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Methodology of modular design of construction machines

Pavol Zaujec, Jana Gulanová and Ladislav Gulan

Slovak University of Technology in Bratislava, Slovakia

ABSTRACT
This paper describes a method of CAD structural design of modular mobile working machines, especially telescopic excavators. It is mainly focused on the creation of CAD model tree structure and the application of parametric and generative engineering methodology in process of modeling modular construction machines.

KEYWORDS
CAD model structure; modular design; generative engineering; parametrical engineering

1. Introduction

Engineers in the automotive industry nowadays, prefer modular design or platform vehicles to increase the efficiency of the process of designing newly released models. In the design of construction machinery, it is also possible to choose a common platform for a group of devices. Several excavator options has been drawn for the research of modular design methodology.

Over a period of two years have students of engineering study modelled, the conceptual study of wheeled telescopic excavator of weight category up to 14 tons, which is represented on Fig. 1. Because of patent protection, some designed solutions and used components cannot be presented in this work. The design of the selected components is property of manufacturing company, the potential machine manufacturer. This model of wheeled telescopic excavator presents proposal of the new size range of universal finishing machine, which will appropriately complement the company manufacturing program. This size range of excavator is developed with different variants of chassis, work equipment or superstructures, with using flexible principles of modular assemblies on common platform.

2. General modularity

The product modularization increases efficiency of development process and reduce the time demanded for it. Positive effect may occur even on co-development (concurrent engineering), where it is possible to save time not only on design changes but also on application of changes in the process of designing manufacturing technologies and tools. Improvement can be seen also in the whole material flow, for example, in reducing delivery time, reducing number of suppliers, improving ergonomics of assembly, etc. Thanks to the platform design, the time required to develop new models is significantly reduced and so are the financial requirements reduced. On the other hand, ability to differentiate products can be limited and it raises risk of losing tangible uniqueness of product [4], [6].

Basic technical specifications of the excavator were calculated by using derived criterial similarities, their quantification based on evaluation of statistical data and by their dependency for the presently known sets of excavator parameters data. According to this approach, there was proposed an evaluation of data with the use of quantitative indicators, such as modularity degree k_M or economic efficiency factor K_{ef}, for the most suitable assemblies of machines [2]. For those assemblies was chosen the basic solution, for which the proposal of cad model was created. It consists of available modules representing the platform. It is applicable in different range and also to solve the other possible variants of machine construction. The modularity degree increases with enlarging platform and with the use of other modules in different structural solutions. Such modules are usually drivetrain, slewing ring bearings, axles, hydrostatic converters, cabin, etc. Modules create the common platform of variant solution but their applicability is limited by the complexity of construction in terms of their connection and assembly. In case of fixing or connecting elements for some variant require significant intervention to frame design, or aggregates being connected, it decreases not only k_M value but also, K_{ef}. It doesn't complicate only the construction but also makes it more expensive and such a solution

CONTACT Pavol Zaujec pavol.zaujec@stuba.sk; Jana Gulanová jana.gulanova@stuba.sk; Ladislav Gulan ladislav.gulan@stuba.sk

Figure 1. Wheeled telescopic excavator based on a platform.

cannot be considered as effective. At the current proposal phase of flexible modular design of excavator, on the base of mentioned methodology there are recommended single conception variants of basic building modules represented in Fig. 2 and in the Tab. 1. The basic building modules (also modules of first level) represent chassis, superstructure or work equipment. Second-level modules understood as modules included in the specific modules of first-level. For example, stabilizers can be used on wheeled and on self-propelled chassis, front blade can be used on tracked and wheeled chassis. Because of the same connecting system, those two modules can be combined on the wheeled chassis.

Table 1. Modules of first level.

01_01_	Wheeled chassis	Base variant
01_02_	Tracked chassis	Variant for rough terrains
01_03_	Self-propelled chassis	Variant for fast travel
02_01_	Superstructure with engine	
02_02_	Superstructure without engine	Only in use with self-propelled chassis
03_01_	Telescopic boom – new concept	New profile of telescopic boom
03_02_	Telescopic boom – old concept	Smaller for 14-tons excavator

The design of presented machines was made in CATIA V5. Intuitive work, with tree structure of assemblies, enables to create a common platform for all variants of machine. All parts, components and modules, are connected and each design changed on common modules is reflected in all machine variants which own this module. CAD model of every module contain defined parameters, which affect degree of modularity and coefficient of economic efficiency. Ultimately, during generating bill of material, coefficient of economic efficiency can be used on the final valuation of both coefficients; applicability of variant design is also proven. Design of chassis will be completed soon, so the next paper will be aimed at these parts of excavator. As the wheeled excavator presents the base chassis, its components must fit to another two types of chassis. This fact can complicate design of two another chassis. On the other hand, it is possible to use some similar design solutions of weldments.

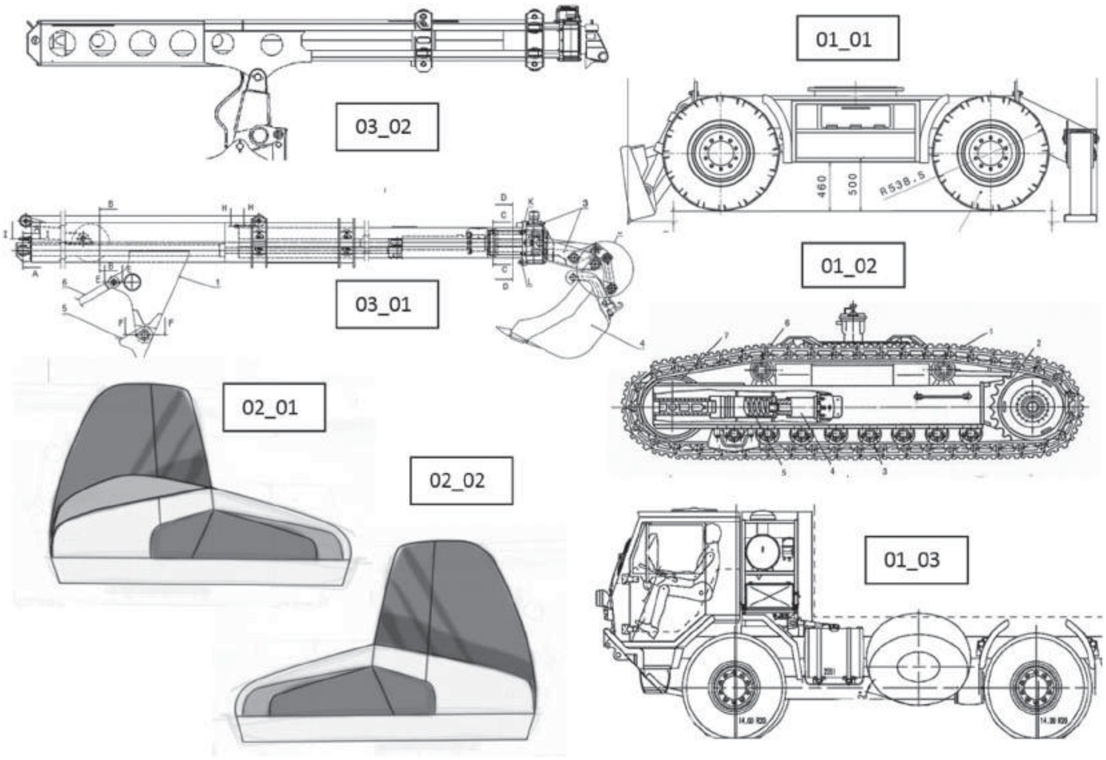


Figure 2. Provisionally selected variants of chassis, superstructure and work equipment, marked with their CAD structure number (described in next chapter).

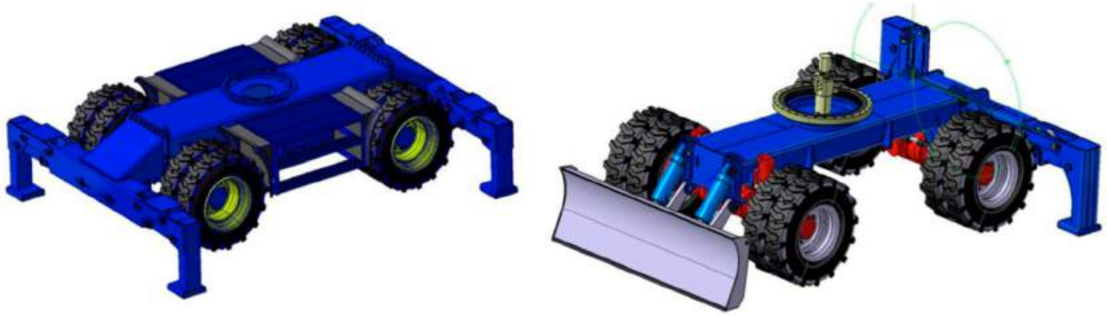


Figure 3. Wheeled chassis with two modules of stabilizers and with one front blade.

Intuitively created assembly tree structure allows simple combination of some modules and parts between variants. Global assembly of machine includes all variants and it is possible to separate common and unique parts of construction. Designation of assemblies and parts describes character and importance in the complexity of assembly. This structure, as well as the whole global assembly, is applicable to future innovations or creation of the new size range excavators and further enlarging of company production program.

3. Structure

Before the design, there were predetermined rules for structuring the different sub-assemblies and parts. All manufactured parts have a common coordinate system positioned on the axis of rotation of the machine upper-body and are fixed to the zero point of space. Each assembly and sub-assembly includes own part entitled skeleton. All skeletons, parts, assemblies and sub-assemblies have the same 8 numerical labeling XX_XX_XX_XX. First two numbers indicate the part of excavator (01 - chassis, 02-upper-body, 03 - work equipment). Next two numbers identify variant of a part (01_01_ - wheeled chassis, 01_02_- tracked chassis, 01_03_-self-propelled chassis). These subassemblies are variants of first level, presented in Fig. 2. The third and fourth numbers indicate the level of sub-assembly of individual modules, components and their order. Module and forming the platform for a given level is indicated by two characters _XX_ in corresponding level. It means that part is used in other variants of the machine at the same level.

All parts and assemblies, with XX in label, constitute the platform of the machine. It is possible to separate modules for each kind of machine variant. Platform size affects the price of manufactured machines. For all machine variants, we can determine the number of modules which are common. For each excavator, we determine the coefficient of modularity. Defining certain parameters in the CAD model allows us to analyze various cost options. Accordingly, it is possible to choose variants, which should be produced or not.

In this condition of construction design, it is possible to separate used modules for chassis variants. A common platform for chassis is formed slewing ring bearings, hydraulic rotary union and some components of hydraulic circuit. From wheeled chassis for self-propelled chassis it is modules of axles, transmission, hydraulic engine, stabilizers and relevant parts of hydraulic circuit. However, it is necessary to make some set up on these modules. For example, stabilizers on rear end of chassis must include light signaling depending on relevant regulations. These components were made in separate parallel subassembly, which includes all added components. These added subassemblies often constitute increase of manufacturing costs for module and in result for the excavator variant. For tracked chassis, there can be used module of front blade with relevant parts of hydraulic circuit. Kinematic mechanism of front blade and stabilizers was designed and optimized for using the same linear hydraulic cylinders.

In skeletons, there are modeled a wireframe geometry, planes, shape geometry and parameters in geometrical sets. Created elements are published and copied sequentially to the last parts, where they are used to create final weldment. For example, sheet plates manufactured by bending, trimming etc., are modeled in the skeleton with shape design as surfaces. Every metal sheet was made as a dimensionless surface in CATIA Generative shape design module. Sheet metals geometrically influence each other. This methodology allows intuitively define their mutual relations, which persist during design changes. However, such relations must be hierarchically organized and superiority of bonds must be gradually defined. All bends of sheet metal parts are determined by parameters. They are defined in main assembly and serve as an instrument of technological modularity. The aim is to use the same bend parameters to the most structural nodes as possible. In the final part of weldment, we determine the thickness parameter of the sheet to dimensionless surfaces and

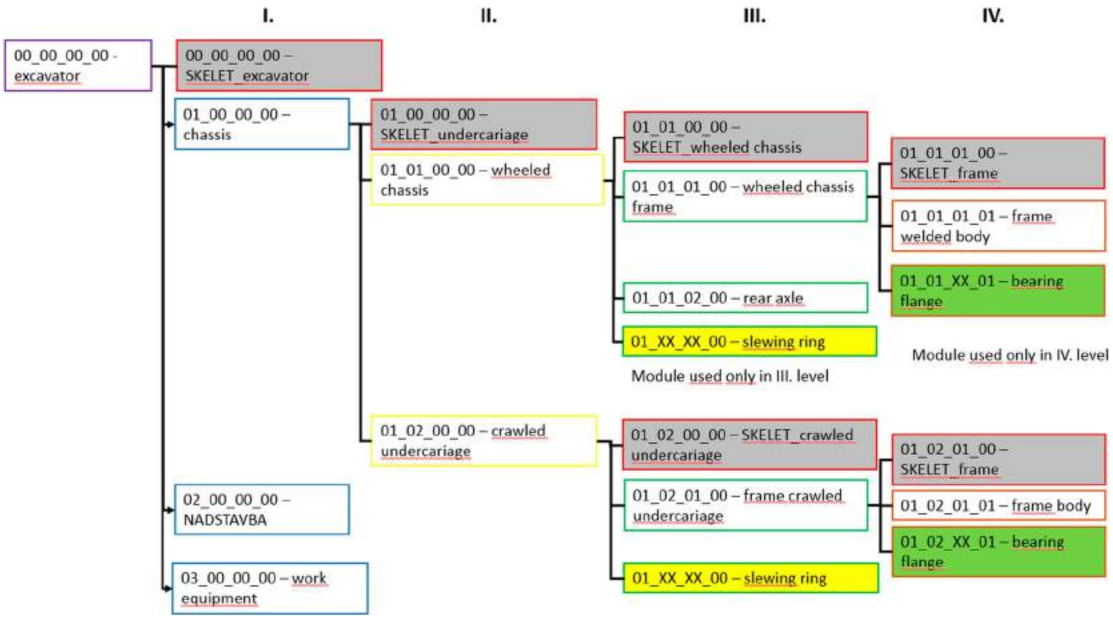


Figure 4. Tree structure with modules and skeletons.

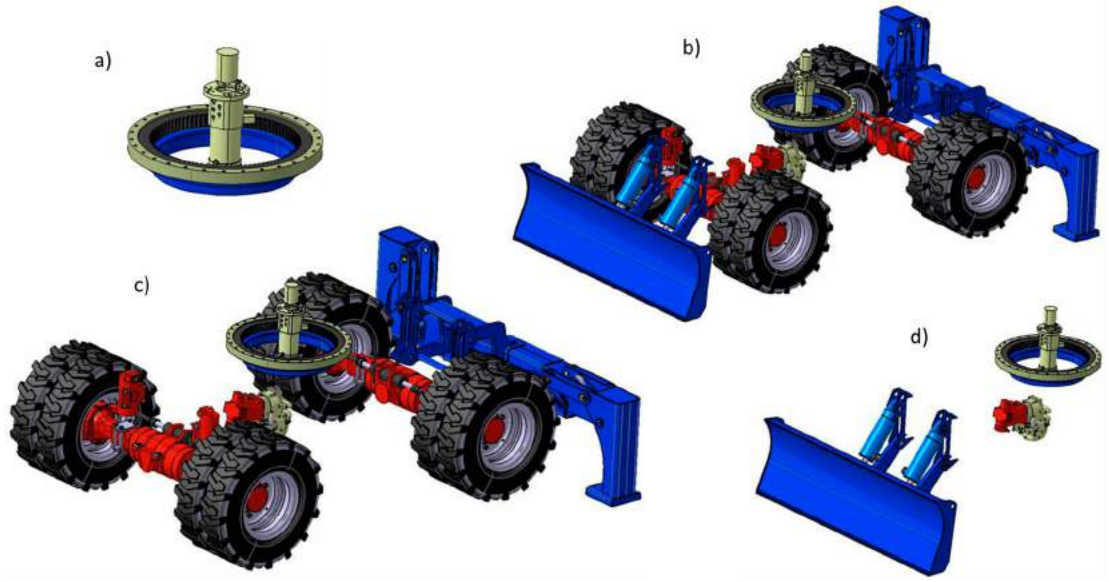


Figure 5. Modules of each variant a) upper left – common chassis platform, b) upper right – wheeled chassis, c) lower left – self-propelled chassis, d) lower right – crawled chassis.

carry out changes as chamfers, fillets, symmetry, drilling holes, etc. Parameters as sheet metal thickness, radius or angle of bending come from publications of main assembly.

In each of the resulting Part, there are Part Bodies, which represent final components. In welded parts, one Part Body represents one single sheet. Whole Part then represents a weldment. Some assemblies, which also serve to be analyzed, regarding to kinematics, are created with different structure. Each independently movable part is a separate part or sub-assembly and does not contain any external references and publications. Every component has an independent coordinate system. The reason is, while we move parts, we change the coordinate system against to the original system, so it would be impossible to move published geometry. Only publications, which can join these parts, are numeric parameters with values of dimensions. For example, they may serve for modeling pin holes. This parameter will represent diameter dimension.

Front blade kinematic system was created in a different way. Blade was made in the skeleton of blade assembly. The finished geometry of sheets was copied into the final weldment assemblies and their parts, without

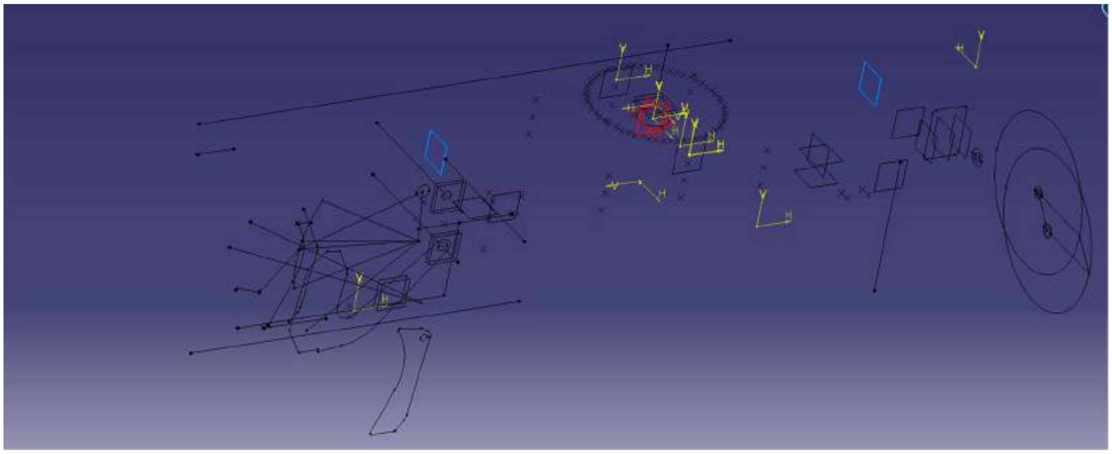


Figure 6. Planes and wireframe geometry of all skeletons.

link to the original geometry in the skeleton. After any change of geometry, it is necessary to copy new isolated geometry once again into the final weldment. This method has been proved to be slow. Because of that, it was used only for kinematic parts, which do not require many design changes. Parts, such as axles, are purchased as complete parts. They should be modeled as movable for purpose of a collision analysis. Therefore, movable components of the axle are published and isolated in a separate part. These parts create a movable assembly of axles. Front blade assembly contains another two subassemblies, housing and piston rod of hydraulic cylinders. All parts which move together were inserted into these sub-assemblies. For housing, it is hydraulic couplings, screws and pipelines. Front blade assembly then contains 5 movable sub-assemblies. Assembly of front blade weldment with all components, 2x assembly of hydraulic cylinder housing and 2x assembly of hydraulic cylinder piston rod.

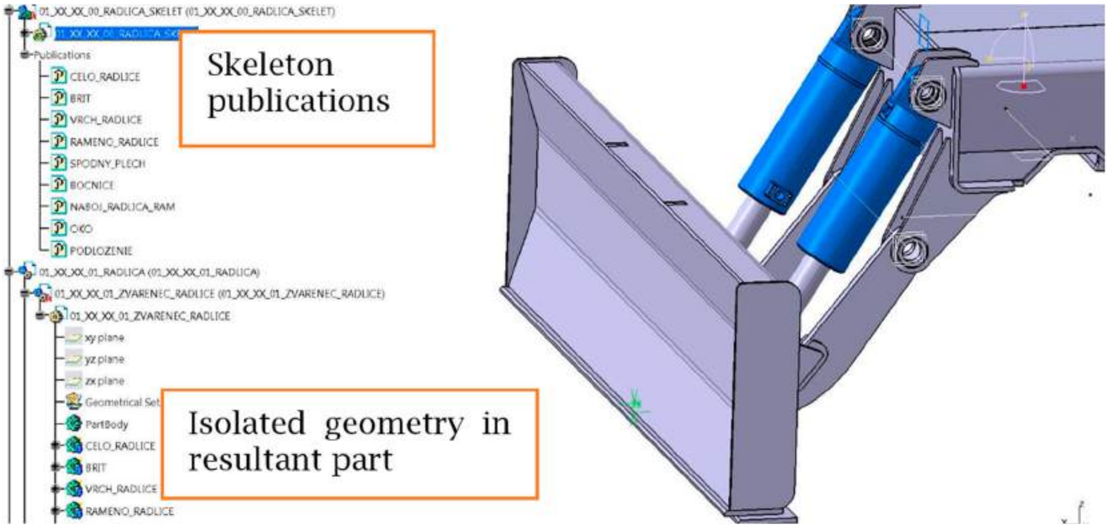
To explain the function of publications hierarchy, the connection between axle and chassis frame is defined in the 01_01_skeleton wheeled chassis to which belong both mentioned assemblies. In this skeleton, there is defined exact position using the points, screw axes and planes. Such geometry is then, using CATIA publications, copied to the required sub-assemblies as an external reference with links to the original skeleton. Here we use the geometry to create very parts. If we change the position of the connection defined in the skeleton chassis, changes are reflected in both dependent assemblies and made geometry will change. Each part is due to generative engineering design methodology bonded to certain elements. In advance, it is necessary to determine which component or element is hierarchically in higher status and make appropriate bonds. During the creation of more parts, it is necessary to use commands which will be bonded on this hierarchically higher status geometry. This automatically affects the scope of changes that can be performed on the subordinate parts during change updating. If more engineers work at the same time on the design, it is necessary, that each one have opened a single custom assemble. Before further modification, it is necessary to update current publications, which are represented in their assemblies.

4. Technological modularity

With parametric modeling methods, there was ensured "technological modularity". Defining common parameters, such as a sheet thickness, radiuses and angles of bends, allows the use of the same manufacturing technology in several parts of the machine. Each part produced need to be optimized in terms of cost of production and considering the technological possibilities of the manufacturer. In the design of machines, we are trying to reduce the diversity of technologies and materials used. Working with parametric modeling in CATIA helps us to analyze this factor.

One of the technological modularity conditions is a usage of the same thickness of sheets. Thickness was added as a parameter in the base assembly. Parameter is from there copied to single parts with publication, with link. With the use of Thickness command in CATIA is to dimensionless surface given thickness, with relation to thickness parameters. Subsequently we can analyze their diversity. Another condition is to use the same bending parameters for metal sheets.

During design, several different bends have been defined, and they were preferably used. The parameters of bending depend on the thickness of the sheet and its material properties. For that purpose, there is made one pack of parameters, which contains thickness and bend parameters together. If it is needed, for every sheet metal thickness can be defined more bending options. Thanks



Skeleton publications

Isolated geometry in resultant part

Figure 7. Isolated geometry of front blade weldment published from front blade skeleton.

to these parameters it is possible to manufacture different tools used during machine manufacturing. Every chassis frame was designed for manufacturing as a weldment. Some sheet metal parts are too large. So, length of bends is also adapted to technological possibilities of manufacturer. But for these bends it is necessary to manufacture or buy new tools, dies for bending press. Therefore, arise a willingness to use the same bending options, and the same tools for all variants as widely as possible.

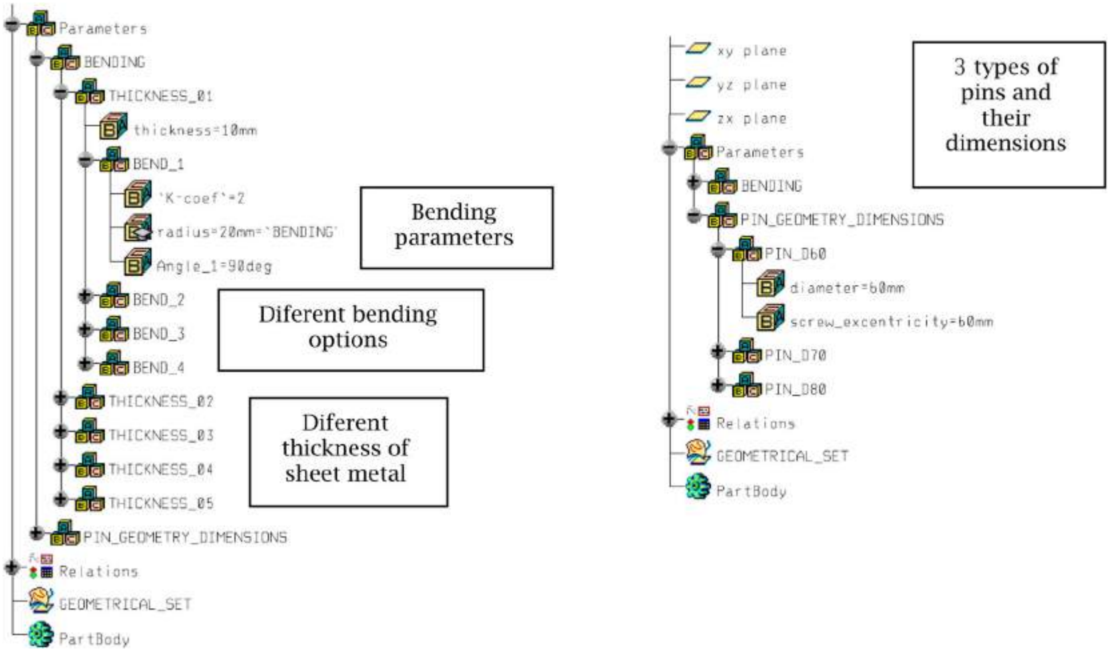
Globally, it is also possible to reduce production costs by using the same construction elements. For example, pin connections are designed with respect to the use of the same diameter and fixing modes. The use of uniform pin dimension allows the use of the same semi-finished products and production process. Pins are secured against movement by a screw with the housing. Fixing screws must also have uniform dimensions. Machine equipment of operator or service technician afterwards require a smaller number of tools. Single pin dimensions also allow use the same sliding bushes for moving kinematic parts.

Technological modularity, however, is contingent on the strength and functionality of the structure. FEM analysis showed inappropriate places in the design of weldments. When removing these places, we were looking for ways that would not significantly affect both modularity's - technical and general. As all weldments are made of individual sheets in the CATIA part, with the use of Boolean operations and simple commands, it is possible to combine these sheets into one unit and create some corresponding welds. This modified weldment part is possible to use in FEM analysis. Individual sheet metal body are used for making drawings and creating pathways for cutting machines in flat form. For this role serves module Sheet metal design in CATIA. Technological parameters for bending sheet metal can also be used in this CATIA module [5].

5. Methodology of generative engineering design

Subject to research methodology was also the possibility of using methods of generative engineering design in process of construction machines designing. From [1], [3] " Generative Engineering Design is a process in which the draft or model is made based on quantitative and qualitative parameters or aesthetic inputs, using algorithms created by individual human intervention for the purpose of generating a variable set of subsequent models following accurate relations and according to hierarchical connections." Modular design can be considered as an important section of the Generative Engineering Design methodology, even though it is mainly linked to parametric modeling.

In the field of modeling welded structures of machinery, based on inputs it is possible to apply new methodology in sections in which design is often changed. The reason for redesigning results may be an evaluation by using kinematic and stress analysis. It is necessary to determine the structural hierarchy of design nodes that can and cannot be affected by such a change. As an example, this process changes the structure of clamping brackets for Front blade (the green parts). To optimize kinematics of the front blade, it is often necessary to change the position of individual pins. This change cannot affect the design of frame weldment (gray parts), as shown in the Fig. 9. During change of design, upper and lower sheet is made as one piece. It is possible to change



Parameters
BENDING
THICKNESS_01
thickness=10mm
BEND_1
`K-coef`=2
radius=20mm=`BENDING`
Angle_1=90deg
BEND_2
BEND_3
BEND_4
THICKNESS_02
THICKNESS_03
THICKNESS_04
THICKNESS_05
PIN_GEOMETRY_DIMENSIONS
Relations
GEOMETRICAL_SET
PartBody

xy plane
yz plane
zx plane
Parameters
BENDING
PIN_GEOMETRY_DIMENSIONS
PIN_D60
diameter=60mm
screw_excentricity=60mm
PIN_D70
PIN_D80
Relations
GEOMETRICAL_SET
PartBody

Figure 8. Parameters for bending and pin dimensions.

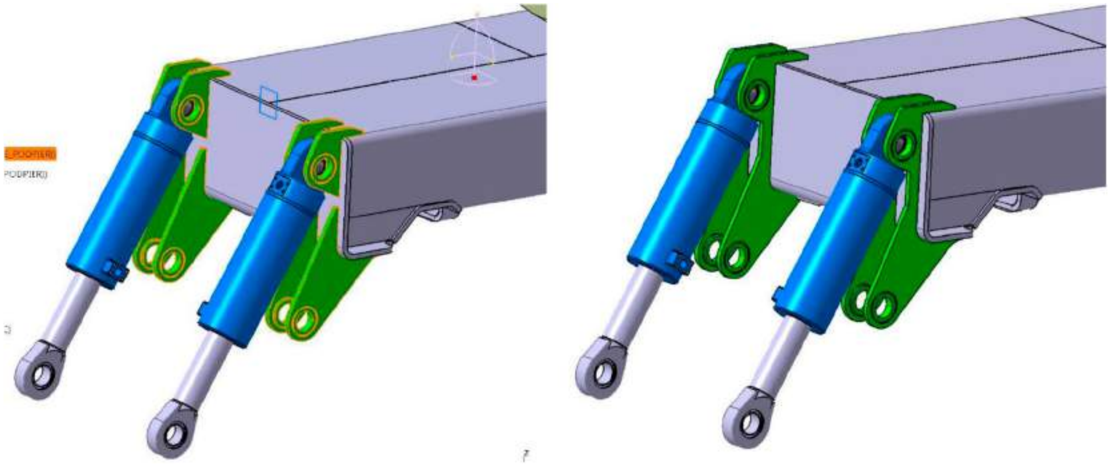


Figure 9. Design change.

geometry of holders, but the geometry which connects to the frame, stays unchanged.

6. Conclusion

The most time-consuming part of engineer's work is to change overall design of the component or to check mistakes. The new Generative Engineering Design methodology describes links and tools, which should be involved into the designing process to reduce time for development. Also, intuitive assembly structures and their connecting can improve engineer's work. In practice, the key factor in the production is the price of the production itself. With the help of parametric modeling in various CAD software we can analyze and optimize pricing complexity of the project.

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ORCID

Jana Gulanová http://orcid.org/0000-0003-2041-1993

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