Digital Prototyping on the Example of Selected Self-Propelled Mining Machines

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INTRODUCTION

Self-propelled mining machines are basic machines used in many underground mines. They are used to exploit metal ores, precious stones, salt and others. The ever-changing working conditions and growing customer expectations fuel continuous changes. The demand for advanced control systems, including automatics and diagnostics, as well as remote controls has been observed for many years. In recent years, we have also seen the first battery-powered machines. Modern, closed and air-conditioned operator's cabs are becoming increasingly common. Rapid changes and small lot or almost single piece production require the design process to be fast and efficient. The manufactured machines, which are frequently prototypes, are almost immediately intended for work in a mine. Any construction or assembly errors are unacceptable as their occurrence has financial consequences. The high requirements of the current market are met by modern CAx programs, which support design works. Basic programmes in the constructor's everyday work include CAD (Computer Aided Design) and CAE (Computer Aided Engineering) programs.

Typical CAD programmes, such as Catia, NX, Creo, Inventor, support design work, including parametric design. CAD programs often have CAE elements and allow for conducting load analyses and strength analyses (Zhang, 2005), (Wang et al., 2008). CAx programs are powerful tools with huge possibilities. Numerical methods of solutions relate to various issues, not only material strength and kinematic and dynamic simulations, but also to the analysis of loose materials, heat flow, fluid flow or magnetism. It is also worth mentioning the specialized programs assisting the creation of injection systems, castings or forgings. Unfortunately, even basic CAD programs are very often used by designers to a limited extent (Bołoz and Castaneda, 2018).

Modern programs enable designing complex machines which, thanks to digital prototyping, have a minimal number of errors already at the prototype stage. Digital prototyping involves making a virtual machine model and conducting broadly defined simulation tests. Simulations carried out in the virtual world are disproportionately cheaper than those performed on the prototype. In addition, their use allows for eliminating errors that are typical of prototypes. Any simple

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construction errors, such as collisions, are practically eliminated. Thanks to simulations, the construction is characterized by the required strength and rigidity. Simulation tests make it possible to estimate the power demand and load on individual nodes, or to test stability during operation and movement. The long and fruitful cooperation of Mine Master Sp. z o. o. with AGH University of Technology in Cracow, Wrocław University of Science and Technology, and EMAG Institute resulted in the development of many self-propelled drilling and bolting rigs as well as other unique machines. Various programs and tools were used at each stage of their design. The article presents selected examples of applications for specific tasks.

DESIGNING IN 3D ENVIRONMENT

CAD type programs are the basic tool used by designers at various design stages. The variety of these programs and their capabilities allow finding a right solution for every application. CAD programs offer a number of possibilities to facilitate the process of designing. Every user of this type of programme has numerous basic possibilities at their disposal, such as:

- 3D modelling – creation of single 3D parts with various degree complexity and detail,
- 3D assembly – connecting the parts in the form of mechanisms or immobile assemblies, including welded ones,
- libraries – use of standardized and standard parts and assemblies as well as embedded libraries offered by producers,
- analysis of collision – detection of collisions in assemblies, taking into account the full range of motion,
- analysis of parts and assemblies – determination of mass, volume, surface, the position of the centre of gravity, moments of inertia of cross-sections and solids.
- 2D documentation – creation of automatically updated documentation of parts and assemblies related to the 3D object.

Many constructors also make use of additional possibilities or modules which among others take into account the following:

- sheet metal constructions – modelling of structures from bent and/or pressed sheets or transformation of standard parts, where the most important advantage is the possibility of obtaining an extension, which is the basis for cutting out the shape,
- frame constructions – making frames from standardized profiles, fast cutting, strength analyses, substitution of profile cross-sections,
- bundle and wire modules – quick insertion of pipes, wires and wire bundles together with terminals,
- node generators and machine parts – they allow for selecting, calculating and generating a model or enable selection of elements: mechanical gears, shafts, bearings, springs, bolted joints and other.

- renderings and animations – creating professional screenshots, operation and installation animations, as well as installation documentation,
- other modules and tools – parameterization and automation, plastic parts, injection moulds, surface modelling and many others.

On the example of Autodesk Inventor, it is worth paying attention to rarely used, but very powerful tools for design parametrization and automation, which accelerate and facilitate work. Working on models and parametric assemblies is possible thanks to such functions as iFeature, iPart, iAssembly and iMate. However, one of the functions that is undoubtedly the most extensive in the context of parametric design is iLogic. The principle of operation of iLogic is based on the creation of rules that enable defining logical conditions, equations and automatic routine activities for a part, assembly or a technical documentation drawing (Bołoz and Castaneda, 2018).The rules are written in Visual Basic .NET. By creating a simple script and using appropriate operators, one can influence the parameters and characteristics of a given object by means of an intuitive form. This function enables standardization and automation of design by creating models, assemblies and documentation in a parametric way as well as reusing previously completed works, although they were not created for the needs of iLogic. Another tool to create a family of structures is iCopy, which after defining the pattern, boundary conditions in the form of paths and scales, automatically generates new parts and assemblies.

CONCEPTUAL MODELS OF MACHINES

As a result of cooperation of the aforesaid units and the implementation of a number of projects, among others the following were developed: Roof Master 2.3 self-propelled bolting rig for high beds with a grid feeder, Roof Master 1.8 AWKM, Face Master 1.7L or Roof Master 1.7K. The design of a machine requires establishing basic assumptions regarding its intended use, functionality and parameters. In the case of self-propelled mining machines, such as drilling or bolting rigs, the assumptions are inseparably linked with their working conditions, especially with the size of the excavations in which these machines are to work and the size of the corridors in which the machines move in the underground mine. The size of the excavation determines the working area of the machine, whereas the size of the corridors determines the dimensions, the most important of which is height. Another key parameter is the turning radius at a certain width of the excavation. In the case of drilling and bolting rigs, proven and reliable construction solutions are applied. However, development of completely new solutions of machines poses a serious challenge. The unique solutions, such as a mobile temporary roof support vehicle (Fig. 1) or a roof protecting machine equipped with a grid feeder (Fig. 2, Fig. 3) required first of all developing a number of concepts. However, the development of completely new machine solutions poses a serious challenge. Unique solutions, such as a mobile temporary roof support vehicle (Fig. 1) or a roof protecting machine equipped with a grid feeder (Fig. 2, Fig. 3) required a number of concepts.

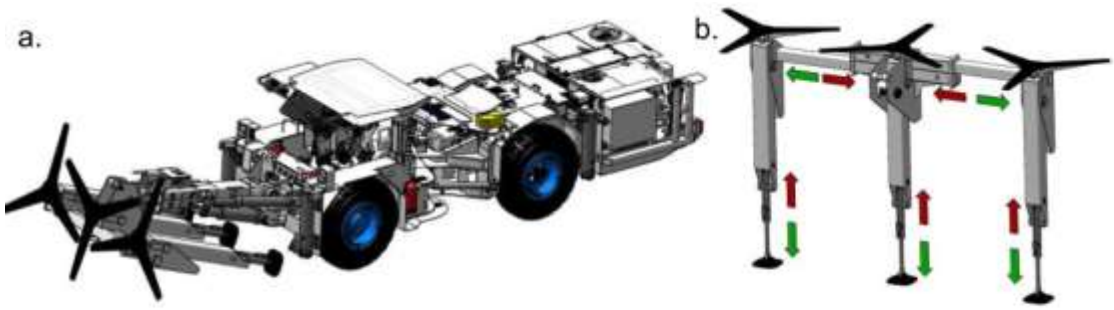

Fig. 1 Mobile temporary roof support vehicle: a. 3D model of the machine, b. 3D analysis of the mobile possibilities of the machine cutterhead

The example of a mobile temporary roof support vehicle as a completely new and unique machine can be used to illustrate the problem of creating a concept. The selection of the best solution required the development of several different ideas in the form of 3D models. The possibilities offered by every CAD programme allow for developing simplified models of the most important subassemblies. The use of a bolt support in places where there is a risk of falling of smaller rock fragments poses a threat to both machines and, above all, underground mine employees. That is the reason why in certain conditions and places, securing the excavation roofs with a surface support is extremely important from the point of view of safety. Therefore, apart from the standard roof bolting, additional protection in the form of surface support is also applied, for example, a mesh lagging fixed with installed bolts. The concepts of a mobile temporary roof support vehicle assumed the use of a mesh hopper and one or more anchoring towers. The concepts were supposed to meet a number of requirements and take into account both the diverse working conditions and the shape of excavations. First of all, it was assumed that the vehicle having a modular construction and a proven previously used chassis would be applied so as to minimize the prototype errors and focus on the machine working assembly. An important aspect was the use of the highest degree of mechanization in order to enable full or partial automation of the process. As a result, six concepts were created; the selected ones are shown in Fig. 2 and Fig. 3a (Bołoz and Mendyka, 2018). Next, one of the concepts was chosen, which allowed for continuing the design of a specific solution (Fig. 3b) (Bołoz and Ostapów, 2017).

Fig. 2 Initial 3D concepts of a mobile temporary roof support vehicle
Source: (Bołoz and Mendyka, 2018)

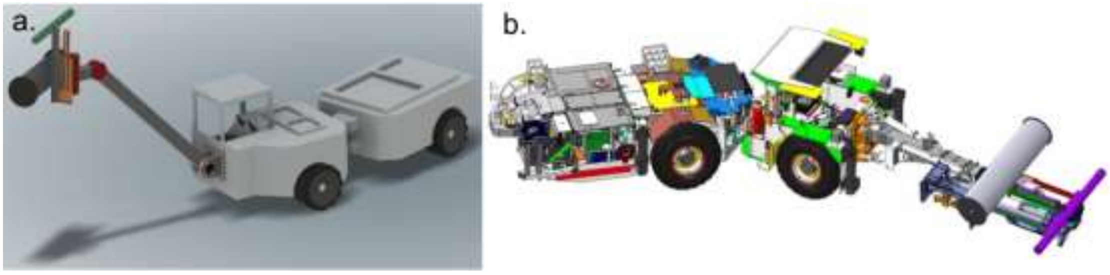

Fig. 3 Machine with a grid feeder
a. selected concept, b. initial 3D design of the machine

Source: (Bołoz and Ostapów, 2017)

STATIC, KINEMATIC AND DYNAMIC ANALYSES

Calculations in the field of statics, kinematics and dynamics are an inseparable element of design. The process of design involves determining loads acting on individual parts and construction nodes. Depending on the needs, static or dynamic calculations are performed. The working range, ranges, and speeds of individual elements are also determined. Traditional calculations are complicated and time-consuming, hence various types of simulations are carried out. Simulation models are applied when it is impossible or very difficult to obtain an analytical solution to the examined problem.

Calculations of the location of the centre of gravity, let alone the moments of inertia, are extremely complex tasks for currently designed machines (Fig. 4).

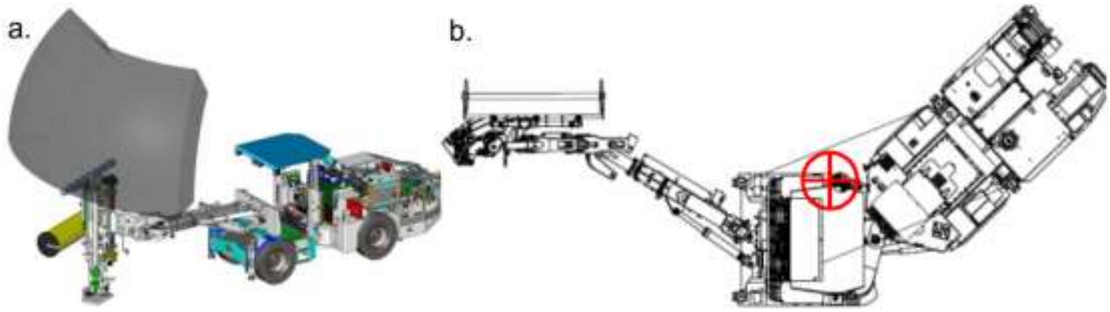

Fig. 4 Calculations and analyses in the virtual environment Roof Master 2.3:
a. determining the outline of work in 3D, b. analysis of the location of the centre of gravity in different configurations

However, an experienced constructor having a properly made model of a machine in the CAD program needs just a few clicks to do the task. An operator can be simulated in the cab or at another workplace, taking into account the ergonomics of the workplace or the field of vision.

Due to the particularly difficult conditions of operation of self-propelled mining machines, it is necessary to carry out model tests, including simulation verification of kinematics and dynamics of the working system of the vehicle and machine chassis. An important point of research is verification of the chassis structure of the vehicle going through an obstacle (Fig. 5). Such simulations are performed using the multi-body systems method. As a result, a full dynamic description of the model is obtained – movement (i.e. also speed and acceleration), forces and moments as a function of time.

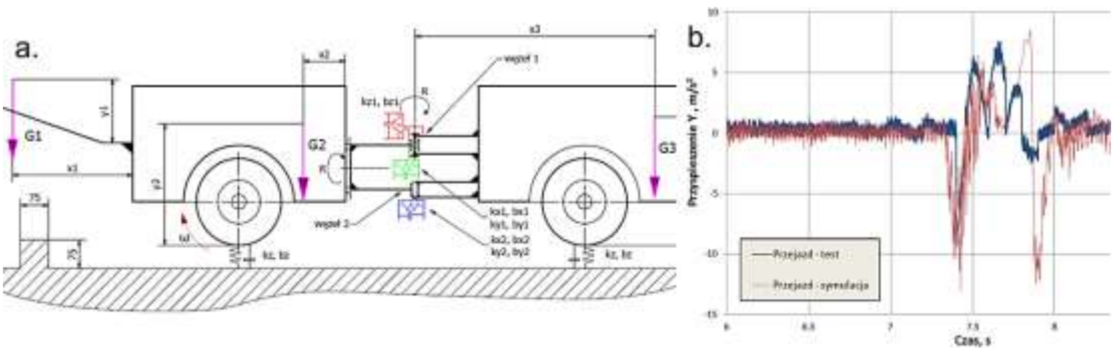

Fig. 5 Dynamic analyses of Face Master 1.7L:
a. physical model of the vehicle, b. comparison of the results of simulations and measurements With Acceleration Sensors

Source: (Gospodarczyk et al., 2016)

FEM STRENGTH ANALYSES

Similarly to load calculations, strength calculations are a necessary stage of the design process (Fig. 6). Traditional calculations, due to the high degree of complexity of the construction, are limited to the approximate determination of the most important sections. The finite element method, which has been commonly applied for many years, is perfectly suited to both conceptual work and verification of final designs. In the case of self-propelled mining machines, all structural elements are analysed. Depending on the needs, the calculations make use of models assuming geometric and material nonlinearity. Special requirements apply to operator cabs, which must meet stringent standards, thanks to which the operator is protected against falling objects (PN-EN ISO 3449: 2009, so-called FOPS) and when the machine has rolled over (PN-EN ISO 3471: 2009 so-called ROPS).

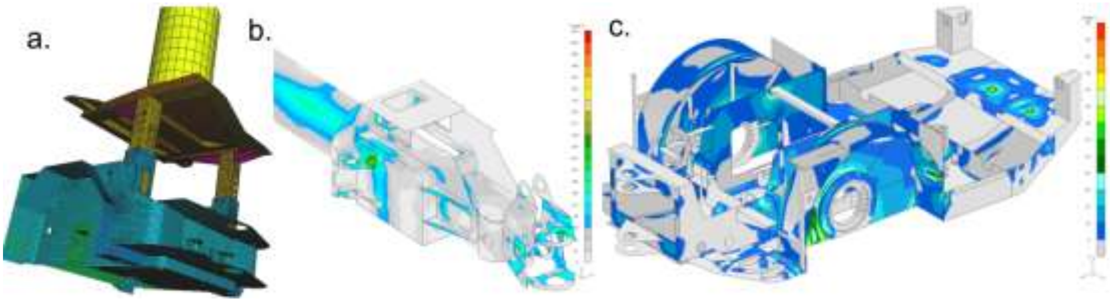

Fig. 6 Strength calculations:
a. operator's cab, b. B40HD boom, c. ramp

Source: (Działak et al., 2018, Derlukiewicz and Karliński, 2012)

Striving to reduce weight while maintaining the strength and rigidity of the structure in such difficult conditions as underground mines requires experience and engineering sense. A very interesting tool offered by some programs is the possibility of optimizing mass and shape. In the case of Autodesk Inventor, this is the so-called shape generator, which can be a useful tool to reduce weight. After configuration, the shape generator proposes the conceptual model of the piece, taking into account ties and loads, as well as the expected weight reduction expressed in kilograms or in percentage terms. The generator also enables excluding specific areas from optimization, enforcing symmetry and the size of the material 'islands' left.

In the presented case (Fig. 7), the straight bracket subjected to analysis has acquired a completely new shape and mass while meeting the requirements regarding permissible stresses and displacements. The generator's concepts are merely a suggestion. Based on one of the proposals, a quite modern look of the bracket was obtained. However, its weight decreased by 37% compared to the full bracket. As you can see from the analyses presented, the internal stiffening can still be optimized.

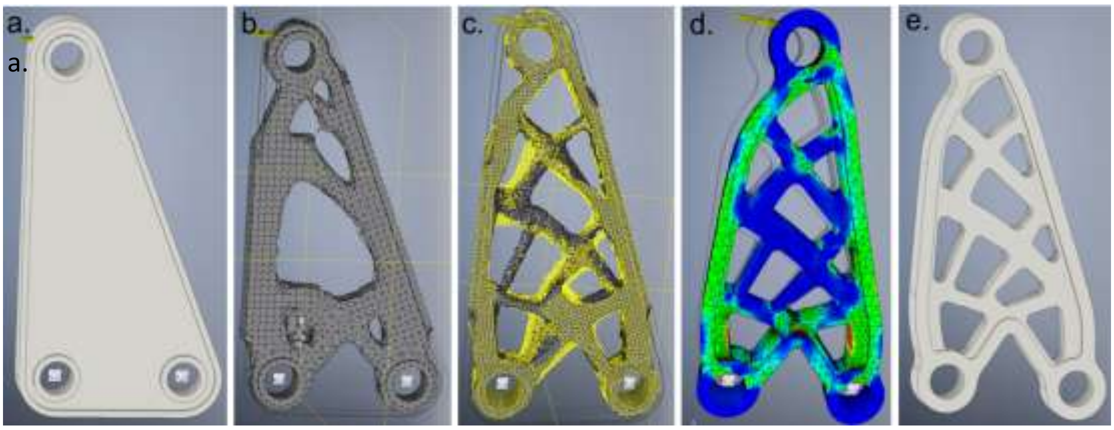

Fig. 7 Example of using the shape generator: a. original bracket, b. and c. two conceptual shapes for different optimization values, d. and e. final version of the bracket

Another useful tool in addition to static analyses is the finite element method, which allows for quick determination of the form and frequency of free vibrations.

MODEL TESTS OF DRIVE SYSTEMS

The selection of size and parameters of drive units requires determining the power demand of the machine. Mining machines work in harsh conditions, where many factors affect the need for power, and analytical calculations entail excessive simplification and are not sufficiently accurate. Therefore, in order to determine the power as precisely as possible, it is necessary to conduct detailed simulation tests. The software applied for system simulations of complex mechanical devices is the SimulationX package, produced by ESI ITI GmbH. This package is based on a set of libraries which significantly facilitate the modelling of specific devices. Propulsion systems modelling, especially when battery drives are used, poses an additional challenge. Hence, simulation tests, especially comparative tests for internal combustion engines are a source of knowledge for further design work. Figure 8 shows a virtual drive model and simulation results for the Face Master 1.7L narrow drilling vehicle (Anchor and Stopka, 2019).

Simulation X allows for simulating very complex mechatronic structures, which can contain mechanical, electrical, hydraulic or pneumatic elements.

Simulations of drive systems are a source of knowledge about the expected behaviour of the machine, the elasticity of the propulsion system or the achieved performance.

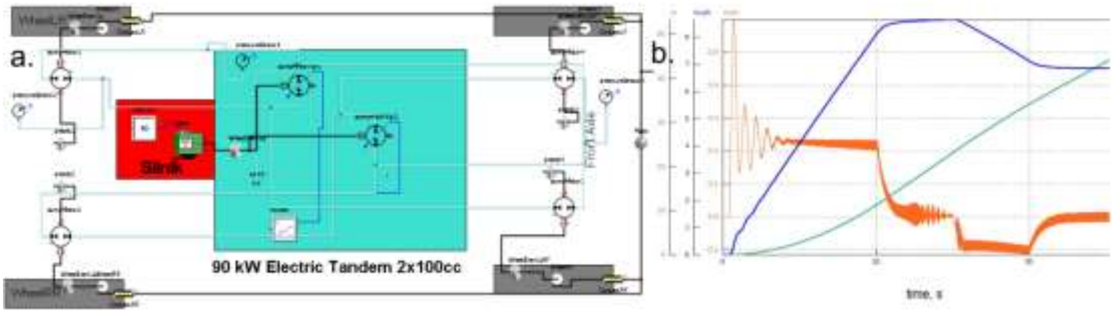

Fig. 8 Dynamic simulations of Face Master 1.7L:
a. electric drive system in Simulation X, b. results of simulation tests
Source: (Kotwica and Stopka, 2019, Szurlej et al., 2019)

VERIFICATION AND VALIDATION OF THE MODELS AND TESTS

In the literature, different views can be found on the concepts of verification and validation of models and methods. A certain group of researchers consider these terms as synonyms, but according to most of them, verification is a necessary but insufficient phase in the validation process (Karkula, 2014). In the analysed case, verification should answer the question whether the computer model corresponds to the physical one, whereas validation answers the question whether the computer model is consistent with reality in the aspect in which it was created. The use of models and simulation tests requires verification and validation on the prototype or real model of the machine.

The ergonomics of the operator's workplace can be validated in the prototype of the machine, which allows checking all aspects, including the field of view. One can also make a real model, for example from wood-based panels, and equip it with the required elements (Fig. 9a).

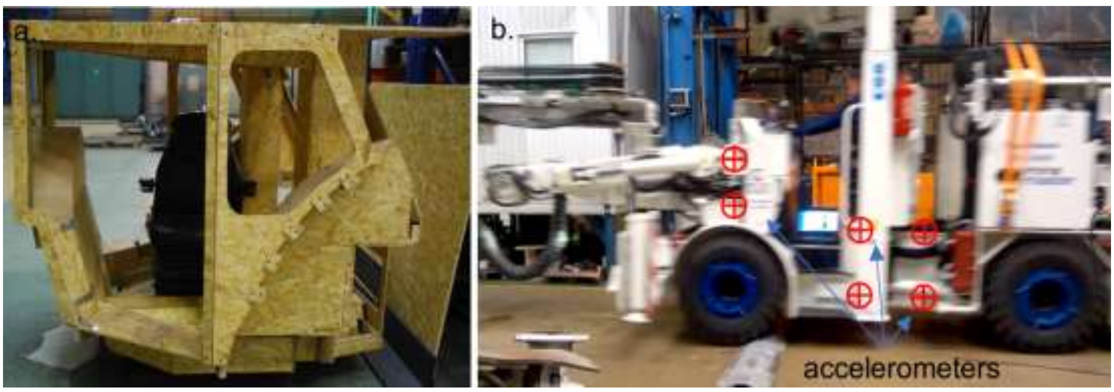

Fig. 9 Validation of models: a. real model of an operator’s cab b. travel over an obstacle

The actual model of the cabin allows for validating the model and making changes before the prototype of the machine is created, which significantly reduces the costs. For the analysis of the location of the centre of gravity, or actually, the analysis of the machine stability, one can use a simple measurement of the pressure force of each wheel or support on the surface. Appropriate overrun scales are used for measurements. The use of ramps and various values of the machine's steering angle enables mapping the working conditions of the machines. The method allows for quick verification of all kinds of theoretical models and simulation tests. It should be noted that such basic validation makes it possible to take into account dynamic forces (road surface, curves, braking, acceleration) only to a limited extent by applying them in the form of static forces.

Dynamic simulations, such as analyses of machine travel over an obstacle or on road bumps can be mapped by going on such a ride in reality. During bench tests, in addition to the recording that enables the reconstruction of movement e.g. of the chassis or machine booms, signals from triaxial acceleration sensors are also recorded (Fig. 5, Fig. 9b).

Fig. 10 Measurements of the pressure force of Roof Master 1.7 K wheels and supports on the ground – model validation

In the case of self-propelled mining machines, their relevant parameters are checked and verified at appropriate workstations. On-site tests of both the movement of these machines and their operational functions are carried out. Then, almost all kinematic, energy, performance and other parameters can be checked. Fig. 11 presents photos from selected tests. In Fig. 11a, Roof Master 1.8 AWKM anchoring vehicle makes holes and installs bolts in the sample prepared at the workstation.

In Figure 11b, both the working area and the mobility of Roof Master 2.3 roof support vehicle are tested.

Strength simulations on a real object can be validated by using e.g. strain gauges, which should be stuck in the right places. Next, tests are carried out for the prepared machine and the measuring system in simulated conditions. The tests are aimed at generating the appropriate load acting on the machine structure, and then, comparing the measured deformations with the results of FEM analysis.

Fig. 11 Verification of the functional properties and parameters of machines at workstations: a. Roof Master 1.8 AWKM anchoring, b. installation of Roof Master 2.3 grid in an artificial tunnel

CONCLUSION

New solutions of self-propelled mining machines, which may be the next step in the development of a model or a completely new solution, demanding users, high competition and extremely difficult working conditions of these machines provide perfect circumstances to apply and develop modern design-aiding tools. Digital prototyping allows for testing a virtual model, which on a real object would be very time-consuming, expensive and, sometimes, impossible. Computer simulations enable checking new, unconventional solutions, without incurring the cost of a failed prototype.

The manufactured machines, which are the final effect of digital prototyping, are subjected to various tests and investigations. Standard test runs are carried out on the finished machine. Tests on a real object also allow for validating computer models and gaining experience needed to create reliable and precise models and to simulate completely new objects, which sometimes cannot be tested in reality. As part of the implemented projects, various tests were conducted at workstations mapping certain aspects of real conditions, so that individual functions and parameters could be checked and verified in bench tests on the surface.

Digital prototyping develops creativity, but it is also a tool for verifying and rejecting unfeasible ideas. It is not a rare occurrence that projects which seem impossible to implement at a given moment wait for the right technology and determine the direction of development.

ACKNOWLEDGEMENTS

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Abstract: The changing requirements and needs of users as well as the demand for new mining machinery solutions pose a challenge for designers. Time spent on the design phase of a new machine is often reduced to a minimum. Small lot production and sometimes single piece production entails the necessity to frequently design and manufacture commercial copies, which are also prototypes. The only effective solution is to apply available CAD and CAE programs enabling digital prototyping. Their use allows for making a complete machine in a virtual environment. The virtual model is subjected to tests aimed at eliminating collisions, optimizing the construction as well as obtaining a lot of information concerning the load, kinematics, dynamics, stability and power demand. Digital prototyping enables avoiding the majority of errors whose detection and elimination in a real object is time-consuming and expensive. The article presents examples of the application of broadly understood computer aided designing of self-propelled mining machines, produced by Mine Master. The effects of applying the modelling, FEM strength analysis, static and dynamic simulations, modelling of drive systems have been demonstrated. The methods used to validate computer models and verify the parameters of finished machines have also been discussed.

Keywords: self-propelled mining machines, digital prototyping, CAD and CAE, computer simulations, dynamic situations