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Comparison of methods of topological optimization of a selected module of a mobile working machine and assessment of the possibilities of production by additive technology

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ABSTRACT

The paper deals with the objectification of the methodology of design of large-scale modules of mobile working machines (MWG) using the principles of topological optimization (TO) and its application through additive manufacturing, namely the WAAM (Wire Arc Additive Manufacturing) technology, and the verification of this methodology. The methodology involves a sequence of steps from the selection of a suitable module, its comparative subjecting to TO using available software tools, to the subsequent implementation of the available module through the dynamically developing additive manufacturing technology from affordable materials. Safety requirements in terms of EN ISO 3471 were chosen as a benchmark. It can be concluded that the above methodology represents an efficient design for the development of the MPS module with regard to its safety, functional and manufacturing parameters. The comparison of G3Si1 and ER 5356 materials focused on strength characteristics and weight. The results show that the ER 5356 material performs better in terms of overall cabin weight, achieving a weight of 422 kg, a reduction of 28% compared to the original solution.

Keywords: modular construction, topological optimization, additive manufacturing.

INTRODUCTION

Topological optimization (TO) represents a modern innovative approach to the module design process, enabling optimal material distribution based on realistic load and boundary conditions within a predefined space [3–11]. This method is gaining more and more attention, especially in combination with additive manufacturing (AM), as the latter allows the creation of complex functional shapes, more difficult to produce by traditional or conventional manufacturing technologies [2, 31]. This paper deals with the analysis and implementation of a TO purpose-selected module, a mobile work machine (MWM) cab-excavator, while available software tools were used for the sake of comparing the results [2, 10, 12]. The aim was to compare the results obtained when verifying the functionality of the investigated module in terms of the applicable safety requirements and to recommend a suitable type of software tool allowing to obtain an optimal design of the module structure with the same input parameters. Subsequently, the additive manufacturing of the MPS deleted module was also carried out using the available innovative WAAM technology [2]. This study presents a comparative analysis of topology optimization (TO) methods applied to the design of a cabin module for a mobile work machine, with subsequent fabrication utilizing Wire Arc Additive

Manufacturing (WAAM) technology. The primary objective is to evaluate the structural performance, manufacturability, and overall feasibility of integrating advanced computational design approaches with modern additive manufacturing processes.

OPTIMIZATION METHODOLOGY

The methodology of designing functional modules was based on a modular analysis of the architecture of the selected MPS and its technological variants, which resulted in the determination of a platform of common modules that would be appropriate to innovate in terms of the production portfolio (Figure 1) [1, 2]. For this purpose, a computational script was designed. The selected module was subsequently configured to be a suitable input for TO in different software. The second and third steps were the design of the input CAD design and subsequent TO in multiple software. As a result, the software and user interfaces were compared in terms of TO [3–11]. The penultimate step was the creation of a stable CAD model of the selected module created by surface modelling, which further served as a

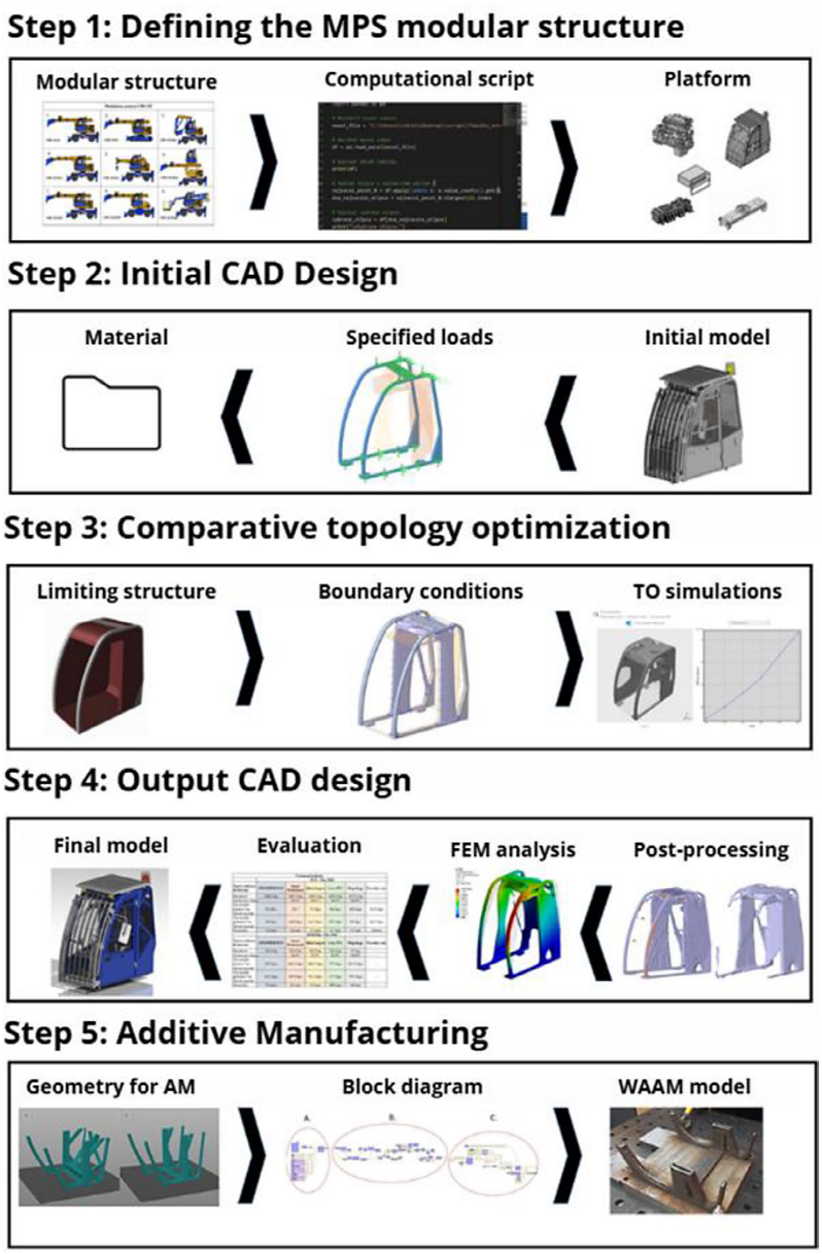


Figure 1. Methodology of comparative optimization of the selected module

prototype for the validation of the new additive technology tested at the Brno VUT [2].

MODULAR MACHINE STRUCTURE

Part of this step was to establish a common platform of unified parts. For the quantification of the degree of modularity, the MPS with the designation UDS 132 was selected, which was developed at the UAIK, where 9 other variant solutions were developed within the project for the implementation of different working technologies (Figure 1, 2) [1]. The whole methodology of platform determination was simplified with the help of a computational script in Visual Studio Code using the Python programming language. The input to the analysis was a table summarizing the usability of the modules within each machine design option [1, 2].

The platform modules of the individual machine assemblies selected by the calculation script can be considered relevant for the application of the innovative component design method DfAM (Design for Additive Manufacturing) and, at the same time, the most suitable for efficient production, since they are used in only one variant of all the machine assemblies considered (Figure 2) [1, 2].

INPUT CAD OF THE CAB MODULE

The next step was the design of the initial CAD design, which covers the selection of a suitable structural assembly, the selection of suitable material and the determination of realistic loads [3–14]. The UDS 132 concept used an available cab used by CSM Tisovec. It was selected for the DfAM application as it provides an important function in terms of operator safety and safety, operator comfort and ergonomics. It is also a visually important module in terms of overall machine design. For these reasons, it was necessary to pay attention to the frame design, which must absorb the forces generated during the ROPS tests, which were simulated in the cab design process using loads determined in terms of STN EN ISO 3471 [31]. The materials used for the following comparative simulations, due to the possible use of the DfAM method, were selected as 316L steel and AlSi10Mg alloy [17–20].

COMPARISON OF TOS FOR INDIVIDUAL CAD SOFTWARE

Description of the used software

The following available software was used in the process of investigating and comparing the

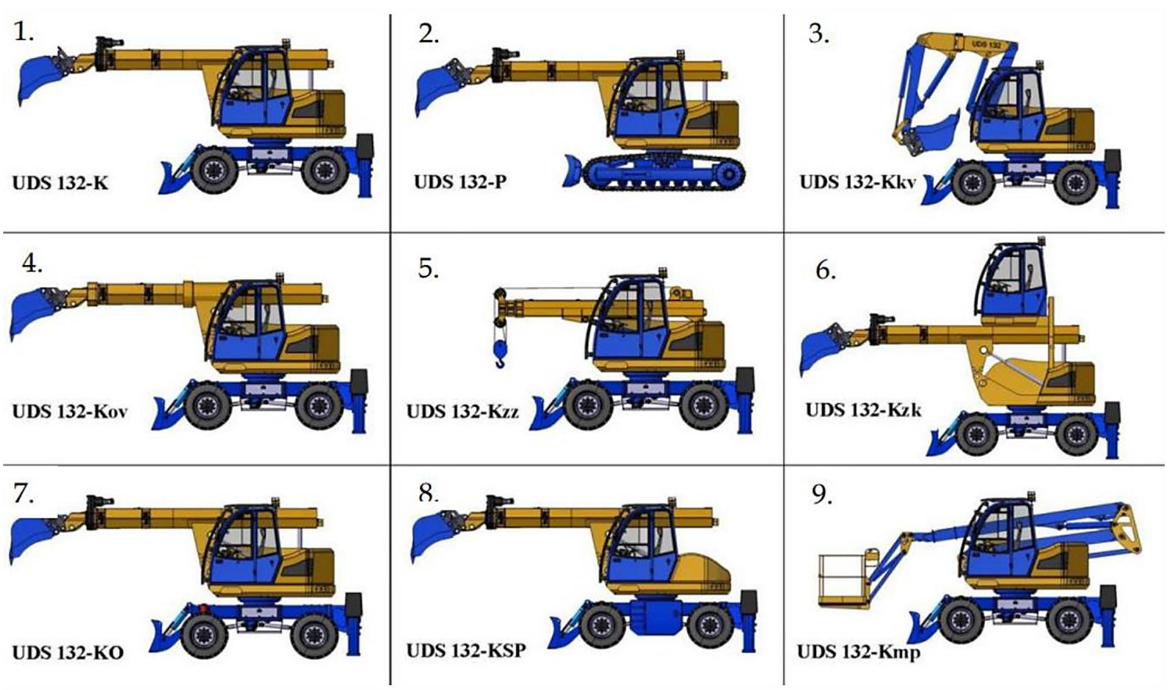


Figure 2. Variant solutions UDS 132

results for the proposed methodology of the cabin module design process. Their characteristics are listed in (Table 1) [10]:

1. 3DEXPERIENCE:
- uses SIMP (solid isotropic material with penalization) optimization algorithm,
- works with both linear and quadratic mesh elements,
- allows the definition of a custom constraint space,
- includes control over the FE mesh before and after topological optimization,
- advantages include support for direct conversion to volumetric CAD models and the availability of various geometry editing tools.

2. Ansys workbench:
- combines SIMP and OC (optimality criteria) algorithms,
- uses quadratic elements with geometry control,
- limitations include fewer user options for editing the FE network after optimization and limited support for defining the limiting space.

3. Altair inspire:
- applied SIMP algorithm, supplemented with the ability to generate lattice structures,
- optimization focuses on strength and mass, but without extensive FE network control options,
- significant limitation is the need for specific input settings.

4. Creo parametric (PTC):
- supports SIMP algorithm in combination with RAMP (rational approximation of material properties) method,
- includes advanced optimization including generative design,
- enables multiple TO (Multi-TO) and has robust support for modeling and post-processing.

5. nTopology:
- works on the principles of the SIMP algorithm and provides grid generation capabilities,
- supports multi-TO and requires quadratic mesh elements but limits geometry control [15–16].

Topological optimization

Topological optimization is a systematic approach to improve the geometry of structural elements in order to reduce weight while maintaining mechanical properties. Prior to the optimization, it was necessary to determine an appropriate optimization strategy, defining the volume to be optimized and identifying

Table 1. Overview of general characteristics of available software tools

Softwer name / Criterior	Comparison in terms of the main criteria				
	3DEXPERIENCE	Ansys workbench	Altair inspire	Creo, PTC	ntopology
Software availability	Commercial license	Commercial license	Commercial License/Student License	Commercial license	Commercial License/ Student License
Optimization algorithms	TO (SIMP)	TO (OC, SIMP)	TO (SIMP), Lattice	TO (SIMP, RAMP), Generative Design	TO (SIMP), Lattice
Optimization conditions	Stiffness/Mass / Frequency	Compliance / Mass/ Frequency	Stiffness/Mass / Frequency	Strain energy / Mass/ Stress/ Displacement / Strain/ Moment of Inertia / Reaction force / Frequency / Heat transfer compliance	Compliance/ Volume / Displacement / Stress
Definition of own limiting space	√	√	√	√	√
Control over the FE network before TO	√	√	X	X	√
FE network arrangement elements	Linear/Quadritically	Linear/Quadritically/ Control by the program	Quadritically	Quadritically	Linear/Quadritically
Use of multiple load states	√	X	√	X	√
Conversion to solid CAD models	√	√	√	√	√
Geometry check	√	X	X	√	X
Safety factor	√	X	√	√	X
Multi TO	X	X	√	√	√
Control over the FE network after TO	√	√	√	X	√

its functional elements that must be preserved, (Figure 3). A key step was to determine the loads and constraints under different load scenarios (Load Cases) that provided realistic simulation conditions. These are based on the requirements for ROPS tests, as set out in STN EN ISO 3471 [31]. The creation of the computational mesh (mesh) was followed by an initial strength analysis, which evaluated the stress-strain state of the original geometry. Based on this data, optimization conditions were established, including the objectives, namely minimization of mass at maximum stiffness. The boundary conditions for each software are defined in (Table 2) [3–11]. The topological optimization itself is performed using iterative algorithms that remove redundant material and redistribute it as needed to make the structure efficient. The resulting concept was then subjected to strength analysis and compared in terms of functionality, manufacturability and load resistance. The final design represents an optimal combination of reduced weight, mechanical strength and technological feasibility, while being suitable for implementation, especially in the context of additive manufacturing [3–11].

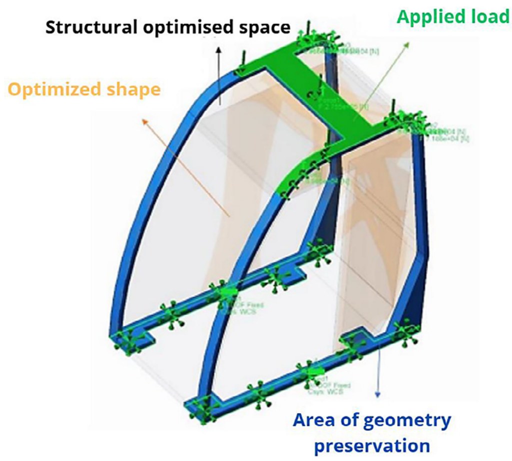


Figure 3. Optimized volume

Table 2. Marginal conditions of available software resources

Softwer name / Criterior	316 L - Max Stiff				
	3DEXPERIENCE	Ansys workbench	Altair inspire	Creo, PTC	Ntopology
Type of mesh	Linear	Quadritically	Quadritically	Quadritically	Quadritically
The size of mesh	20 mm	20 mm	20 mm	20 mm	20 mm
Number of burdensome conditions	1	1	1	1	1
Type of limiting space	intersect	non-intersect	non-intersect	intersect	intersect
Computerised weight of the semi-finished product	4908.8 kg	4903.2 kg	4908.7 kg	4909 kg	4909 kg
Geometry check	yes	no	yes	yes	no
Optimization method	Max Stiff	Min Compliance	Max Stiff	Max Stiff	Max Stiff
Safety factor	no	no	no	no	no
Softwer name / Criterior	AlSi10Mg - Max Stiff				
	3DEXPERIENCE	Ansys Workbench	Altair Inspire	Creo, PTC	Ntopology
Type of mesh	Linear	Quadritically	Quadritically	Quadritically	Quadritically
The size of mesh	20 mm	20 mm	20 mm	20 mm	20 mm
Number of burdensome conditions	1	1	1	1	1
Type of limiting space	intersect	non-intersect	non-intersect	intersect	intersect
Computerised weight of the semi-finished product	1678.5 kg	1676.6 kg	1754.5 kg	1606.4 kg	1678.5 kg
Geometry check	yes	no	yes	yes	no
Optimization method	Max stiff	Min compliance	Max stiff	Max stiff	Max stiff
Safety factor	no	no	no	no	no

OUTPUT CAD MODEL OF THE CABIN

The conversion of polygon models to volumetric models in.step format is a key step for further use in CAD design and FEM analysis. Polygon models in.stl format, although suitable for 3D printing, require additional modification for FEM analysis. This process can be accomplished in three ways: direct conversion, use of software tools, or complete remodeling. Direct conversion is a fast way to convert triangles into a volumetric model, but with limited accuracy and without the possibility of undoing changes, with suitable tools such as Ansys SpaceClaim or nTopology. Software tools such as 3DExperience, Altair Inspire or Creo Parametric, (Table 3), allow user-friendly redrawing of geometry with an emphasis on preserving details, but are not entirely suitable for solid and functional structures. Complete remodelling is the most challenging of all the methods, but also the most accurate, as it ensures a stable and high quality CAD model. The choice of a particular approach depends on the requirements of the project and the capabilities of the software used [2, 10].

FEM analysis

The original cabin frame structure was subjected to a finite elements method (FEM) analysis, which demonstrated its unsatisfactory mechanical properties. The applied forces according to ISO 3471 caused high global stresses (up to 3000 MPa) and deflections (229 mm), making the cab unsafe to use in the event of a machine overturn. The main problem was the thin roof structure made of 2 mm sheet metal and its insufficient strength parameters. The results highlighted the need to develop a new frame structure that would meet safety standards and protect the operator even in difficult working conditions [2]. In order to optimize in the design process of the cab made of the selected materials (316L and AlSi10Mg), the analysis was performed in different software. The global stresses were kept below the yield strength, with strains not exceeding 2 mm, confirming the sufficient stiffness of the structure (Table 4, 5). Locally higher stresses (e.g. 428–448 MPa) were related to notches and imperfect connection of the polygon model, but these locations can be subsequently corrected. The 316L material has the required strength but is weight intensive, while AlSi10Mg provides a lighter alternative with similar mechanical properties but is more costly to use [2].

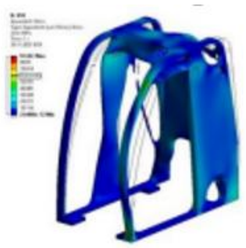
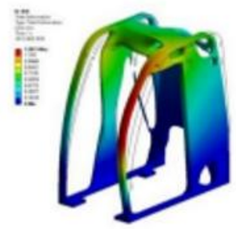
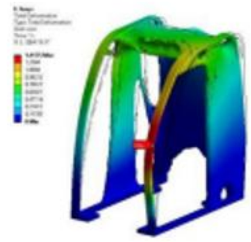
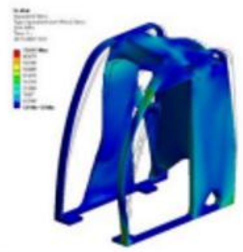
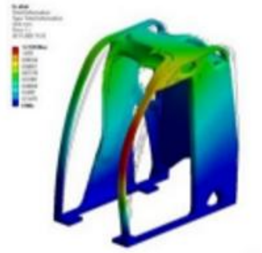
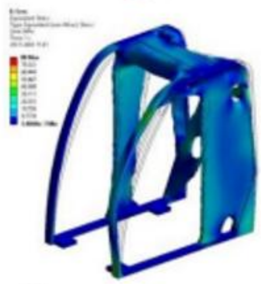
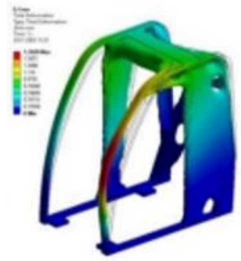
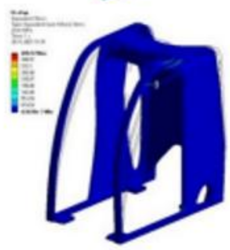
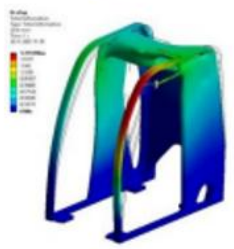
Evaluation of optimization methods

Comparison of topological optimization in different software environments showed differences in results when different materials and optimization methods were applied. Software such as Ansys, nTopology and 3DEXPERIENCE showed similar results for AlSi10Mg and 316L materials, while Altair Inspire and Creo Parametric generated significantly different shapes. The results were influenced by factors such as Young's modulus, material density, and optimized design space. The main objective of the optimization was to maximize stiffness and minimize deformation, with the optimization space itself and the algorithms of each software having the greatest influence. The results indicate that the software differ in their ability to interpret and apply the same input conditions, leading to demonstrably different results shown in (Table 6) [2]. Based on the results obtained using the aforementioned software, 3DEXPERIENCE and Creo Parametric were evaluated as the most suitable for best fit, using which the lowest weight and consistent weight reduction of approximately 30% was achieved while maintaining structural integrity. Ansys Workbench systems were shown to have the highest weight and also limited optimization capabilities. Using

Table 3. Post-processing options of available software resources

Softwer name / Criterior	Post - processing				
	3DEXPERIENCE	Ansys Workbench	Altair Inspire	Creo, PTC	nTopology
Conversion to volume models directly in the software	√	√	√	√	√
Freeshape design	√	X	√	√	X
Surface modeling	√	X	√	√	X
Management FE mesh after TO	√	√	X	X	√

Table 4. Maximum global stresses and strains when using 316L steel

316L – Maximize stiffness			
Software	Values	Von mises stress	Displacement
3DEXPERIENCE	Max. global stress = 50.5 MPa		
	Max. deformation = 1.3 mm		
Ansys Workbench	Max. global stress = 75 MPa		
	Max. deformation = 1.4 mm		
Altair Inspire	Max. global stress = 50 MPa		
	Max. deformation = 1.2 mm		
Creo Parametric, PTC	Max. global stress = 39.1 MPa		
	Max. deformation = 1.7 mm		
nTopology	Max. global stress = 95 MPa		
	Max. deformation = 1.7 mm		

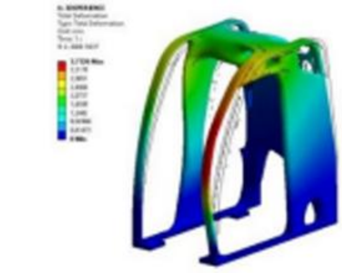
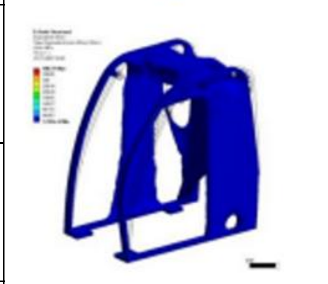
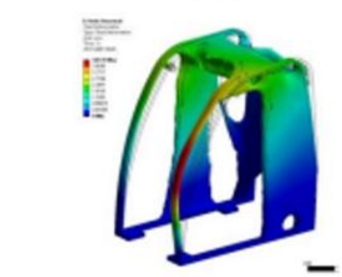
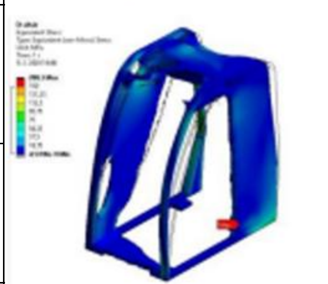
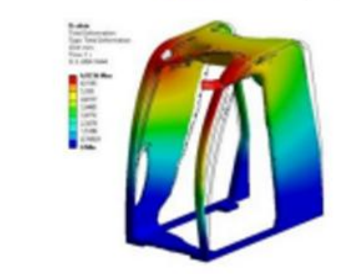
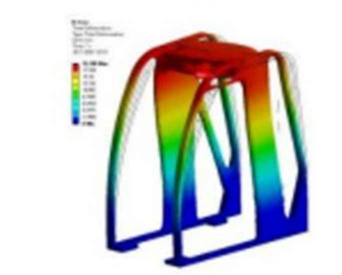
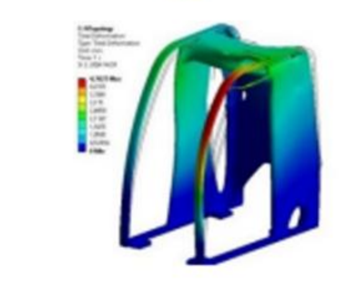
materials with linear characteristics such as steel and aluminium, the design was considered satisfactory. However, when applying non-linear materials (e.g. composites), significant differences in material distribution and computational requirements are expected, complicating their use. Optimization methods have emphasized the need for proper determination of the design space and elimination of geometric irregularities to achieve positive results [2].

IMPLEMENTATION OF A TOPOLOGICALLY OPTIMIZED MODULE AND ASSESSMENT OF THE POSSIBILITY OF ITS PRODUCTION

Design modification for software tools

In the framework of cooperation with the Faculty of Mechanical Engineering VUT Brno, there was also an opportunity to produce an optimized module using WAAM (Wire Arc

Table 5. Maximum global stresses and strains using AlSi10Mg aluminium alloy

AlSi10Mg – Maximize stiffness			
Software	Values	Von mises stress	Displacement
3DEXPERIENCE	Max. global stress = 54.7 MPa		
	Max. deformation = 3.6 mm		
Ansys Workbench	Max. global stress = 49.9 MPa		
	Max. deformation = 4.1 mm		
Altair Inspire	Max. global stress = 96.1 MPa		
	Max. deformation = 6.9 mm		
Creo Parametric, PTC	Max. global stress = 173 MPa		
	Max. deformation = 19.8 mm		
nTopology	Max. global stress = 99.5 MPa		
	Max. deformation = 4.8 mm		

Additive Manufacturing) technology, so it was necessary to design a CAD model for prototype tests. This technology has a great potential for further development in the field of aerospace, energy, ship and automotive industry. However, there is a need to ensure the right combination of advanced control systems in materials compatibility to ensure the reliability and desired quality of this technology, [24–29].

The design of the cabin frame was optimized for the use of available G3Si1 steel, which was also suitable in terms of strength. However, after modification, it was found that the resulting weight exceeded the weight of the original cab by several

Table 6. Output values for comparison of software and selected materials

OUTPUTS VALUE						
Softwer name / Criterior	316 L - Max stiff					
	3DEXPERIENCE	Ansys Workbench	Altair Inspire	Creo, PTC	Ntopology	Original frame
Weight	1473 kg	1687.3 kg	1686.1 kg	1499.4 kg	1675.1 kg	-
preserved volume	30%	34.40%	34.30%	30.50%	34%	-
Maximum local Von Misses tension	91 Mpa	291.7 Mpa	75 Mpa	88 Mpa	428 Mpa	5975 Mpa
Maximum global Von Misses tension	50.5 Mpa	75 Mpa	50 Mpa	39.1 Mpa	95 Mpa	3325 Mpa
total deformation	1.3 mm	1.4 mm	1.2 mm	1.7 mm	1.7 mm	87.2 mm
Softwer name / Criterior	AlSi10Mg - Max stiff					
	3DEXPERIENCE	Ansys Workbench	Altair Inspire	Creo, PTC	Ntopology	Original frame
Weight	507.5 kg	576.9 kg	565.5 kg	513.1 kg	573 kg	-
preserved volume	30.2%	34.4%	32.20%	31.90%	34%	-
Maximum local Von Misses tension	82 Mpa	448.1 Mpa	288.3 Mpa	779 Mpa	447.6 Mpa	-
Maximum global Von Misses tension	54.7 Mpa	49.9 Mpa	96.1 Mpa	173 Mpa	99.5 Mpa	-
total deformation	3.6 mm	4.1 mm	6.9 mm	19.8 mm	4.8 mm	-

times, which could cause problems in the distribution of the aggregates on the rotating superstructure of the machine. A further modification to the design addressed the weight reduction and eliminated complications in the design. Because of the weight reduction, ER 5356 material was chosen to meet the required mechanical properties [21–23].

The optimization for G3Si1 and ER 5356 maintained the same design with input constraints where the critical printing angle was 25° in the Z-axis direction and the mesh mesh values for a single element were set to 20 mm. Minimal use of support structures was considered in the design.

The final CAD model was symmetrical, consisting of simple separate surfaces, allowing for easy modifications. However, some parts did not conform, which could subsequently cause printing errors. This resulted from numerical constraints and the iterative nature of the solution, where the aim was to ensure maximum stiffness in the material distribution.

The optimised shape had to be adapted to the relevant safety standards, which involved changes to the geometry to ensure strength in critical areas. Although TO reduces weight and cost, the resulting shape can be costly due to its complexity. Therefore, modifications are recommended to simplify and reduce manufacturing costs. This illustrates the evolution of the design and subsequent remodelling of the cabin module, (Figure 4) [2]. The proposed cabin design was based on a topologically optimized model, while ensuring stability and adaptation of functional parts. The cabin was simulated in the structure shown in (Figure 5). The G3Si1 and ER 5356 materials were compared in terms of strength and weight, where the ER 5356 material performs better in terms of cabin weight – 422 kg (28% lower than the original one). The resulting FEM analysis values for both materials are below the strength limit and meet the requirements of ISO 3471 [31]. The results obtained are presented in (Table 7). The reduction in model complexity allowed for efficient production and lower costs.

Testing of the WAAM production technology on the cab module

A robotic welding system used for WAAM (wire arc additive manufacturing) technology was tested at the Brno University of Technology for the experimental production of a 1:3 scale cabin frame made of G3Si1 steel. Printing was controlled using block programming in Grasshopper software, and during testing several limitations of the manufacturing process were identified, leading to simplification of the component geometry. When printing overhangs at a 45° angle, it was found that the tilt of the robotic head in the print direction needed to be adjusted, which required advanced programming

Figure 4. Modification of area modelling and final TO cab assembly

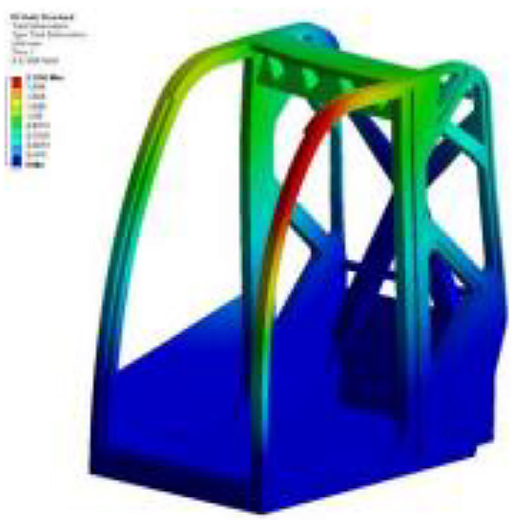


Figure 5. Von Mises stresses for material ER 5356

solutions. When printing long trajectories, overheating and warping due to heat build-up continuously occurred, which was addressed by optimizing cooling and modifying the print trajectories [2]. The block programming in Grasshopper was divided into three main areas (Figure 6).

Stocks in buffers 8, 9 and 10 (Figure 6) is sufficient from the point of view of the use of the assembly workplace. Inventory levels range from 5 to 9 components. A negative phenomenon is a greater accumulation of material in the buffers.

- A – Import STEP model, mesh creation and generation of basic trajectory curves.
- B – Sorting and filtering curves, dividing into points and generating the welding torch orientation at each point.

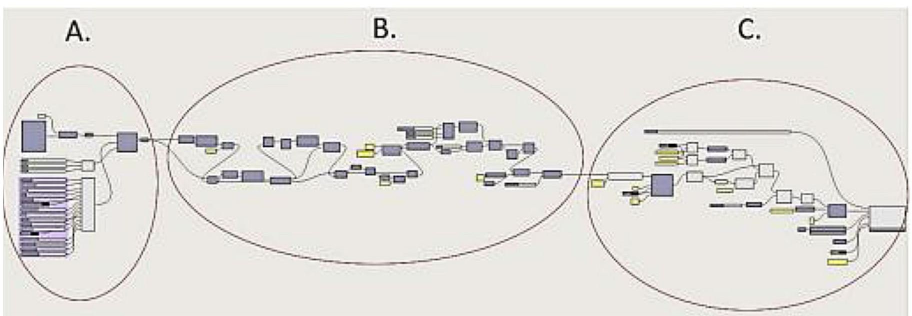


Figure 6. Conceptual scheme of the block diagram

Table 7. Comparison of resulting values after FEM analysis

Material/Results	Von Mises tension local (MPa)	Von Mises tension global (MPa)	Overall deformations (mm)	Mass (kg)
G3Si1	114 MPa	75MPa	2.2	1253
ER 5356	115 MPa	75MPa	5.4	422

Figure 7. Part of the frame module made by WAAM technology

- C – Defining the robot arm movement speed along with implementing commands for the welding process. Generation of SRC code for controlling the robotic arm.

The resulting sub-cab module was fabricated with dimensions of 517 × 360 × 316 mm at a wire feed rate of 5 mm/s and a torch speed of 0.005 m/s in conjunction with a 15-second interlayer interval (Figure 7). Experimental printing was carried out on a simplified model of the frame. Despite the limitations encountered, progress has been made in the additive manufacturing of large-scale components, with the model fully functional and ready for completion [2].

CONCLUSIONS

The MPS cab is considered to be a complex machine building module in terms of operator safety, production and assembly. Based on the knowledge of the current state of the art and the knowledge gained of modular structure and the subsequent successive application of TO and WAAM technologies, it can be concluded that this is an effective approach to the implementation of such types of structures. The decisive requirements remain the required safety aspects, the weight of the cabin and the choice of suitable materials.

The design of the TO cab has confirmed a significant improvement in the stress-strain characteristics compared to the original cab frame. With the help of a prototype model, the optimization of the parameters of large-scale robotic additive manufacturing investigated at the Faculty of Mechanical Engineering of Brno University of Technology was achieved. A pilot application of the production of a module of larger dimensions on this platform applicable to the field of development and production of MPS was created. The achieved results will be further applied in the process of optimization of WAAM technology parameters.

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