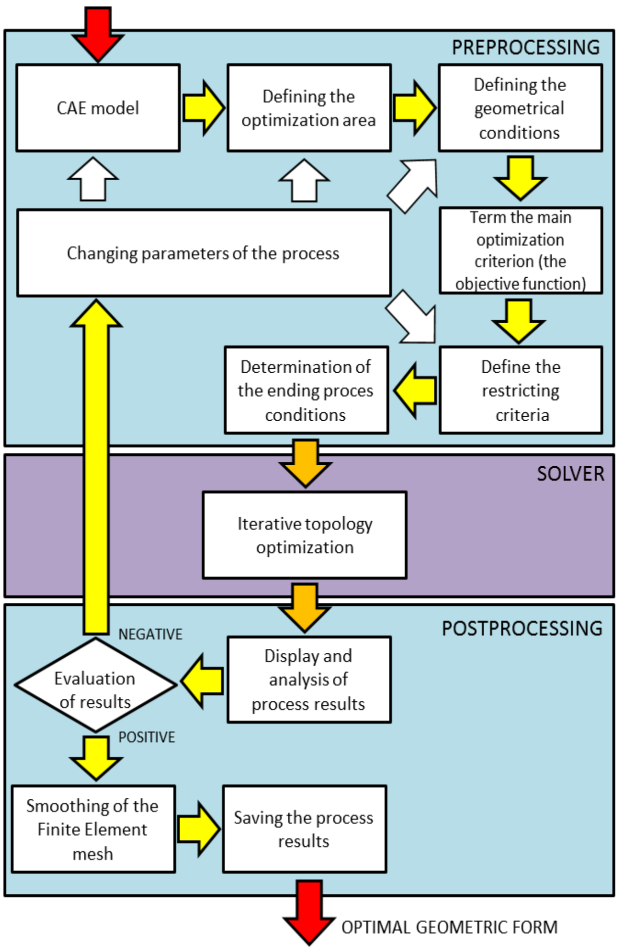

Fig. 4. Stages of the geometric form optimization process

In the next stage, it is necessary to determine the maximum number of iterations that, when exceeded, will cause the optimization algorithm to stop the process. In this stage, one should also define additional parameters of the process such as a way and value of the „mass repositioned" between finite elements. After defining the process settings and verifying their accuracy one may start the optimization process. Algorithm, having FEM solver as its base, iteratively „repositions the mass" from the domains with low levels of material strength to areas with higher strength values. The process is finished when distribution of material inside the defined domain optimally satisfies the established conditions (Fig. 5b). Duration of the optimization process strongly depends on the power of calculation unit, type and quantity of finite elements, number of load conditions, defined restricting criteria and the manner and value of "repositioned mass". Having finished the process one should analyze the obtained results every time and verify them with the assumptions of the design and engineering process as well as manufacturing capabilities. If the optimization results do not satisfy the defined criteria, one should modify the parameters of the process and perform second optimization.

In case of positive assessment of the results, one should start the process of smoothing the finite element mesh and save the results (Fig. 5c).

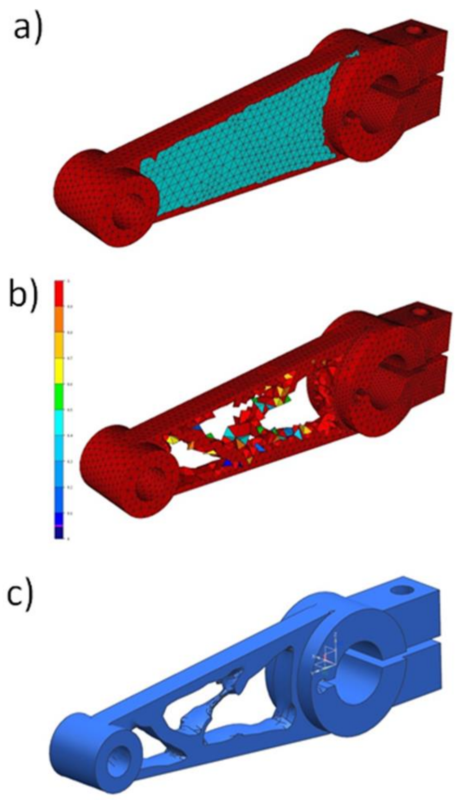

Fig. 5. Selected stages of the topology optimization process (in TOSCA STRUCTURE software):
a) defining the domain subject to optimization,
b) results of the optimization process in the form of finite element model,
c) CAD model of the optimum construction form

A received construction form usually requires modification due to the criteria resulting from the manufacturing capabilities (Dietrych, 1985; Gendarz, 2009), ergonomic and operating criteria.
However, it should be remembered that due to errors in the methodology, results of the topology optimization can only be treated as a good suggestion how to distribute the material in order to improve the use of model surface in view of the selected criteria (Kutyłowski, 2001; Oczoś, 2011).

5.2. Parametric optimization

In parametric optimization, geometric form is determined via topology optimization or defined by the engineer (Π_g=const), and decision variables are the values of geometric dimensions (W_g=var). Criteria of the optimization process for the dimension values are the same as in case of topology optimization.
Optimized dimensions and their range of variation are determined on the basis of the sensitivity analysis of the dimensions in relation to the defined criteria (Sensitivity Analysis) and on the basis of the graph illustrating the coupling relations of interoperating elements of the construction. A requirement necessary to carry out the process is the necessity of having the parameterized model of the optimized model (Gendarz, 2009; Gendarz and Cielniak, 2013, Gendarz and Chyra 2009). In the next iterations of the parametric optimization, the intermediate solutions are determined performing structural analysis for different values of decision variables. In the next steps, numerical algorithm of the process compares the results of the performed analyzes with the values of defined criteria selecting the values of dimension variables in a way that allows obtaining concurrence of structural analyzes results with the established objective function (Cielniak, 2011; Gendarz, 2013). Fig. 6 presents stages of the parametric optimization process. Looking at the results of the strength analysis of the parameterized CAD model and design-engineering intent, an engineer is able to identify the criteria for the optimization process. In machine construction, similarly as in the case of topology optimization, usually the superior criterion of the process is the minimum mass of the construction elements and the restricting criteria are limited to not exceeding certain values of stereomechanical conditions (not exceeding stresses and permissible displacements). A crucial phase of the selection process is defining the variable dimensions (optimized). It may be achieved following the selection method or applying sensitivity analysis that identifies the impact of dimensions on the defined criteria (Gendarz 2009; Stadnicki, 2006). Another stage of the process is determining limit values of the optimized dimension variation. Exceeding the boundary values may result in lack of possibility of coupling interoperating elements or their collision. Further, it is necessary to define the conditions of process completion, usually only determining maximum number of iterations. After defining all parameters it is possible to start the optimization process. The result of work of the numerical algorithm is diagrams of geometric dimension variations in particular iterations of the process and their corresponding values of objective function and defined criteria (Fig. 7a). When analyzing dimension variants best fulfilling the defined criteria, an engineer needs to make the decision which variant to use in the next stage of the design and construction process. If the optimization did not bring positive results, it is necessary to modify the parameters of the process or consider the possibility of changing the material-related features if stress or reposition values were the reason of the lack of expected optimization results. Fig. 7b presents the comparison of a model before and after the dimension value optimization.

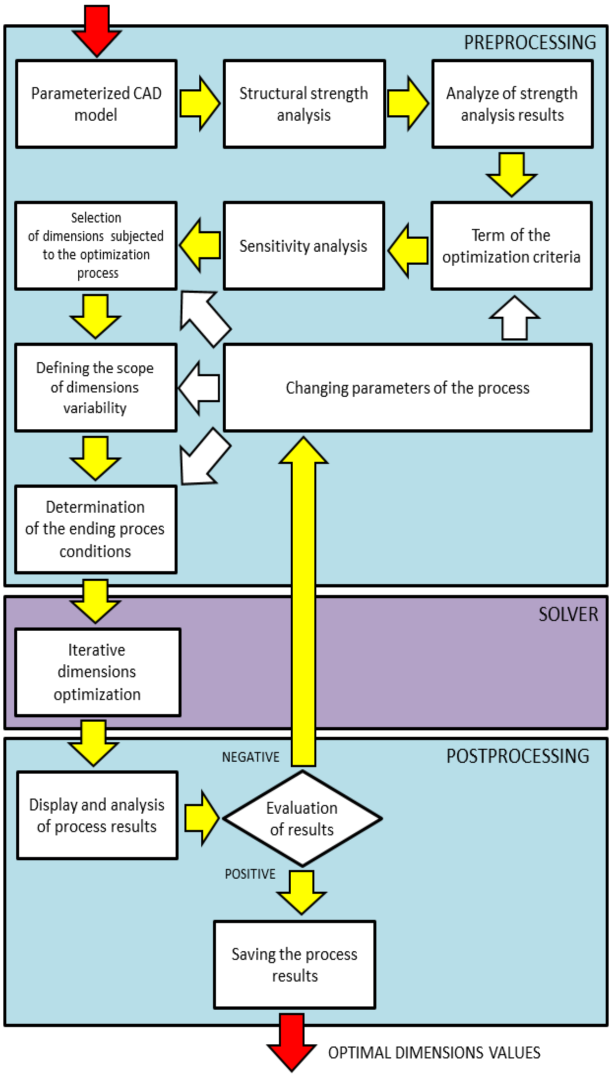

Fig. 6. Stages of the dimension values optimization process

In engineering practice, it is advised to start the dimension value optimization process from the construction elements that are most dependent on the parameters of the future technical means (Dietrych, 1985; Gendarz, 2009). In the process of described optimization, most commonly the goal is to minimize the capacity (mass) at the expense of the increase of construction elements strength, taking into account strength and stiffness criteria (not exceeding permissible stresses and deformations).

a)

Optimization History					
Based on Altair HyperOpt					
Design Objective Function Results					
Minimum Weight [N]	**0**	**1**	**2**	**3**	**4**
	5,26	5,05	5,21	3,95	3,95
Design Variable Results					
Name	**0**	**1**	**2**	**3**	**4**
"model_wej_AV"::GR=25	25	24	25	20	20
"model_wej_AV"::DR=80	80	80	79	75	75
Design Constraint Results					
	0	**1**	**2**	**3**	**4**
Result Measure					
Lower Limit = 0.100000 [mm]	0,01276	0,01314	0,01305	0,01833	0,01833
Result Measure					
Lower Limit = 140.000000 [N/mm^2(MPa)]	122,56	124,29	122,47	135,68	135,68

b)

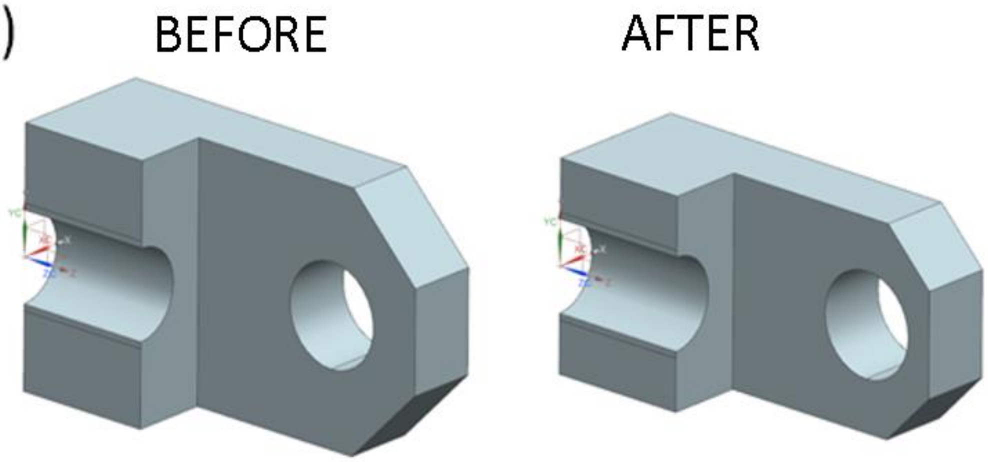

Fig. 7. Results of parametric optimization (in NX Geometry Optimization module):
a) values of the process criteria in particular iterations,
b) model before and after parametric optimization

7. SUMMARY

The publication provides the selected possibilities of geometric design features optimization with the use of the computer-aided Finite Element Method.
Capabilities of construction form optimization were represented on the example of the long reach connector model, where thanks to the use of topology optimization, it was possible to reduce the element mass by 27% and at the same time not exceed the permissible stresses and displacements. In case of the presented example, the process of adjusting the optimal construction form to the requirements of the particular technological process was not performed.
In case of the geometric dimensions optimization of the clevis, it was possible to obtain the mass reduction at the level of 25%, whereas the defined stereo mechanical states were not exceeded.
It should be noted that each design and construction process requires the interdisciplinary approach to the subject of selecting design features. For that reason, besides construction form and dimensions values optimization, it is also necessary to follow the criteria to choose the optimal material, taking into account the specificity of technological processes.
Using the MES-based analysis, it is essential to remember that it is only an approximate method. The obtained results are burdened with error, whose quantity depends on many factors. Errors of analyses results using finite element method occur mostly due to: oversimplification of the geometric model, discretization errors, inadequate identification of the

restraint and load conditions and numerical errors being the result of rounding the figures.
Awareness of the method inaccuracy, ability to minimize the errors and correctly interpret the results of the analysis is the key element of the optimal construction process.

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