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CONSTRUCTION PROJECT OF A LONG REACH COMPACT EXCAVATOR

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Abstract: The purpose of research was to comprehensively develop the construction project of a long reach compact excavator. Optimal solution was selected and its frames were determined by carrying out classic structural calculations. Then, based on them, a preliminary three-dimensional model was designed in the CAD environment. The prototype was subjected to a series of verification calculations and simulation tests using the finite element method under typical, but also non-standard operating conditions. Then, the structure was optimized and then tested again. Next, technical documentation of the final version was created. In the final part of work, technical and operational parameters of designed compact excavator were summarized and the direction of further actions was determined. The research ended with a summary of the observations arose during its implementation.

Keywords: excavator, construction, exploitation, CAD, FEM

1. INTRODUCTION

Design of an excavator is a highly complex process. This manifests itself primarily in its high level of interdisciplinarity. The fundamental knowledge required for the design of an excavator is, of course, that connected with construction of these machines. However, it is also important to obtain knowledge about hydraulic drive and automation systems (both in terms of construction and practical use). Due to the specific nature of excavator operation, selective knowledge of civil engineering is required for proper excavator design.

In order to delivering top-quality machines to the market, the design must be developed on the basis of more than just technical science. It might seem that aesthetics can be safely disregarded in the case of excavators for a known purpose. Well, not necessarily. Due to the number of active manufacturers on the market, the appropriate design is that, what may decide on the possible purchase of the product. The same conclusion applies to ergonomics. Implicating thoughtful solutions to the design, will open the way for promoting it as functional and user friendly object. This is an undisputed advantage. To know what is currently considered as attractive and to be able to sell it effectively, designer need to have certain marketing skills. Culmination of needed skills and knowledge is that about economic. It is in part used at every level of design. Mainly for calculating budget for purchasing parts and materials and estimating cost of design and production.

2. MATERIALS AND METHODS

Excavators are used for a wide range of jobs. From simple works in form of small excavations, through standard operations such as opencast mining, to highly responsible work in difficult conditions requiring high precision. This differentiation directly necessitates the existence of excavators adapted to different jobs. Such designs of course exists. They are defined by a number of classification criteria. In this section, they will be explained in more detail.

Excavator is a relatively complex structure. It is defined by a number of standards that standardize its construction, design process, operation, but also industry definitions. Standard PN-ISO 7135 (1996) establishes names for the basic machine and the basic or auxiliary attachments. Definition of an excavator in this standard is defined as follows: "Basic machine – a self-propelled excavator without attachments, having necessary equipment for driving and controlling the hydraulic drive" [1].

Single-arm excavators (Fig. 1) belong to the group of excavators operating in the discontinuous work system. This is connected with the nature of their work, which consists mainly of excavating the ground and then moving the spoil to a designated place for unloading. Most excavators operate in this cycle and it is very difficult to classify them based on this aspect. In literature, their classification is usually based on [2]:

1. Four distinctive design features:
   - type of attachment;
   - type of chassis;
   - type of power source;
   - type of power transmission.
2. Operating parameters:
   - capacity of bucket, m^3;
   - operating weight, kg;
   - engine power, kW;
   - digging force, kN;
3. Technical parameters.

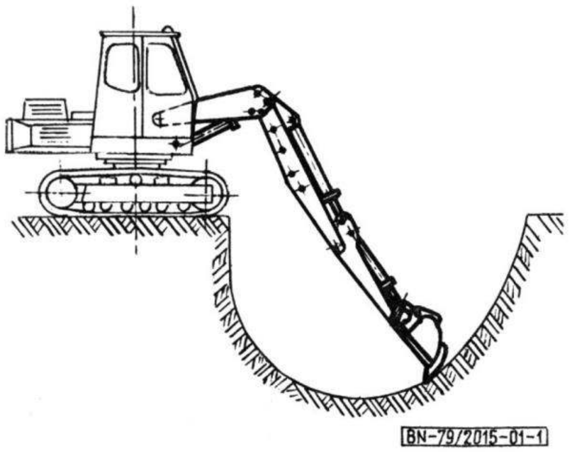


Fig. 1. Excavator equipped with backhoe equipment

3. KINEMATICS OF EXCAVATORS

Excavator is an assembly of mechanisms that can be considered kinematically as a flat lever mechanism in the form of a closed vector polygon. Kinematic chain of a traditional backhoe excavator consists of the basic machine, i.e. the chassis with body, and the working attachments. There are several typical local elements in this chain, they are [3]:

- driving mechanisms;
- rotation mechanisms;
- attachments mechanisms.

Only the rotation and attachments mechanisms are involved in the working cycle. The driving mechanisms do not participate in the typical mining process. Using the above-mentioned elementary mechanisms, it is possible to perform elementary working movements with the excavator, such as [2]:

- movement of the boom;
- movement of the arm;
- movement of the bucket;
- rotation of body;
- travelling and turning.

Diagram of the kinematic system of an excavator with a backhoe attachment during a typical work process is shown in the example figure (Fig. 2).

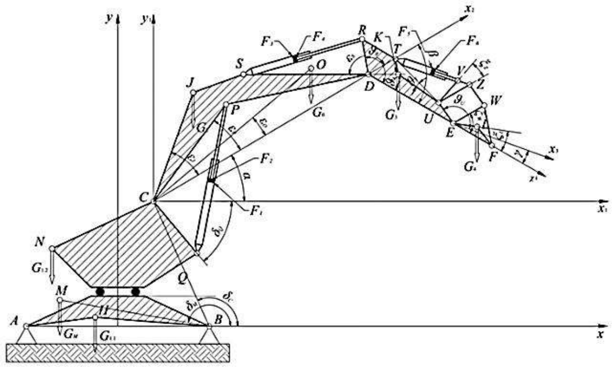


Fig. 2. Kinematic diagram of backhoe excavator with symbols

4. DESIGN ASSUMPTIONS

Defining technical assumptions is one of stages of the technical design. It follows after identification of the need. Formulation of the design assumptions should be preceded by an analysis of the problem in terms of labor intensity, time consumption, production-possibility and a preliminary cost analysis. Performing such analysis is supposed to help in the initial estimation of the project profitability. Literature distinguishes questions on the basis of which it can be conducted and thus the following design assumptions can be defined [4]:

4.1. General considerations

1. Purpose of the machine: universal mini-excavator.
2. Justification of technical rationale: designing an universal mini-excavator.
3. Economic rationale: designing a low-cost mini excavator.
4. Performance requirements: operational efficiency ≥ 100 m^3.
5. Handling requirements: standard.
6. Durability requirements: all systems with a service life ≥ 25000 operating hours.
7. Compliance with national and international standards: full.
8. Production range: international.
9. Production volume: mass.
10. Content of semi-finished and finished products in the design: minority.

4.2. Preliminary design assumptions

1. Attachment type: extended backhoe.
2. Type of undercarriage: caterpillar.
3. Type of power source: electric.
4. Type of transmission: hydraulic.
5. Nominal volume of bucket: ≤ 0.16 m^3.
6. Operating weight: ≤ 6000 kg.

4.3. General assumptions for optimization

1. Type of optimization: multi-criteria optimization.
2. Optimization method: mixed, simulation method and design variants.
3. Maximization: reach, efficiency, bucket capacity.
4. Minimize: weight, price, overall dimensions.

5. CONCEPTUAL DESIGN SOLUTIONS

Over the years, many types of excavators have been developed for specific earthmoving jobs. The differences between them range from minor to major constructional measures, which completely change not only shape of the machine. Conceptual solutions were presented using selected examples of existing excavator solutions. They have been considered from the perspective of the basic structural modules of a single-arm hydraulic backhoe on a crawler chassis. The following parts of the modules are distinguished [5]:

1. Arm.
2. Boom.
3. Bucket.
4. Track with traction frame.
5. Undercarriage frame.
6. Rotating platform.
7. Counterweight.
8. Operator's cab.

Layout of the modules is shown in the figure (Fig. 3).

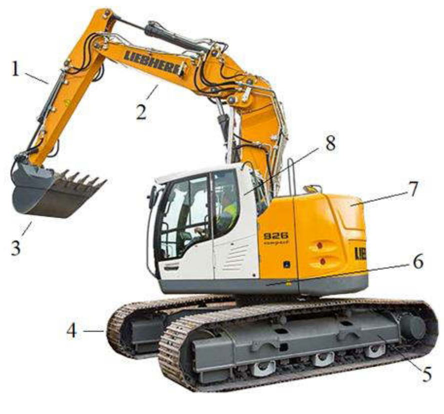


Fig. 3. Arrangement of the basic structural modules of a single-arm hydraulic backhoe on a crawler chassis

Parts of module listed above are the part of the five basic ones used in excavators. These are [5]:

- attachments module (no. 1, 2, 3);
- body frame module with power transmission system (no. 4, 5);
- main frame module with rotation mechanism (no. 6);
- counterweight module (no. 7);
- operator's cab module (no. 8).

5.1. Attachments module

Attachment module is the most frequently adapted module in excavator designs. There are a very large number of ways to vary this module. There are several possible solutions:

- extension of the boom or arm;
- replacing a conventional boom or arm with a telescopic version;
- increase of the number of work attachments;
- modification of the kinematic system of typical excavator.

Based on a comparative analysis. Combination of the third and fourth conceptual solutions was chosen. It was decided to increase the number of sections to three. In fact, the decision was made to split the boom into two parts. Extending the arm while using a typical boom would have made it impossible to work at close range. The division was intended to ensure long-range operation while maintaining optimum close-range performance. For a similar reason, it was decided to use the design idea presented in the fourth concept solution. Thanks to the reverse movement, the machine operator will be able to excavate the ground in a wider range of the working field.

5.2. Design calculation

Calculating of a designed excavator only on the basis of a few design assumptions is not an easy task. For this reason, designers of these machines use the results of statistical analyses in the form of their parameter dependencies. Tables with detailed data are freely available in the literature. Usually they are presented as graphs created on the basis of comparing results of a several dozen or more existing models and determining the regression line. Tables with a 90% fit coefficient can be considered authoritative. As a rule, the best fitting factor results are recorded for typical structures. With the increase in the complexity of the design, the matching coefficient decreases, and so for excavators with an extended reach in the case of comparing the capacity of the working vessel to the operating mass, the value is only 59% [5].

5.3. Calculation of excavator working dimensions

One of the values that can be preliminarily estimated from statistical charts are the working dimensions of the excavator. Calculations have been carried out on the basis of charts which have been developed by [5].

Author of the mentioned publication gives the coefficients A and B to some of the basic dimensions. Following values can be calculated on their basis:

– RR1 (A:2718; B:0.644; R2=92%);
– RR2 (A:2727; B:0.610; R2=94%);
– HH20 (A:2442; B:0.590; R2=85%);
– HH23 (A:1774; B:0.394; R2=80%);
– HH24 (A:1475; B:0.429; R2=84%).

In parentheses are given the values of the fit factor related to the dimension. Two of them have values above 90%, the rest above 80%. The fit coefficient can therefore be considered as at least good.

For compact excavators with an operating mass less than or equal to 6000 kg, the author describes the regression line with the formula of a linear function.

$$y = A + Bx, \quad (1)$$

where: A - function coefficients; B - operating mass in [kg].

In order to use formula (1), the operating mass of the designed excavator must be determined. It is assumed in the design assumptions that it cannot be greater than 6000 kg, as this is the conventional limit for mini-excavators.

In [5] authors provide a formula based on which the recommended bucket capacity for extended reach backhoe crawler excavators can be calculated. One of the assumptions for optimization is to maximize the bucket capacity. In the project assumptions, this was specified as less than or equal to 0.16 m^3. In order to meet the optimization conditions, the bucket capacity must be taken as the upper limit.

This part should contain sufficient detail so that all procedures can be repeated. It can be divided into subsections if several methods are described.

Nominal volume (with overflow) of the working vessel Vn = 0.16 m^3 has been assumed.

Formula for calculating the recommended volume of the working bucket for backhoe crawler excavators with extended reach can be transformed so that the operating weight of the excavator can be calculated from it. After the transformation, the formula is as follows:

$$x = |(y - 0.181)/0.012|, \quad (2)$$

where: x - operating mass, t; y - nominal volume of the working vessel, m3.

The recommended operating weight of the excavator was calculated using formula (2);

$$x = |(0{,}16 - 0{,}181)/0{,}012|, \quad (3)$$

$$x = |-1{,}75|, \quad (4)$$

$$x = 1{,}75 \text{ t}. \quad (5)$$

Assumed:

$$x = 1{,}75 \text{ t}. \quad (6)$$

Once the operating mass has been calculated, the basic dimensions of the excavator can be calculated. Value of RR1 was calculated by using formula (1):

$$y = A + Bx, \quad (7)$$

$$y = 2718 + 0{,}644 \cdot 1800, \quad (8)$$

$$y = 3877 \text{ cm}, \quad (9)$$

$$y = 3{,}877 \text{ m}. \quad (10)$$

Rest of dimensions were calculated in the same way. Results are summarized in Table 1.

Tab. 1.Table of results for preliminary calculations of selected principal dimensions

Symbol	Description	Calculated value, m
RR1	Longest range	3.877
RR2	Longest Z-plane distance	3.825
HH20	Highest cutting edge position	3.504
HH23	Largest dumping height	2.483
HH24	Largest digging depth	2.247

In order to correctly select the matched values, computer methods should be used for graphically select of the parameters. Suitable diagram was made in the Autodesk Inventor environment and is shown in the figure (Fig. 4).

Figure graphically presents variants of the accessory selection. Preceding series of calculations were used to prepare the analysis. In order to ensure the greatest possible legibility of the drawing, only the average and the lower and upper limit values of each position are presented.

The figure graphically presents variants of the accessory selection. The preceding series of calculations were used to prepare the analysis. In order to ensure the greatest possible legibility of the drawing, only the average and the lower and upper limit values of each position are presented.

Based on the selected parameters of the equipment, an outline of the working field was drawn up (Fig. 5). This was done on the basis of guidelines which were developed by author of [3]. This outline should be treated purely theoretically. In reality, no one would undertake digging directly under the machine, although once the working field has been outlined such a move is possible. The example of excavators on an earth-moving chassis can be cited as an exception where it would be possible to use the full range. The reason for this would be, in this case, a stable and not susceptible to wedge-shaped ground in the form of a sheet of water.

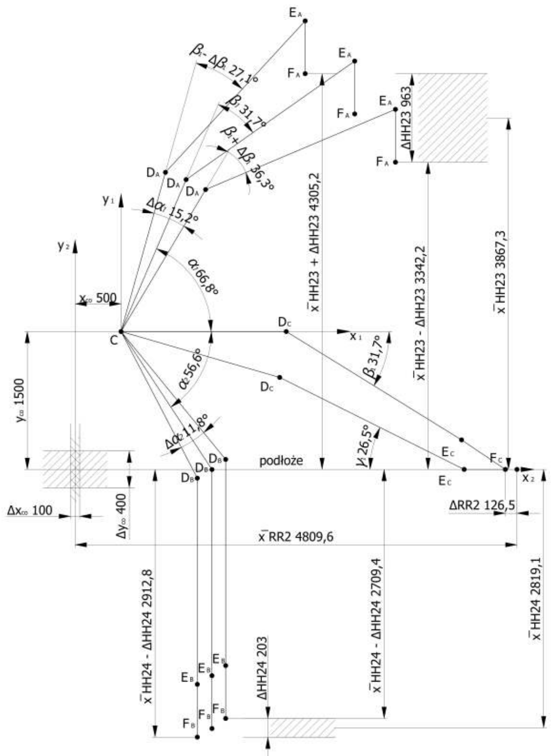


Fig. 4. Graphical representation of accessory selection

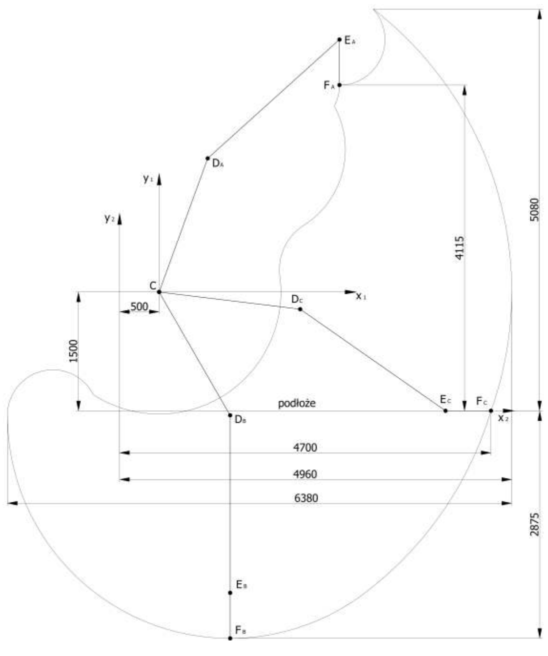


Fig. 5. Field outline drawn up on the basis of selected parameters

Calculation and determination of parameters of the designed compact excavator was necessary to continue the calculation of other parts of the machine. According to the optimization principle of reducing the size of the machine, it was necessary to know its estimated dimensions.

6. PRELIMINARY DESIGN ANALYSIS

With beginning of stage defined in the title of this chapter, next part of the construction process should begin. Main difference between first and second parts of this stage is the form of the construction figure. In previous stage it may have been approximate. In the current stage it must be more accurate. Although not completely accurate. Considering this issue from the point of view of the scheme developed by authors of [5], it may be stated that the present stage is a CONCEPT, not a DESIGN OF CONSTRUCTION as [6] author points out.

This is caused by the necessity to perform additional analyses of the functionality of the structure and its optimization. Nobody is able to construct an ideal and optimal structure at the first time, because such a structure does not exist. One can approach such a solution by designing an intermediate form between prototype and the final solution. Only the parts that are most important from the point of view of the final design are strictly considered, while the unimportant steps are omitted.

7. PRELIMINARY STRUCTURAL DESIGN

In order to carry out functional analyses, a structural model of excavator working system was developed (Fig. 6). It was designed on the basis of previously calculated assumptions regarding length and working range. The material and cross-sectional shape were also taken into account.

Fig. 6. Preliminary design of an extended reach excavator working system

Applying the principle of simplification of insignificant elements at this stage, the top-down optimization of shape was abandoned and the simplest structure was designed in accordance with the assumptions of the previously adopted section. All parts were constructed from flat bars. The selection of bushings and pins were skipped. Plates reinforcing the structure were used.

7.1. Numerical analysis of preliminary design

In order to check the functionality of the developed system, an appropriate motion simulation was prepared in the ANSYS environment. Dynamic analysis type was selected to carry out the numerical analysis. Assumption was made to consider the problem in terms of rigid body mechanics. To simplify the analysis, the same material was used for the entire system, i.e. high-strength steel A572GR50. Cylinders, pistons, working vessel, plates of working system members and its support were eliminated from the parts analyzed. It was considered that the values recorded with their participation would be overestimated and less reliable. Ties, contacts and the direction of the gravitational force were determined (Fig. 7).

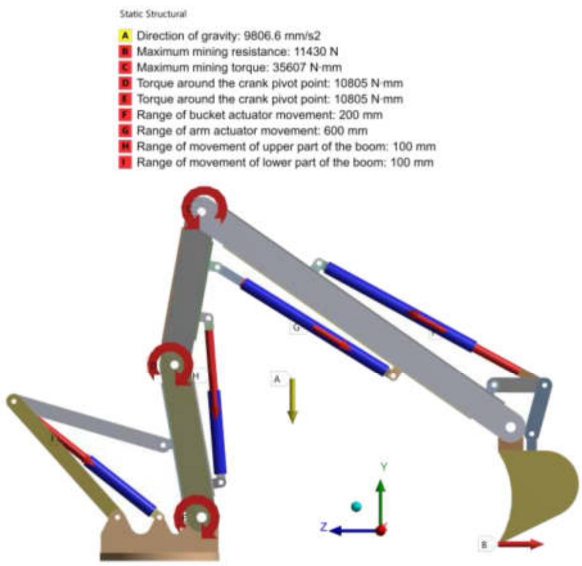


Fig. 7. Forces, moments and displacements assumed on the basis of theoretical considerations

Structure was considered in terms of three properties:

1. Total Displacement (Total Deformation).
2. Equivalent Elastic Strain.
3. Equivalent (von-Mises) Stress.

Part of the test results is presented in the Table 2. Results of the analyses should be considered as illustrative. At this stage, more attention should be paid to average and lower average values than to extreme values. The inflated maximum values are further exacerbated by design simplifications.

8. STRUCTURAL DESIGN

With beginning of this chapter, one of most important chapters was closed. It could be named "determining" part of design, in which best solutions were selected. On the basis of this and all preceding steps, the final form of detailed design assumptions has been developed from which the final design of the excavator working system has been realized.

8.1. Designing excavator bucket

The guidelines in the design process were elementary design assumptions and the content of the chapter on calculating the bucket. Method of construction variants was adopted as the optimization method. According to this method, described in more detail in the chapter, the existing solutions were analyzed. Based on the conclusions from the analysis, the bucket shown in the figure (Fig. 8) below was designed.

Fig. 8. Visualization of a designed bucket

Main goal during design of the bucket, was to maintaining the assumed volume. This assumption has been fulfilled. A high compliance with the estimated dimensions was obtained. The differences, although slight, resulted from the use of technological measures, which could not be taken into account at the stage of estimating dimensions.

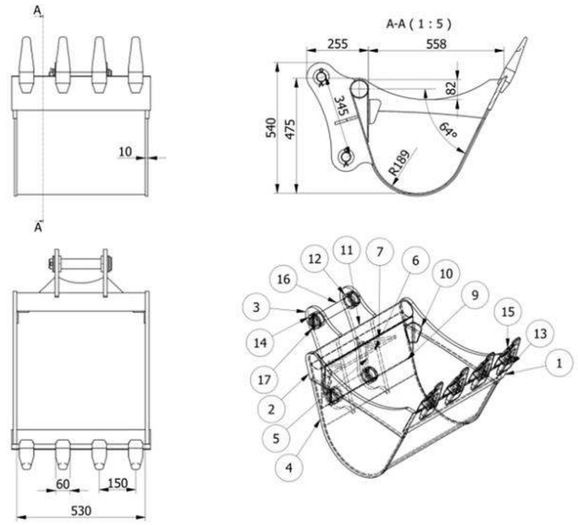
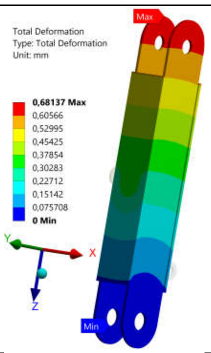
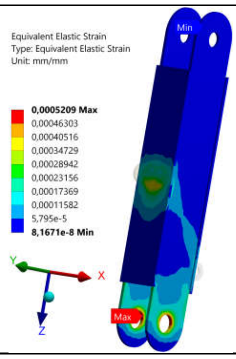
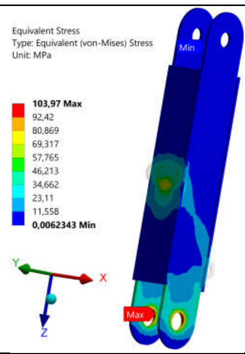
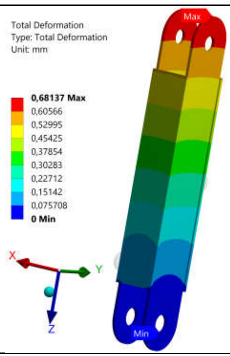
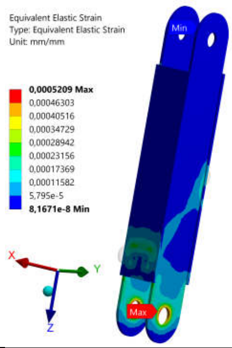
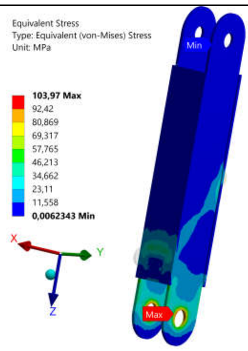
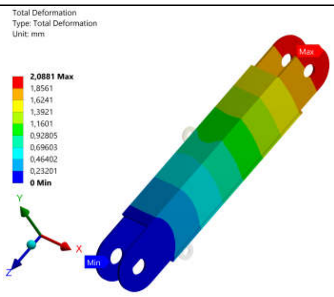
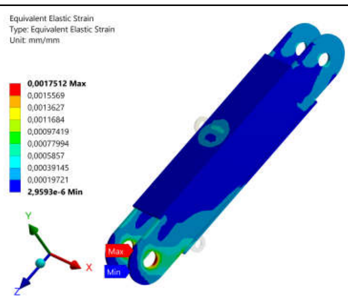
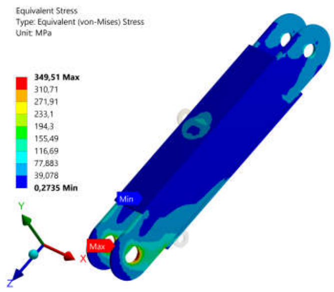
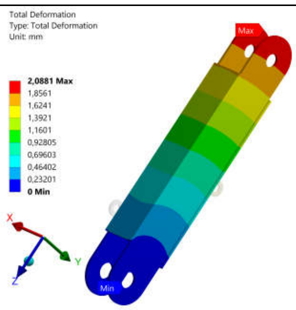
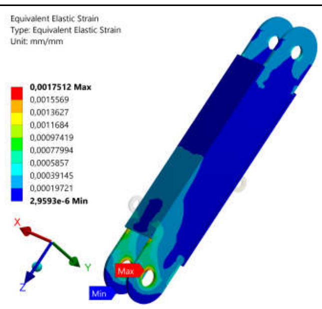
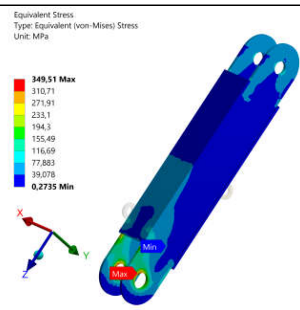


Fig. 9. Dimensions and assembly of designed bucket

Dimensions and components are shown in the drawing (Fig. 9). This drawing should be analyzed together with the parts list presented in the table (Tab. 3). Empty bucket weight was estimated at 60 kg. Weight of designed bucket is approximately 105 kg. The difference is due to the use of sheets of different thickness. The estimation assumed a thickness of 10 mm for each part. In the project, for parts numbered from 1 to 7, 15 mm thick sheets were used, and for parts 8-10 – 10 mm thick.

Tab. 2.Results of numerical analysis for preliminary structural design

Analyzed property	Total Displacement [mm]	Equivalent Elastic Strain [mm/mm]	Equivalent (von-Mises) Stress [MPa]
		LOWER PART OF BOOM	
Initial position (front)			
Measured values	Max: 0.68; Min 0	Max: $5.2 \cdot 10^{-4}$; Min $8.1 \cdot 10^{-8}$	Max: 103.97; Min 0.0062
Initial position (back)			
Initial position (front)			
Measured values	Max: 2.9; Min 0	Max: $1.7 \cdot 10^{-3}$; Min $2.9 \cdot 10^{-6}$	Max: 349.51; Min 0.27
Initial position (back)			

Tab. 3.Bill of materials of designed bucket

No.	Quantity	Part no.	Title	Weight [kg]
1.	1	MWZ 01.01.01	Jaw base	9.921
2.	2	MWZ 01.01.02	Side plate reinforcement	6.233
3.	2	MWZ 01.01.03	Ear plate	6.555
4.	2	MWZ 01.01.04	Wall plate	10.400
5.	1	MWZ 01.01.05	Lower plate reinforcement	0.416
6.	1	MWZ 01.01.06	Ear plate reinforcement	1.207
7.	2	MWZ 01.01.07	Ear plate	0.393
8.	1	MWZ 01.01.08	Bottom plate	21.036
9.	1	MWZ 01.01.09	Upper plate	4.159
10.	2	MWZ 01.01.10	Reinforcement plate	0.261
11.	1	MWZ 01.01.11	Seamless steel tube	3,411
12.	4	MWZ 01.01.12	Steel sleeve	0.319
13.	4	Caterpillar General Duty K80 00.02	Tooth adapter	1.724
14.	4	MWZ 01.00.01	Brass sleeve with collar	0.032
15.	4	Caterpillar General Duty K80 00.01	Tooth	0.991
16.	2	PN-90_M-83002 - B 40x250	Clevis pin	2.593
17.	2	PN-76_M-82001 - 8 x 56	Pin	0.029

8.2. Design solutions used in designing of the bucket

In order to design a bucket with the highest possible quality, following construction solutions were applied:

1. Using tube as a main supporting element for the whole construction (optimization criterion: time, cost) – this solution is simpler than most of solutions used on market. Commonly, reinforcing of that part is obtained by bending the lower plate. This is a difficult operation, because already existed rolled part of the lower plate will make it more difficult. Or vice versa, depending on the order of technological operations.
2. Combination of side cutting edge with its extension combined with simultaneous reinforcing of the side wall (optimization criterion: strength, durability) – typical solution is using of sharp bolted (less frequently welded) cutting edges. Often this edge is additionally extended. Usually they are not connected with each other in any way. This necessitates use of a large number of fasteners. Using a one piece of material welded to the side wall eliminates this problem. Additionally, the structure is strengthened. This edge will not be as sharp as those in the rejected solution (although it can be chamfered accordingly), however, due to the general purpose of the bucket, it does not matter.
3. Use of reinforcing plate for wall plate, upper plate and tube (optimization criterion: strength, durability) – major manufacturers reinforce even their smallest buckets this way. Without testing it is impossible to say if was this is necessary. However, the fierceness of the manufacturers in applying this procedure is in a way a vouch for its necessity. In addition, the low cost generally reinforces the structure.
4. Use of metal sheet to reinforce the lower plate between it, the upper plate and the pipe (optimization criterion: strength, durability) – a solution that generally reinforces the structure.
5. Use of sheet metal and angles to strengthen ear plates (optimization criterion: strength, durability) – solution that generally reinforces the structure.

8.3. Numerical analysis of bucket

In order to check the durability of designed bucket, its strength analysis has been performed. Initial boundary conditions were assumed in the form of complete filling of the bucket with excavated material with simultaneous lifting of the bucket.

Results were shown in Fig. 10. where: a) zoom to the sleeve in the upper cylinder seat; b) stress focus at the extreme point of the plate of the cylinder mounts; c) stress focus in the front hub; d) stress focus in the rear hub; e) stress in the lower cylinder seat; f) side wall truss; g) zoom to the stress focus at the indentation in the side wall; h) top of isolated I-beam; i) bottom of isolated I-beam.

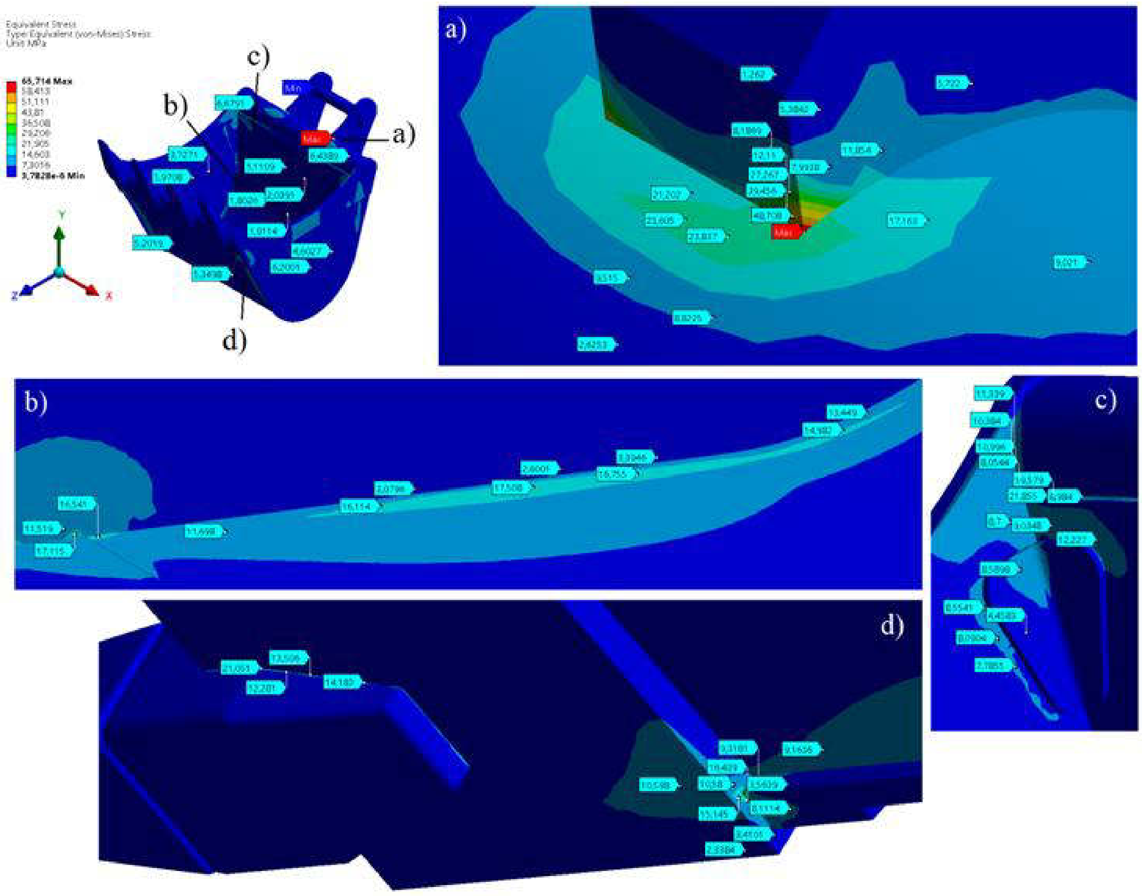


Fig. 10. Summary results of Huber-Mises reduced stresses hypothesis for the designed bucket

8.4. Conclusions of numerical analysis

1. Maximum value was 65.714 MPa located at the extreme point of the mounting ears on the outside of the ears in direct contact with the pipe (Fig. 10a). Stress focus is located only on the sheet metal. The pipe was covered by the local zone. Values recorded there were low. In the weld area between the bottom and the side plates of the bucket, even lower results were get (Fig. 10b). Maximum values didn't exceed 18 MPa. Stress continuity can be an alarming signal. At higher values, it would be necessary to use plates to break them into transition zones.
2. Use of side plates reinforcements was an effective solution to eliminate the continuous fatigue line within the weld (Fig. 10c). However, the maximum stresses were recorded elsewhere. They are located at the weld area of the pipe with the top shell and reach about 22 MPa.
3. Typical tooth analysis was abandoned by adopting the widely used Caterpillar General Duty K80 teeth for the design. Only the bonding points between the teeth and the bucket structure were analyzed. (Fig. 10d). Stresses were ranged from 12.2 to 21 MPa. Additionally, place of occurrence of a potential stress focus located in the junction of as many as four plates was inspected. However, the values recorded there are not high. The maximum value was 13 MPa.
4. Total displacement and equivalent elastic strain were also tested. The maximum value of displacement was 0.00032857 mm and was located in the focus of maximum reduced stress. The maximum strain was recorded at the center of the lowest point of the lower bucket plate and was only 0.16 mm. Side walls deformed by a maximum of 0.08 mm.
5. Despite the overall relatively low values of analysis results, their location has to be subjected to additional quality control at the production stage for determining its compliance with the technological process assumptions.

8.5. Conclusions of structural design

1. It was possible to design all elements of working system in full compliance with the applicable standards [1].
2. Obtained values of stresses in the vast majority were in the acceptable range (maximum 0,4 - 0,5 of factor of safety).
3. All values close to the limit are subject to the error resulting from the simplification of welded joints, caused by the limitations of the program.

4. However, even in this case they are lower than the acceptable values (8.3; a).
5. Due to the adopted form of construction (long welded joints, many shape joints, minimization of potential stress areas), more attention during analyzing the test results should be paid to the stress distribution obtained over the entire analyzed surface.

9. MAIN ASSEMBLY

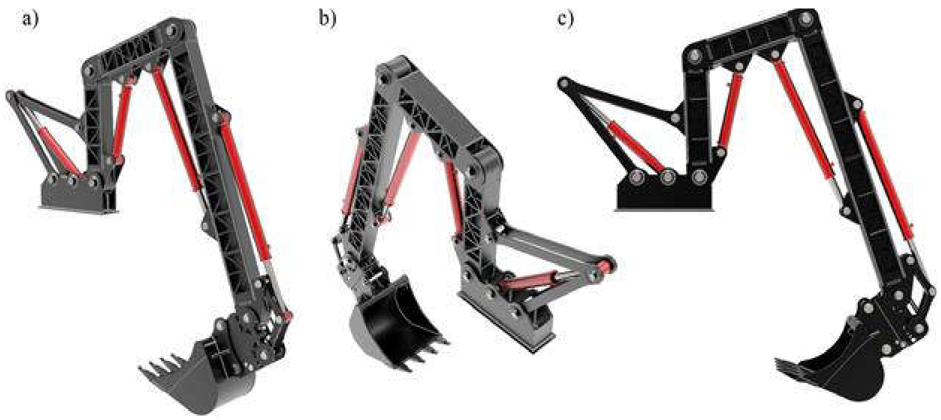


Fig. 11. Visualization of main assembly of designed attachments module in transporting position, where: a) front isometric view; b) rear isometric view; c) side view.

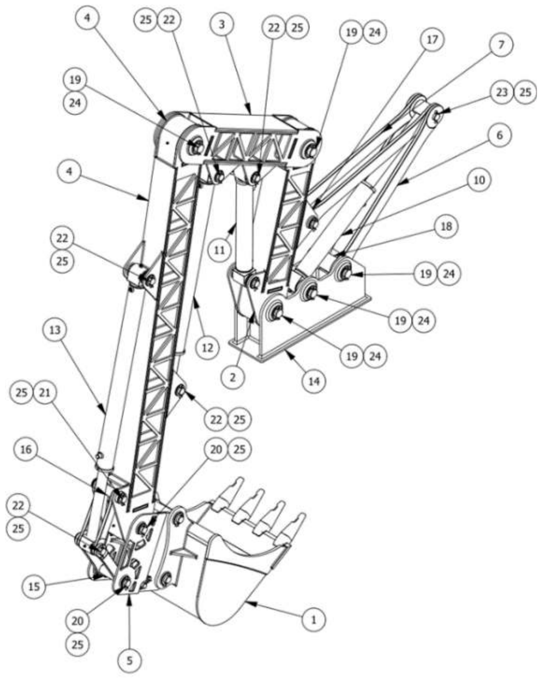


Fig. 12. Assembly drawing of finished attachments module

Once all the components of design were prepared, main assembly of them were proceeded. A full degree of component fit has been achieved. Analysis of collision has been performed in the Autodesk Inventor environment and it did not detect any collisions in the full range of fixture mobility.

Result are illustrated in the figure (Fig. 10). Components are illustrated in the figure (Fig. 11). This drawing should be analyzed together with the parts list in the table (Table 4).

Tab. 4.Bill of materials of designed bucket

No.	Quantity	Part no.	Title	Weight [kg]
1.	1	MWZ 01.00.00	Bucket	105.858
2.	1	MWZ 02.00.00	Lower part of boom	78.261
3.	1	MWZ 03.00.00	Upper part of boom	82.171
4.	1	MWZ 04.00.00	Arm	147.131
5.	1	MWZ 05.00.00	Quick coupler	46.867
6.	2	MWZ 06.00.01	Right boom linkage	11.595
7.	2	MWZ 06.00.02	Left boom linkage	11.570
8.	2	MWZ 07.00.01	Right bucket linkage	2.488
9.	2	MWZ 07.00.02	Left bucket linkage	2.556
10.	1	MWZ 08.00.00	Lower boom part cylinder	26.686
11.	1	MWZ 09.00.00	Upper boom part cylinder	26.115
12.	1	MWZ 10.00.00	Arm cylinder	40.583
13.	1	MWZ 11.00.00	Bucket cylinder	43.136
14.	1	MWZ 12.00.00	Base	81.538
15.	1	MWZ 00.00.01	Spacing sleeve	0.283
16.	1	MWZ 00.00.02	Spacing sleeve	0.203
17.	1	MWZ 00.00.03	Spacing sleeve	0.460
18.	1	MWZ 00.00.04	Spacing sleeve	0.535
19.	5	PN-90_M-83002 - B 50x260	Pin clevis	4.210
20.	2	PN-90_M-83002 - B 40x235	Pin clevis	2.445
21.	2	PN-90_M-83002 - B 40x205	Pin clevis	2.149
22.	6	PN-90_M-83002 - B 40x175	Pin clevis	1.853
23.	1	PN-90_M-83002 - B 40x170	Pin clevis	1.803
24.	5	PN-76/M-82001 - 8 x 63	Pin	0.031
25.	11	PN-76/M-82001 - 8 x 56	Pin	0.029

Surprisingly good working ranges of the designed attachment module has been obtained (Fig. 12). Dimensions that create outline of the work area (RR1; RR2; HH23) are on average 50% larger than comparable excavators available on the market. This occurred because of picking the upper limit of the weight assumption, what was 6000 kg. If the entire excavator could be designed to a weight of less than 5000 or 4000 kg, the difference would be magnified in favor of the designed attachment.

Weight of the designed attachment was close to 780 kg. Based on an analysis of existing solutions, weight of the attachments module was found to have a relationship to the weight of the excavator of 1:5 - 1:6. Estimating the weight of the entire excavator based on these relationships should oscillate within 3900 kg to about 4700 kg. These values are far below the assumed limit of total weight of the excavator for which the equipment has been designed. This places the developed solution among the constructions better than average on the market. Not only in terms of reduced weight, but at the same time ensuring a greater working range.

Difference in weight can be used to expand the innovation of the design or to extend the attachment even further while taking into account the proportional increase in weight of the excavator without the attachment.

Calculation of pin connections was abandoned. Pins analogous to those used by excavator manufacturers were applied. Pins used for 6000 to 8000 kg machines were assumed. Almost two times difference in weight in favor of the developed solution gives the impression of oversizing the construction, but in the absence of calculations it is justified.

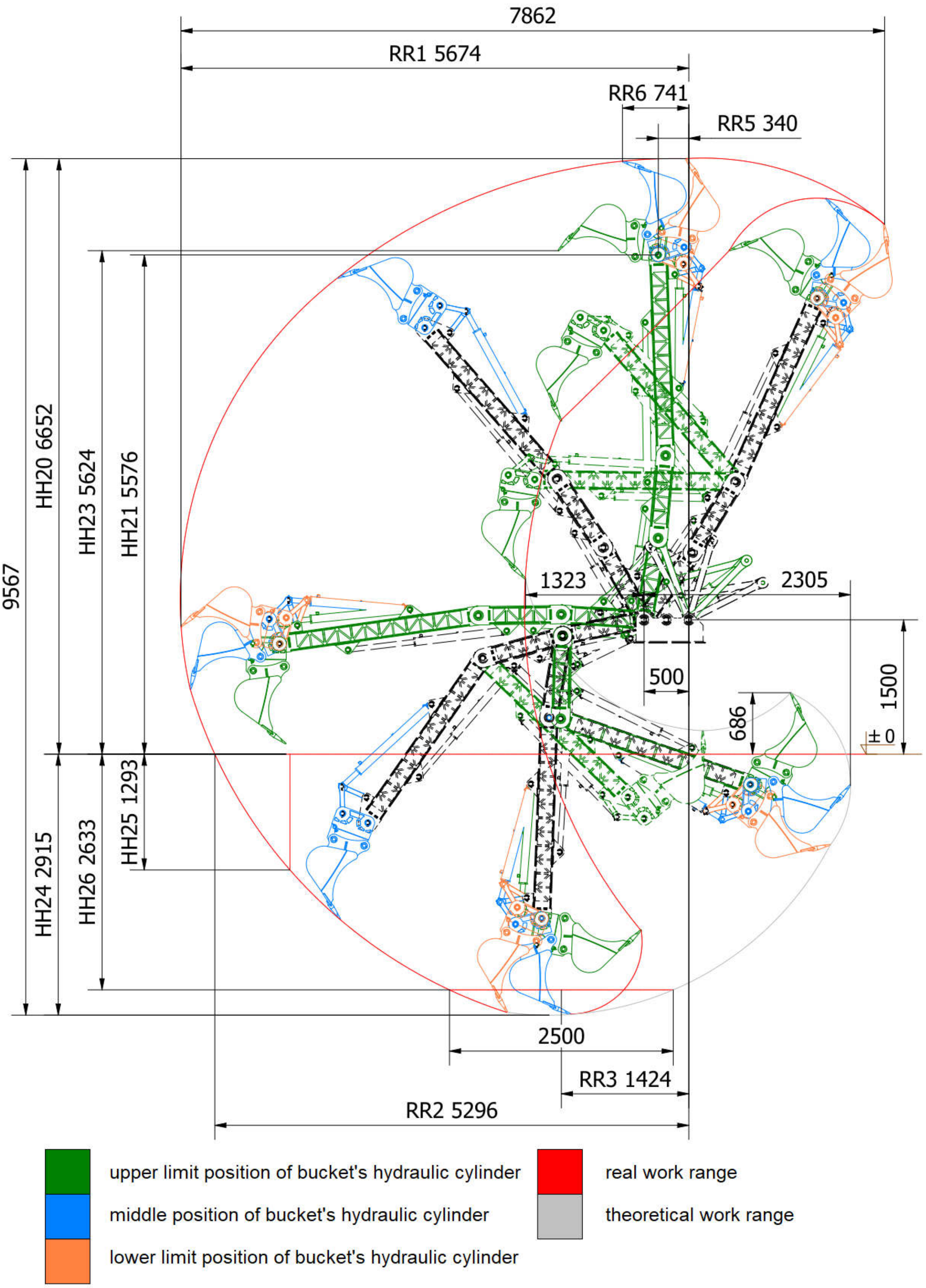


Fig. 13. Outline of working field drawn up by analysis movement of designed attachments module

10. DEVELOPMENT OPPORTUNITIES

Due to the nature of this work, only issues related to its purpose and the assumptions were implemented in this paper. Therefore, some contents were simplified or omitted altogether. Extending scope of the work could be beneficial for the quality of the product. Scope of further work for the considered case of extended reach excavator is specified in the subchapter.

10.1. Further developments

While carrying out further work on the project, two directions could be distinguished. First corresponding to the further development of the working attachments. And second concerning design of the other components of the excavator.

Even top quality designs can almost always be further improved. This is related to applied optimization criteria. Quality of the realized design can be measured, among other things, by determining the degree of adaptation of the designed design in relation to the optimal design, i.e. the design defined by the optimization criteria. Solution is then best only for a strict set of assumptions. When they are modified, shape of the optimum is also modified. For this reason, in order not to increase the volume of the paper too much, some structural solutions which could be introduced as improvements of the designed structure have been omitted. Those pertaining to hardware issues are listed below.

1. Additional range increase by replacing boom or arm with a telescopic version.
2. Increasing number of attachment module parts.
3. Further topological optimization, e.g. quick coupler or I-beam.
4. Increase range of motion of the bucket.
5. Integration of arm with a pneumatic hammer located inside it. Work would be possible when bucket reaches the extreme top position. Operator could then extend the chisel.

   Consideration of printing designed attachment components but with a highly optimized cross sectional area.

Determining direction for further work of designing other components of excavator is easier. Its overall design has not been developed, so design assumptions for individual components could be set as such guidelines. Figure 14 shows a visualization of the developed hardware mounted on the excavator's concept.

Fig. 14. Visualization of designed attachments module mounted on excavator concept

Several solutions were implemented there, the sense of which is described below.

1. Modification of the typical two-track running gear used in excavators to four independent tracks with a triangular cross-section, driven in a manner analogous to wheeled excavator systems. This would translate into comparable stability at higher speeds.
2. Removing counterweight and motor from the excavator rotation. It would be necessary to divide the undercarriage into two sectors. The first fully rotating based on a rim bearing. On this part would be located equipment and operator cabin (Fig. 14). Second sector would not be rotating and would contain, among others, the counterweight and the engine.
3. Design of "intelligent" counterweight. Use of control systems coupled to the work system. The further reach of the attachment, the further counterweight should extend. This ensures that the center of gravity remains in its original position. This makes it possible to use counterweights with smaller masses than those classically suspended at the rear of the vehicle. An interesting solution in this respect is proposed by [7].
4. Designing for optimization of the standard working cycle. Longest phase of the excavator work cycle is while excavated material transport phase and the bucket return phase. It accounts for 75% of the entire single work cycle. This appears to be a definite disadvantage. Trying to eliminate this longest phase may seem like an abstraction today, but it would be revolutionary. One way could be to integrate the boom with a conveyor belt mounted on the upper parts of its individual members. Alternatively, the excavated material could be transported in a sort of tunnel inside the

attachment. In either case, a suitable bucket for such work would need to be developed.

Additionally, while continuing work on the described project, it would be necessary to develop:

- hydraulic transmission system;
- ergonomic operator's cabin based on current standards;
- engine selection process;
- stability analysis of the structure;
- analysis of operational efficiency.

10.2. Future of excavators in context of Fourth Industrial Revolution

Industry 4.0, also known as the fourth industrial revolution, is a concept according to which, using benefits of technological advances, the aim is to transform factories into self-driven and capable of making decentralized decisions, intelligent manufacturing centers. In context of this concept, issue of excavators can be divided into two parts. The first one concerning structural design and the second one corresponding to manufacturing processes.

In the case of design, assumptions of the industrial revolution are primarily oriented around maximum automation and integration of products with the Internet. A very important part of Industry 4.0 is the issue of deep learning for machines and devices. This is the opposite of machine learning, where information was entered into a computer only under human supervision. Idea behind deep learning is that devices acquire knowledge without human intervention. In the case of machine learning, the success of excavator automatization is related to human ability to predict all possible situations that may occur during operation. With deep learning, an appropriately designed machine will be able to adjust itself to current operating conditions. The word adapt is used here for a reason. Only maximally adaptable and modular machines will be able to be fully integrated into Industry 4.0. Therefore, the excavators of the future should be designed for maximum versatility in terms of both operation and design. All modules should be fully interchangeable and preferably jointly interchangeable. Interchangeability of components should equate to shaping a machine with an alternative application. The greater interchangeability, and therefore the greater the number of optional designs, the greater chance of selling the machine.

11. SUMMARY

Main objective of research has been successfully achieved. Compact excavator with an extended reach has been designed. Attachment module, its most important part, were developed on a meticulously conducted design process. Rest of the assembly has been presented in a conceptual visualization.

Design of the attachment module was performed in classical way. Literature analysis was used to define design assumptions. Based on these, conceptual solutions were defined and the best one was selected. Structural framework was estimated based on the results of traditional design calculations. In order to check correctness of calculations, a preliminary version of structure was designed and subjected to numerical analyses. Based on conclusions, final version of structure has been designed and subjected to more detailed analyses. At the end, technical documentation of the product was prepared.

An informal assumption of the work was an attempt to implement as many engineering innovations as possible. Kinematic system of equipment was shaped in a way that allows comfortable work at short and long range. Classical solutions for range extension were rejected in the design process due to their template character and the number of disadvantages, disproportionate to the number of advantages. In designed construction range suitable for medium excavators with weight within the range of mini excavators has been achieved. Original system of installing the bucket has been developed, realized in semi-automatic and fully functional way, free from electronics, with appropriately adapted quick coupling.

Despite the application of non-standard design solutions, results of all strength analyses of designed structure were within the range of allowable values. Tests were conducted in conditions corresponding to intensive exploitation. Highest values, although still not exceeding the allowable range, were noted for welds connecting the sockets for the actuator pins with the plates strengthening these sockets. Lowest results in principle were recorded for most of the side surfaces of the designed fixture. This highlights the further vulnerability of the design to optimization.

One of the philosophies of today's world is to offer more for less. This slogan also applies to the world of engineering. Designed structure fits perfectly into these assumptions, and with additional improvements it could certainly be an interesting alternative to the typical solutions advocated by the largest manufacturers.

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Biographical notes

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