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Chapter 2

Computer-Aided Manufacturing of Working Units for High-Performance Mining Machines

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Additional information is available at the end of the chapter

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Abstract

Mining machines (roadheaders, long-wall shearers, continuous miners, milling machines and others) are the key mechanised systems used in mining works—in underground and surface mining and in civil engineering (tunnelling). Rock cutting is carried out with working units fitted with cutting tools (most frequently picks mounted in pickboxes welded to side surfaces). It is important to appropriately arrange and position such tools in order to adapt them to the operating conditions (rock workability). This will guarantee very high efficiency of the cutting process. For this reason, such parts are designed with dedicated software. Designing is based on the simulation of the cutting process according to which the solution established is accepted. A prerequisite ensuring that the working process is performed highly efficiently by mining machines is to guarantee the high manufacturing quality of working units, especially with regard to the placement of cutting tools on the working unit side surface according to technical documentation. Robotised technologies are helpful here. Due to a large variety of solutions, utility programmes for robotised production sockets are developed with software for designing and simulating the operation of robotised stations.

Keywords: mining cutting machines, working unit, computer-aided design, computer-aided manufacturing, quality control, reverse engineering

1. Introduction

Mining machines create a broad group of heavy-working machines designed for mining natural materials such as soils and rocks with different petrography, and composite materials —concrete or bituminous masses. Although the mining industry is the key area of application for such machines, they are also employed extensively in civil engineering—for the construction of transportation tunnels using trenchless methods (road, railway, metro tunnels), sewage collectors, underground tunnels and networks (microtunnelling), or underground engineering structures (water channels in hydropower plants, garages, etc.). Cutting machines with their construction and working principle similar as in the mining sector are utilised in road engineering—for cutting (milling) concrete and asphalt surfaces during construction and for road surface renovation.

Mining cutting machines (roadheaders/shearers) are multifunctional machines enabling the full mechanisation of the basic activities in mechanised technologies for drilling dog headings and tunnels and excavation of minerals in underground and surface mining. Among the many other activities, rock cutting or cutting other materials such as concrete, asphalt, and so on is the most important activity performed by such machines. A mechanical cutting process may be carried out in various ways depending on the properties of the medium being handled—by cutting, using static pressure or a stroke. Mining by way of cutting is the most popular method of those mentioned. In such case, cutting machines are equipped with working units most often in the form of rotating bodies, on which pickboxes are positioned. Picks acting as cutting tools are attached on the pickboxes. A cutting process of the medium being cut is carried out when the picks are travelling along a trajectory which can be either a straight line or a curved flat or spatial line.

Machines that are mined by way of cutting are used in underground mining for hard coal, salt and other materials. They are used in opening and preparation works (for drilling of dog headings—roadheaders—**Figure 1**) and for excavation of minerals (including, among others, shearers and coal ploughs). They are used in surface mining for extracting deposits of certain

Figure 1. Boom-type FR 160 roadheader designed for drilling dog headings in underground mines and tunnels in civil engineering [6].

rock resources, coal, salt, lime, bauxite, iron ore, phosphorus, bituminous shale and kimberlite. They are even used in subaqueous mining—for extracting the deposits of mineral resources from the bottom of inland water reservoirs and sea areas and oceans (e.g. polymetallic sulphides of copper and gold) [1].

Mining practice and the results of theoretical and experimental studies conducted for decades in many research institutions acting in the field of mechanical rock cutting show that the system of picks (the number and method of arranging and setting the pickboxes spatially on the side surface of the working unit of the mining machine) has a substantial effect on the performance and efficiency of the cutting process carried out. It is essential from the user's viewpoint because it translates into drilling progress (in case of drilling dog headings and tunnels), the output (for operating works), energy consumption and the wear of picks per worked material unit, which is conditioning the economic profitability of conducting such type of mining works. It is therefore not possible to develop a universal system of picks for the working units of cutting machines ensuring the efficient cutting of rock and other materials with varied mechanical properties.

The aspect of computer aid should be approached—in relation to the elements considered here—in an area encompassing: design – production – quality control. It covers a number of activities based on the use of a graphical environment and simulation models (virtual reality). The computer tools used for this purpose represent a so-called virtual-manufacturing system [2–4]. Such a system, already at the stage of process preparation, delivers information about the product itself (at the stage of product design and optimisation), as well as about the progress of the manufacturing process. A virtual-manufacturing system is centred on product design (aided design), production (optimisation of production process implementation) and control (utility programmes are created for real production lines) [4, 5].

A manufacturing process of the working units of mining cutting machines consists of a number of successive stages. The sequence of such events can be considered in terms of the project lifecycle. In a classical approach, the cycle consists of the four basic phases: initiation, planning, execution and completion (implementation). Those phases encompass a whole spectrum of activities associated with organisation and management, economic analysis and analysis of technical activities, which are aimed at achieving the set objective according to the adopted time, cost and efficiency criteria [7–9]. Technical requirements are defined by the user at the stage of project initiating by focussing on the technical aspect of the process considered in this paper (**Figure 2**). In terms of the implementation of cutting process, the basic information for a designer of the considered working units is to identify technical conditions for mining machine operation, for which working units are to be designed and produced, including mechanical properties of the worked rocks. As pick systems on working units of mining machines lack universality, they are designed using state-of-the-art computer techniques for specific applicational conditions. Apart from standard computer-aided design (CAD) software for preparing the components of technical documentation, dedicated programmes are utilised enabling the optimisation of pick systems and their verification based on a computer-simulated working process [10–14]. Computer aid at the stage of designing a pick system for the complex operating conditions of a cutting machine is meant to deliver information to the designer allowing to assess the suitability of the created solution being a basis for its acceptance or rejection (modification). The number and method of arranging and setting the picks spatially on the side surface of the working unit of the cutting machine is selected (optimised) according to a number of criteria (objective functions) ensuring the achievability of the expected functional and operating features, while satisfying the condition of a given solution's technical feasibility.

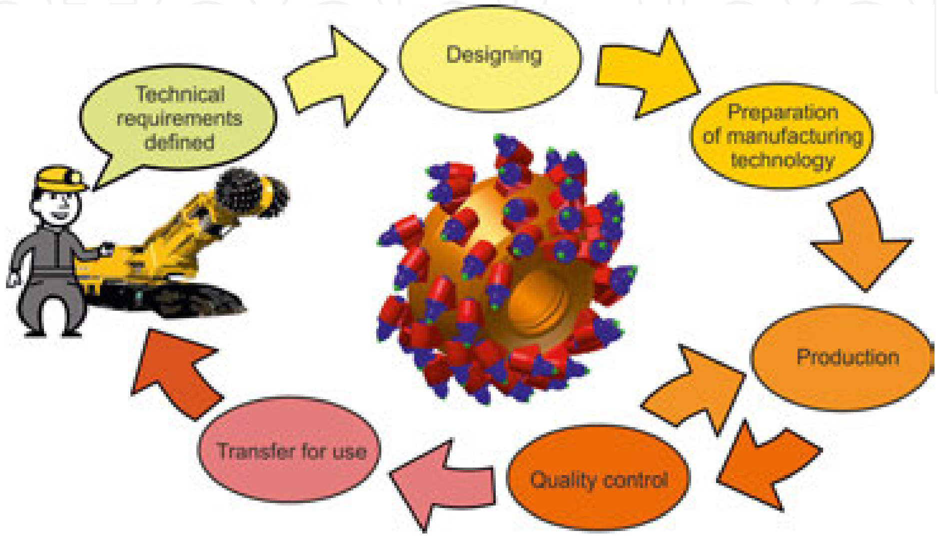

Figure 2. Manufacturing process of the working units of mining cutting machines—project lifecycle.

Technical documentation becomes a starting point in developing a manufacturing technology of the working units of mining machines. The efficient work of the working units considered in the paper is not possible without ensuring their high manufacturing quality and repeatability. This applies especially to the accurate representation of the position of pickboxes in compliance with the established technical documentation. A solution guaranteeing the fulfilment of such requirements is the use of robotised technologies, especially at the stage of the preliminary installation (attaching) of pickboxes to a working unit's side surface. As particular pickboxes are set differently and considering their, often, large number, a robotised station-programming process should be aided with computer tools intended for offline programming. When such operations are robotised, utility programmes are generated at the stage of technology development, controlling the work of the automated production sockets.

Quality control is an inherent part of each manufacturing process—even this, utilising robotised techniques. Quality control for working units of cutting machines consists of, in particular, establishing whether the actual location of pickboxes is compliant with the technical documentation. The stereometry of working units in mining machines should be measured after the completion of two stages, during which pickboxes are mounted—after the completion of pickbox placement, and after final welding. As large-size welds have to be made, which guarantee the high strength of welds between pickboxes with the working unit side surface, there is a risk that post-welding deformation will occur. Such deformations may be a reason for the displacement of pickboxes, as a result of which deviations may occur in the actual values of stereometric parameters describing the spatial arrangement and position of individual pickboxes in relation to the values defined in the design. Product compliance confirmation is fundamental for transferring a product to the user for utilisation. If inadmissible dimensional deviations are identified, a working unit is again transferred to the production department to make the necessary modifications.

Computer-aided design of working units of mining cutting machines is based on the use of various software and computer modules, which form an integrated system CAD/CAM/CAQ (computer-aided design/computer-aided manufacturing/computer-aided quality). These modules are grouped according to the tasks they have to fulfil in successive stages of the process (**Figure 3**). The (uni- and bidirectional) exchange of information between the individual modules of the software enables the efficient creation of the components of technical documentation (at the stage of design), the development of technology (at the stage of manufacturing preparation) and the control of the progress of the manufacturing process of cutting machines working units having optimally designed parameters. An example of such system is presented in the following chapter.

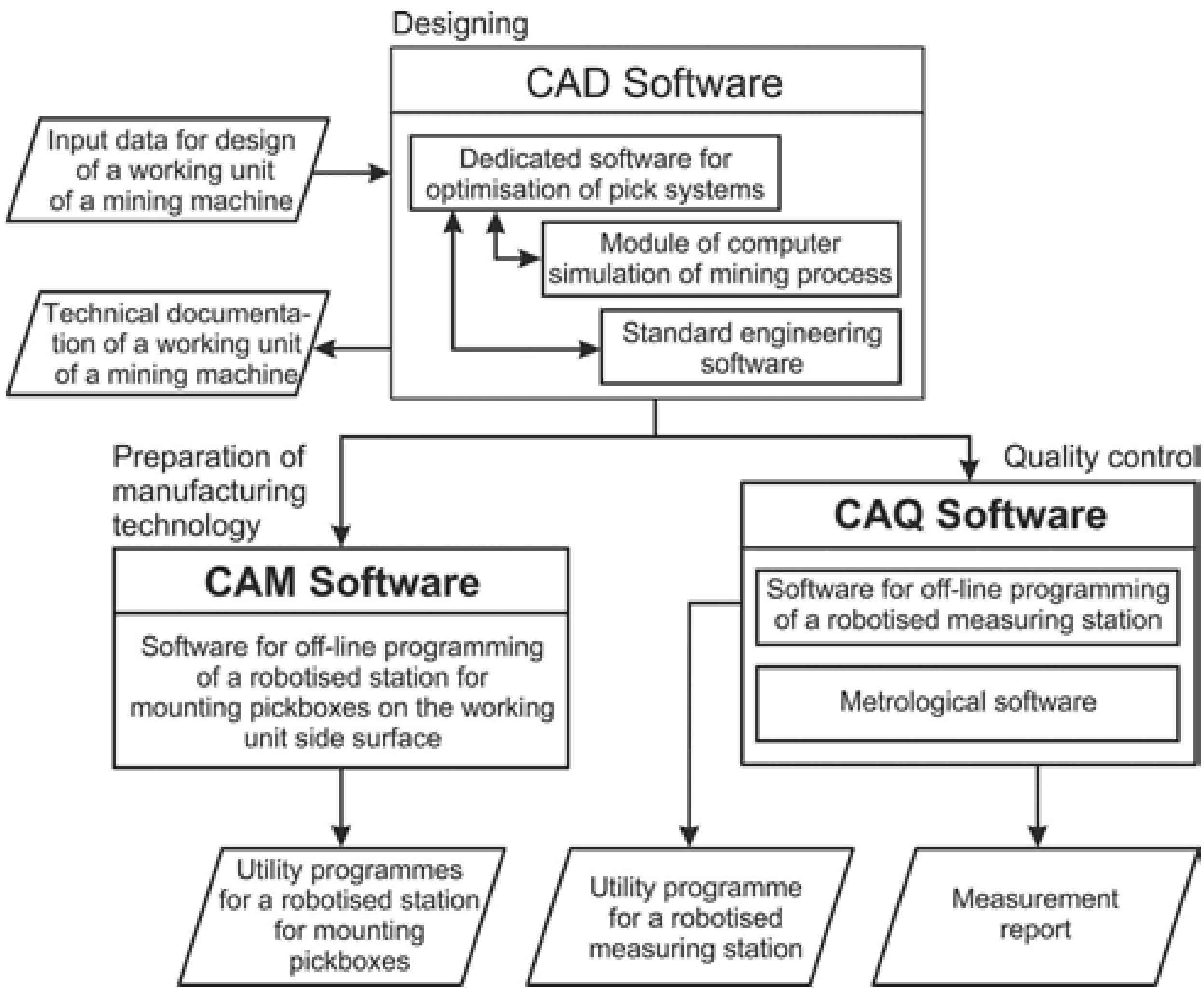

Figure 3. The integrated system of the computer-aided design of mining machines working units.

2. Computer-aided design of the working units of mining machines

The underlying functional requirement of the software intended for the computer-aided design of pick systems in working units of cutting machines is the possibility of generating rapidly alternative solutions creating a field of possible solutions for an optimisation task. The solution can be selected manually or with automatic optimisation methods and tools. A computer-simulated cutting process is the basis for seeking an optimum solution in both cases. It is executed using experimentally verified mathematical models.

The theoretical and experimental investigations of roadheaders and shearers were fundamental for determining evaluation criteria (objective function) for the suitability of solutions of mining machines working units in complex mining and geological conditions. These include [15, 16]:

- the minimum criterion of the average cutting picks load;
- the minimum criterion of dynamic load in the cutting system;
- the anti-resonance criterion;
- the criterion of maximum cutting efficiency and
- the minimum criterion of cutting energy consumption.

The computer-aided design of mining machines working units mostly consists of specifying the advantageous (optimum) picks' arrangement on their side surface ensuring the achievement of a feasible technical objective [16]:

- high rock cutting efficiency;
- reduced energy consumption of cutting and wear of picks;
- reduced dynamic loads in the cutting heads drive;
- limitation of excessive output crushing in the cutting process and
- reduced risks related to mining machine operation, such as dusting, sparking, and so on.

The term of a system of picks is understood as the number and method of spatial arrangement and positioning of a working unit at the side surface.

The mining machine (type, size, power, etc.) is selected in the first place when designing a mechanisation system for the performance of mining works during which mechanical rock cutting is carried out for the defined parameter values characterising the mining and geological conditions—**Figure 4**. The following working units are designed for the selected mining machine. This usually consists of generating a pool of solutions for the systems of picks with varied configuration. The particular variants are then evaluated based on the adopted criteria (objective functions). Solutions were compared based on the evaluation with scores and weight. A general evaluation of a given solution is in this case a weighted average of partial scores corresponding to particular criteria. The solution with the highest score is considered to be adopted for implementation. Further design works are carried out for such a design, the outcome of which is the established detailed documentation.

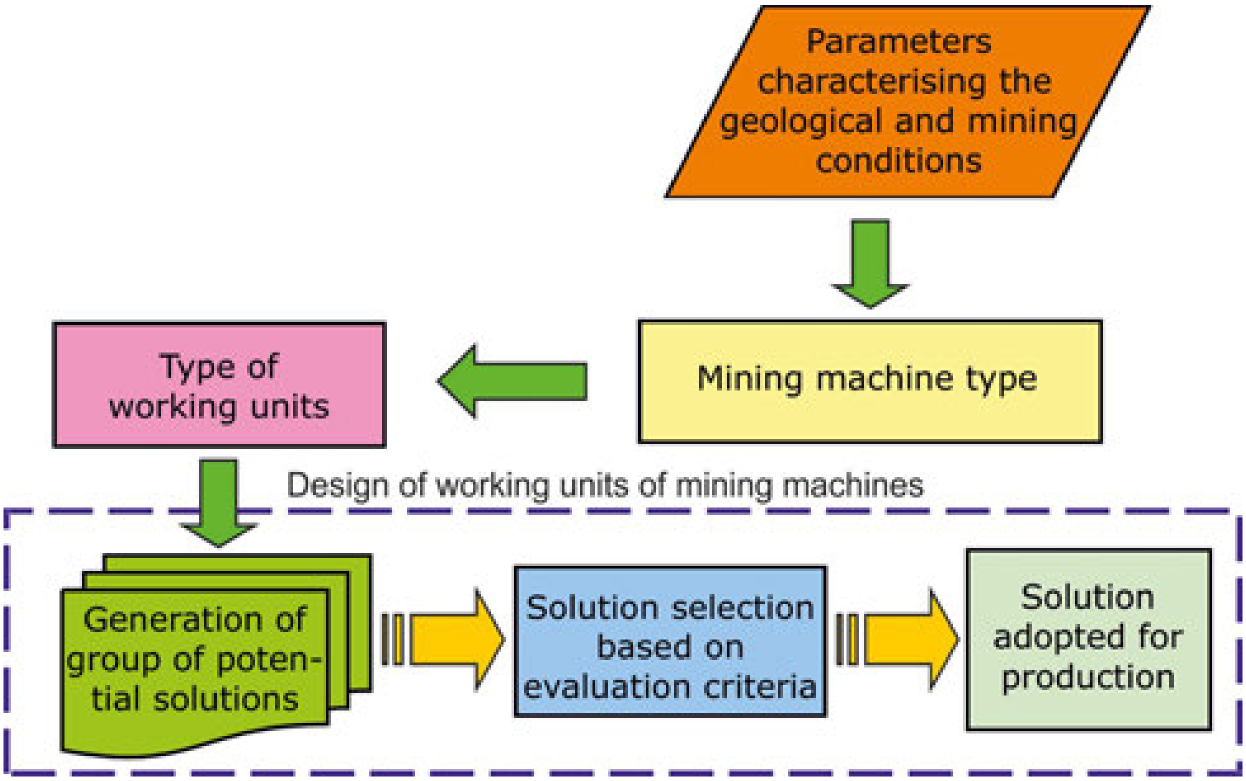

Figure 4. Designing of mechanisation system—stage of selecting a mining machine for the set operating conditions and designing of working units for the machine.

The best configuration of picks on the side surface of the mining machine working unit for the specific operating conditions is searched with a set of solutions which are technically feasible, differing in the number and method of picks arrangement and positioning. For such a procedure, different pick systems have to be generated rapidly to be evaluated technically. This is possible by using dedicated computer software for the aided designed process of such type of elements. Such a computer tool is exemplified by *KREON* software developed by the Institute of Mining Mechanisation, Faculty of Mining and Geology, Silesian University of Technology in Gliwice, Poland, for the computer-aided design of boom-type roadheader cutting heads. The software is employed by internationally recognised Polish manufacturers of mining machinery (Famur S.A. and Kopex Machinery S.A.) for computer-aided design, selection and approval of boom-type roadheader cutting heads. The software provides multiple functionalities to the designer, in particular [14]:

- a system of picks is generated manually or automatically on a cutting head;
- the generated solution is exported to CAD software;
- the cutting process is simulated and the so-produced results are visualised;

- scripts are generated automatically in Python programming language for the purpose of offline programming of a robotised station for mounting pickboxes on the cutting head side surface.

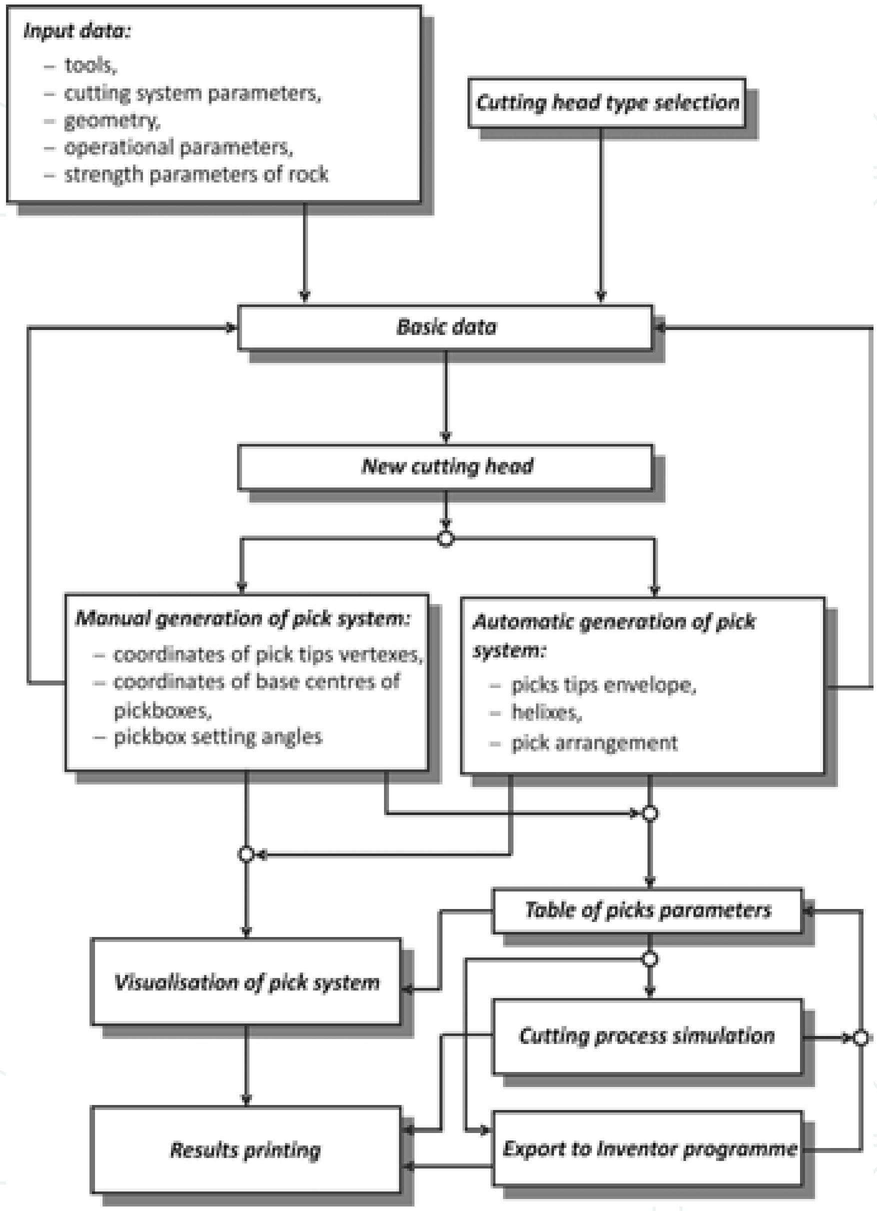

Figure 5. Algorithms for procedure of computer-aided design of cutting heads of boom-type roadheader in *KREON* software.

Cutting heads designing in the *KREON* environment begins by entering input data identifying the mining machine for which working units are designed (cutting heads here) and cutting process implementation conditions (**Figure 5**). The type of the designed cutting head is being determined at this stage (transverse/longitudinal) and information is entered about its dimensions and number of picks it is to be equipped with (basic data). A system of picks is generated after entering all the necessary data. This can be done manually (which is useful especially for analysing the operation of existing heads) or automatically. In the second of the listed methods, the shape of the picks tips envelopes is designed, the way of arranging picks on helixes is chosen (the number of helixes, twisting angle, etc.) and the method of setting picks in the space is defined along with the corresponding pickboxes. The shape of the picks tips envelopes may be modelled here either manually, automatically or drawn using the available drawing tools (**Figure 6**). The output-generated pick system is visualised graphically and the values of parameters describing it are listed in a table (**Figure 7**). A pick system, further in the design process, after the solution established has been accepted, can be exported to Autodesk Inventor® software to create detailed documentation of the designed cutting head. Corrections to the pick system can be made by analysing the technical feasibility of the given solution by editing the table of parameters for picks.

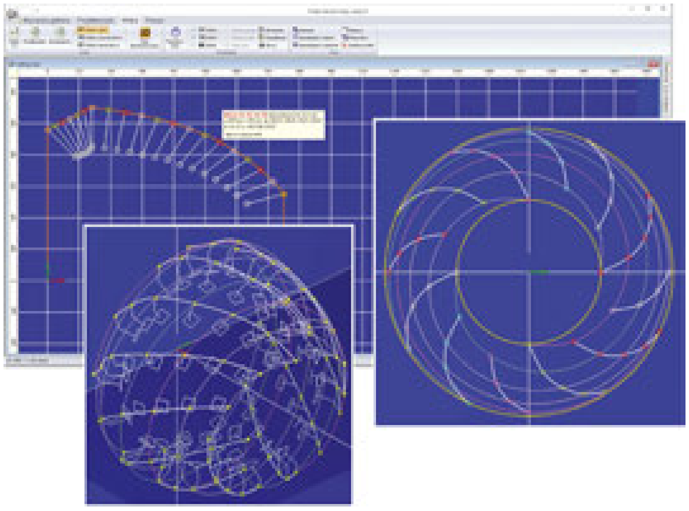

Figure 6. Generation of pick system on the side surface of boom-type roadheader cutting head in *KREON* environment.

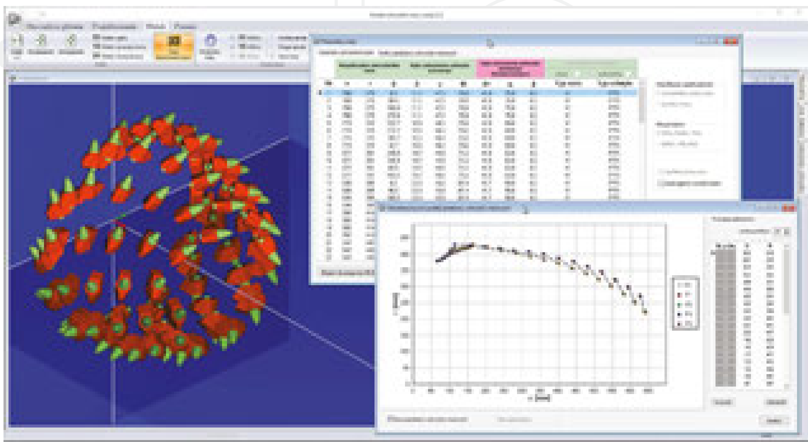

Figure 7. Visualisation of the generated pick system for the newly designed cutting head of boom-type roadheader in *KREON* software.

In order to establish the most advantageous configuration of picks for the set roadheader operating conditions, the designer generates a certain number of solutions differing in the number of picks and their arrangement and the method of positioning on the cutting head side surface with assumed dimensions. A certain shape of the cutting head side surface is usually assumed at the design stage for different systems of picks, with such a shape being adapted to the roadheader cutting system design (the way a cutting head is mounted to an output shaft of the gear in the cutting system, the gearbox shape in cutting heads or the way the water inflow to the spraying system is solved). The shape can be further modified depending on the final setting of pickboxes in the aspect of welding technology optimisation for such holders to the side surface of the cutting head (*KREON* software delivers data on the location of characteristic base points of pickboxes based on which a beneficial shape of the cutting head side surface can be determined—**Figure 7**).

At the decision-making stage, a system of picks is chosen from the created group of potential solutions according to the evaluation criteria adopted. A computer-simulated cutting process is a tool that can provide information allowing to select and accept a specific system of tools (**Figure 8**). The tool enables to establish characteristics for the cutting process of the heading face surface with a cutting head, including, in particular, projections of cuts and a load curve of the cutting heads drive and boom-deflection mechanisms. A dog-heading outline is also generated for the defined cutting system geometry (boom length, turntable dimensions and ranges of boom-deflection angles in the plane parallel and perpendicular to the floor), which can be performed from one roadheader setting with the designed cutting heads. With the dimensions and shape of the outline, the size of the heading cross section can be judged to be tunnelled with a specific type of a roadheader equipped with the designed cutting heads. This information, especially the size of the heading cross section, is given in technical specifications of each roadheader designed for drilling dog headings and tunnels.

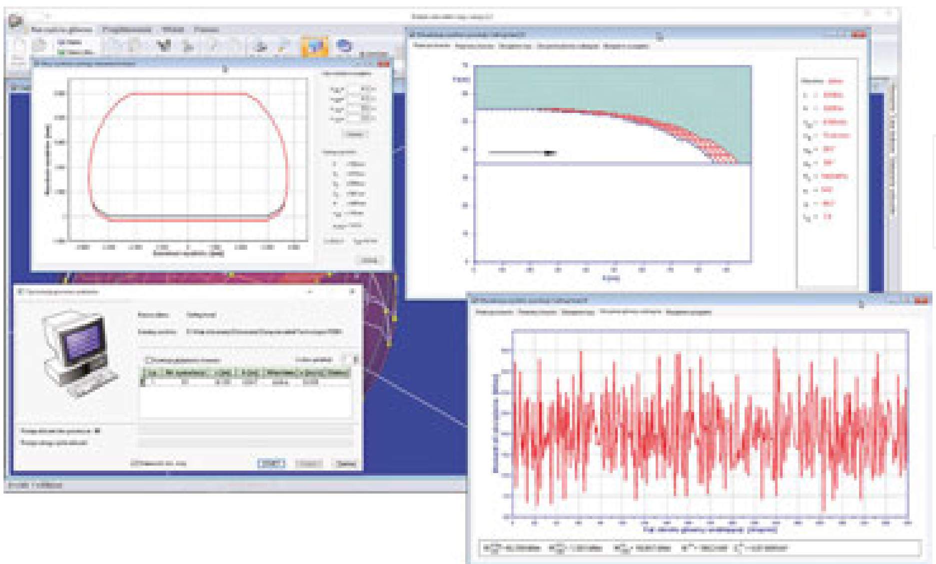

Figure 8. Simulation of cutting process with the designed cutting head in *KREON* environment.

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3. The use of offline programming for the purpose of robotisation of the manufacturing process of the working units of mining machines

In a manufacturing process of the working units of mining machines, the individual pickboxes are basically fitted to their side surface in a way resulting from the technical documentation prepared at the design stage (activities for constructing the side surface itself are omitted here). The process covers basically two stages: pickboxes are arranged on the cutting head side surface and are finally welded to such surface. In the first of the mentioned stages, an appropriately positioned pickbox is initially mounted with a joint weld to the side surface of the mining machine working unit. This is a very time- and work-intensive process. It requires considerable attention and concentration from the operator. The same operations have to be repeated in the pickbox installation process (the number of repetitions results from the number of pickboxes the mining machine working unit is to be equipped with). Each of the pickboxes is set, however, differently, according to the way of arranging and positioning the related picks. For this reason, the robotisation of the pickbox installation process is the right direction.

Utility programmes controlling the work of industrial robots executing main assembly operations are prepared at the stage of developing a manufacturing technology of mining machines working units, and in such assembly operations: the individual pickboxes are collected from the magazine, they are transferred to the set position and attached to the side surface of the mining machine working unit. Software dedicated to the configuration and simulation of operation of robotised stations supplied by manufacturers of industrial robots is used to generate programmes for controlling the work of robots. Robots are programmed here outside the working environment of robots (offline) based on the data generated in the design-aided software of the working units considered in this work (**Figure 9a**). The so-created utility programme has to be recorded in a form acceptable by the robot's operating system into which it is entered (in the implemented programming language). An important part of offline programming is a possibility of testing the so-created control programmes and to introduce modifications. **Figure 9b** shows an interface of an example of a programme created in RAD Studio environment for testing the operation of a programme controlling the work of the IRp-60 robot on an experimental station at the laboratory of the Institute of Mining Mechanisation of the Silesian University of Technology for testing potential automatisation of the discussed assembly process. Free GLScene graphical libraries created in OpenGL technology were used for visualising the operation of this station [17]. Professional offline software delivered by a manufacturer of industrial robots has to be used for the automated assembly of pickboxes on the side surface of the mining machines working units at an industrial scale. An example of such a solution is *KUKA.Sim Pro* software dedicated to offline programming of KUKA Roboter GmbH robots. The software was used for programming KUKA KR 16-2 and KR 5arc robots installed on a test station created in a laboratory of the Institute of Mining Mechanisation of the Silesian University of Technology. Pickboxes can be installed at this station on the side surface of the roadheader and longwall shearer working units in the actual size (at the geometric scale of 1:1). The KR 16-2 robot is designed for positioning pickboxes on the working unit side surface, and the KR 5arc robot is equipped with a welding machine pipe and simulates the installation of such pickboxes with a positional weld (**Figure 10**). As the range of both robots is limited, the side surface of the mining machine working unit is placed on a rotating positioner table with the vertical axis PEV-1-2500 (by ZAP Robotyka).

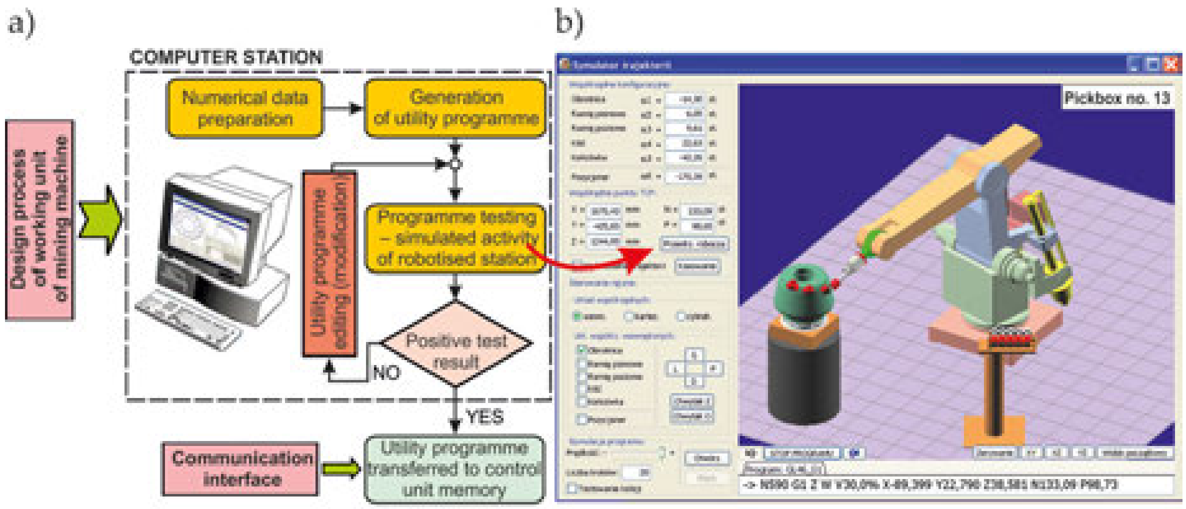

Figure 9. Development of a utility programme for a robotised station for mounting pickboxes to the side surface of the working unit of a mining machine: (a) procedure algorithm [18], (b) simulated work of utility programme [19].

The first phase of generating utility programmes for the positioning and welding robot is performed in the *KREON* environment. It is based on the data set (stereometric parameters) obtained when designing a system of picks of the working unit of a mining machine. A string of instructions controlling the work of robots is generated based on such data in the form of scripts in Python language (an interpreter of this language was implemented in *KUKA.SimPro* software).

For example, a utility programme for the positioning robot, KR 16-2, comprises instructions executing successive operations for a positioning sequence of a single pickbox, namely [14]:

- pickbox is collected,
- a request is sent to a positioner to position the side surface of the working unit of a mining machine in the set position (rotation angle of the positioner disc is an argument of this instruction);
- a given pickbox is brought to a given position on the side surface of the working unit;
- waiting until a positional weld is executed by the KR 5arc-welding robot and
- a gripping device is released and withdrawn to the home position.

Positioning instructions (movement instructions) are the most essential element of a programme controlling the work of a robot distributing pickboxes on the working unit side surface. A set of values is created in *KREON* software for each pickbox for parameters describing the position and spatial orientation of the robot gripping device (being the arguments of robot tool positioning instructions). The parameters' values are determined based on the values of stereometric parameters assigned to individual pickboxes. This is executed according to homogeneous transformations discussed in the work [14]. The scripts, generated as text files, are then read into a script editor implemented in *KUKA.SimPro* environment (**Figure 10**). The Python language interpreter translates the successive utility programme instructions as a code in the form of a string of pictograms symbolising particular instructions. The pictograms are displayed in Teach tab of *KUKA.SimPro* (they are surrounded with an ellipsis in **Figure 10**).

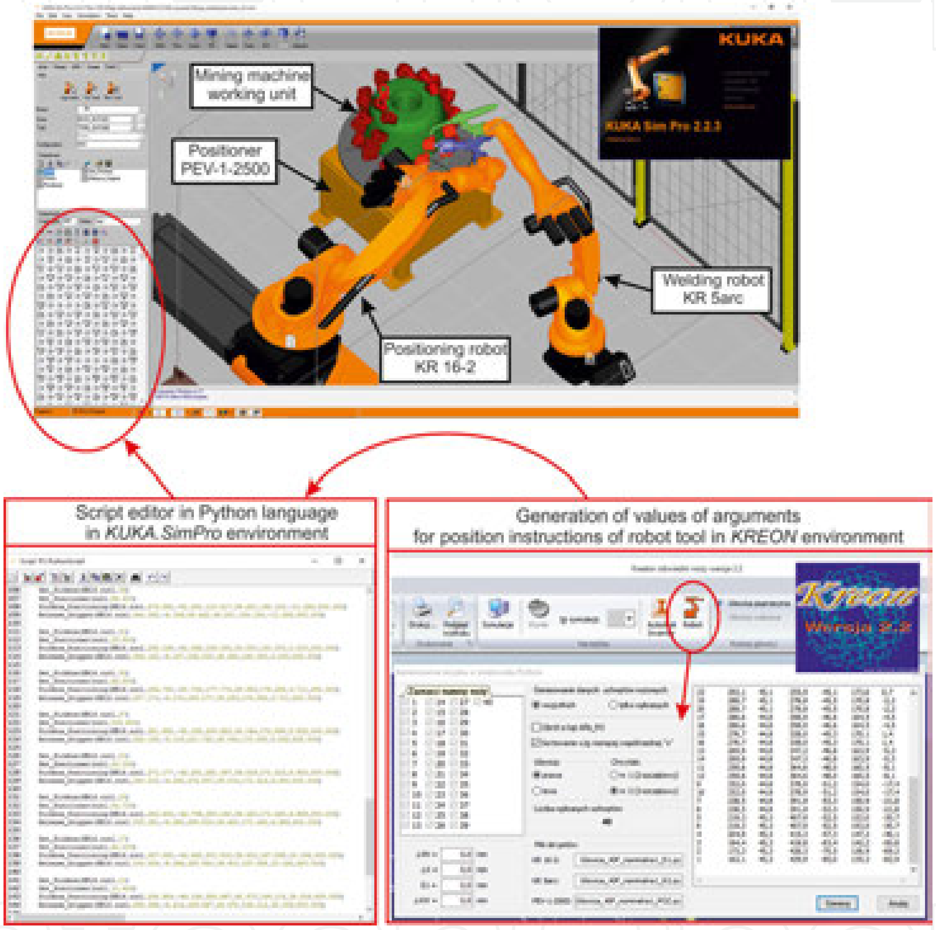

Figure 10. Virtual assembly station and progress of the utility programme generation process for robotised station for mounting pickboxes to the side surface of the working unit of a mining machine with *KREON* and *KUKA.SimPro* software.

Collision analysis is carried out when the generated utility programmes are tested in *KUKA.SimPro* environment. When robot movements are simulated on a virtual stage, the software analyses the distance between the elements indicated by the programmer. The elements for analysis are selected and the minimum permitted distance between them is established in the Collision Detector Editor dialogue window (**Figure 11**). If any collision is detected, the programme executes an action chosen by the programmer (collision occurrence is indicated, the tested utility programme is deactivated) [20]. A utility programme in such case is manually modified to eliminate the risk of collision.

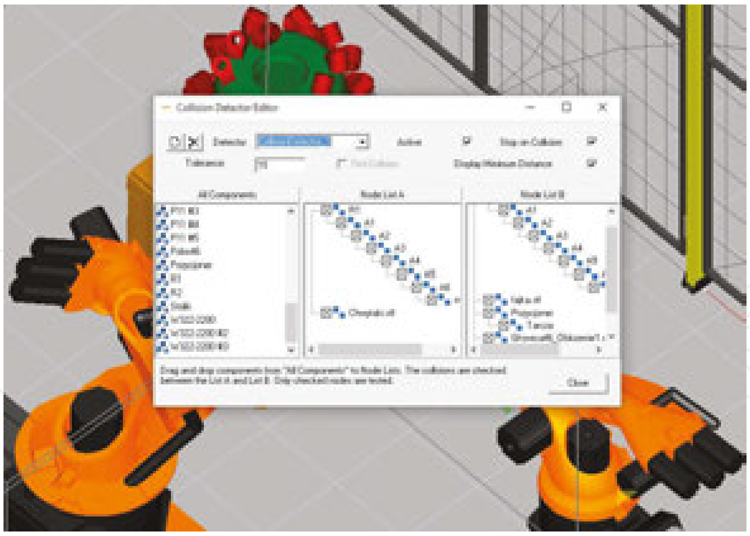

Figure 11. Collision detection module in *KUKA.SimPro* environment.

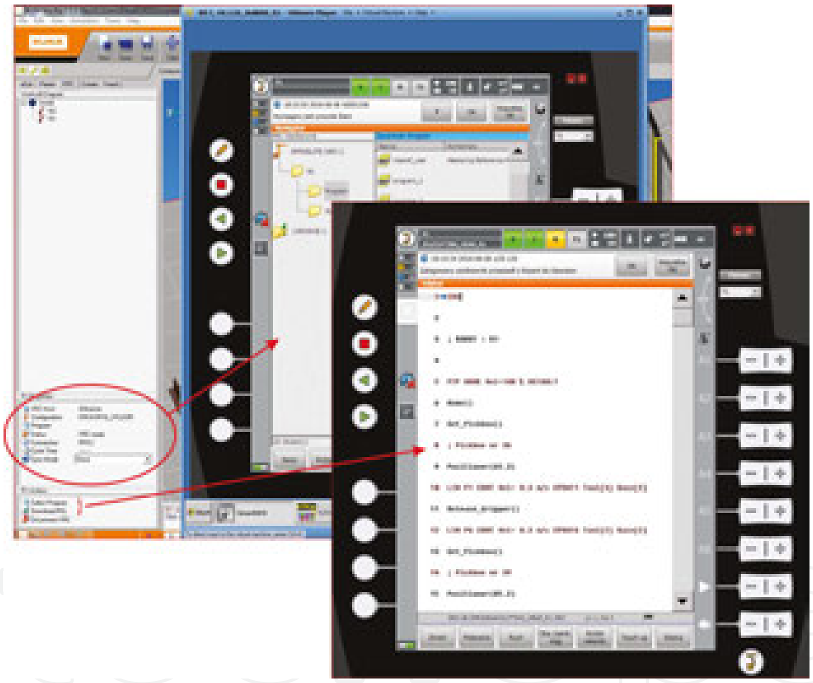

Figure 12. ‘Cutting_head_R1’ utility programme for the robot positioning the pickboxes generated in *KUKA.SimPro* environment transferred to the virtual operating system of *KUKA.OfficeLite* robot.

A positive result of robotised station software test enables to transfer real robots into the operating system via a communication interface. For KUKA robots, this is done via a virtual-operating system, *KUKA.OfficeLite*. It is an image of the actual KUKA robot operating system, installed in *VMware Player* virtual machine [21]. A virtual operating system can communicate with any virtual robot model in *KUKA. SimPro* environment (Connect feature). The connection status is highlighted in Properties → Status (**Figure 12**—rounded with an ellipsis). Such communication enables to transfer utility programmes between *KUKA. SimPro* and *KUKA.OfficeLite* virtual-operating system. When communication is initiated in KRC tab of *KUKA.SimPro* software with a virtual operating system of the robot ('Status: VRC ready') and when Download RSL function is called, the utility programme is transferred and translated into KRL (Kuka Robot Language) language supported by KUKA robots operating system. The utility programme can then be transferred into the actual robot control system with portable USB disc storage.

4. Automation of production quality control

Production quality control is critical for product acceptance and for putting the product into use. Due to the complicated stereometry of the working units considered in this work, this issue can be effectively solved by applying reverse engineering with three-dimensional (3D) scanning. Due to a complex shape of the working units of cutting machines, manual scanning methods already at the stage of measuring data acquisition are not effective and very working intensive. Robotic techniques are useful here again such as automatic scanning using robotised-measuring stations. A utility programme for a robot must be prepared for an automatic scanning process, which can be created using offline programming. The geometric characteristics of a working unit can be identified, in accordance with the way of recording the dimensioning of a pick system in technical documentation, by parsing out information from the data acquired by scanning, based on which a measurement model is built. The process of processing measurement data (scans) to parameter values characterising the arrangement and setting of individual pickboxes is performed with advanced computer techniques—software for processing and analysing 3D mesh. An important aspect for this type of measurement tasks is a possibility of measurement data automatisation to shorten, as much as possible, the time for producing measurement results.

The stereometry of working units in mining machines is measured in two stages. In the first stage, measurement itself is performed with a 3D scanner mounted to a robot arm. The next positions of the scanner—in relation to the scanned object—are set by an industrial robot manipulator executing successive positioning instructions. Measuring data is also initially prepared at this stage for further processing in scanner software. Another stage of measurement is performed with computer software for processing meshes representing the scanned object surface. *GOM Inspect* is an example of such software.

A robotised-measuring station was constructed for the stereometry measurement of mining machines working units in a laboratory of the Institute of Mining Mechanisation, Faculty of Mining and Geology, Silesian University of Technology. It incorporates the KUKA KR 16-2 robot with smartSCAN 3D-HE scanner (by Breuckmann Aicon 3D Systems) attached to its arm and PEV-1-2500 positioner. **Figure 13** shows a virtual 3D model of a robotised-measuring station created in *KUKA.SimPro* software. The measuring station is controlled with a utility programme created for this purpose. Two layers can be distinguished in the software hierarchy. A subordinate layer with a subprogramme is executing the entire scanning sequence for the given setting of the scanned object on the positioner disc (**Figure 14**). It comprises a number of successive instructions for robot arm positioning. A scanning procedure is called after each of them during which the control process scanning system (*Optocat* programme in this case) acquires measuring data. The robot control system communicates with *Optocat* software via a TCP/IP link in client (robot controller)—server (*Optocat* software) architecture using XIRP protocol [22]. A loop is executed in the control programme master layer of the robotised-measuring station, in which the positioner disc setting is changed (its rotation angle ϕ_T) between zero and 360°, with the defined step $\Delta\phi_T$ [1].

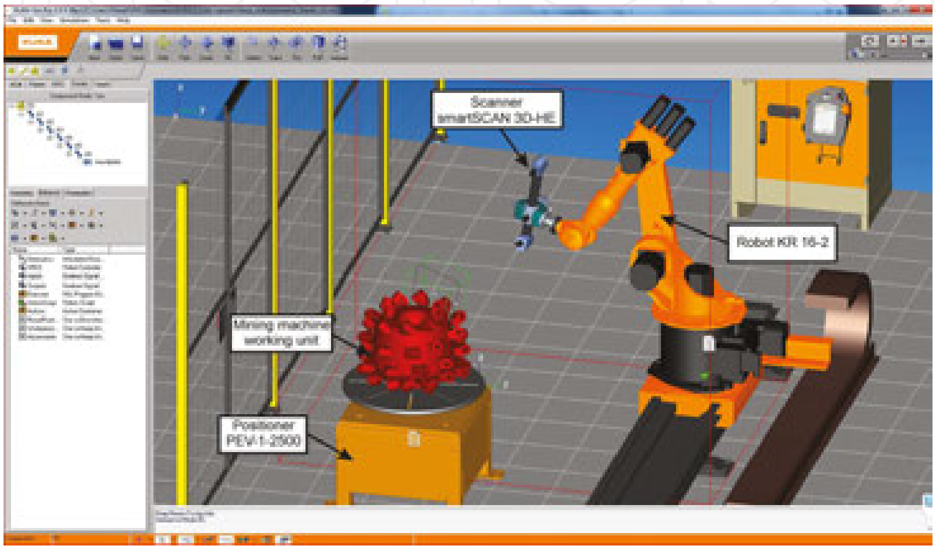

Figure 13. Virtual model of a robotised-measuring station in *KUKA.SimPro* environment.

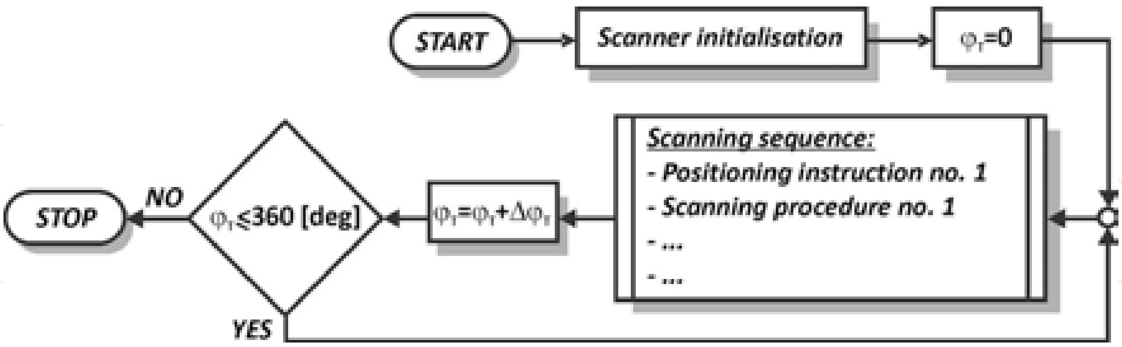

Figure 14. The algorithm of procedure of automated measurement of stereometry of mining machines working units by means of a structured light scanner mounted to the robot arm.

A control programme scanning sequence is generated in *KUKA.SimPro* software. The particular positions of the scanner are set manually, after which they are memorised as positioning instructions. Due to the complicated shape of the mining machine working unit surface, a large number of scanner positions have to be programmed to execute the measuring task considered here. This results from a generally high density of pickboxes. For example, even 68-scanner

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positions had to be programmed to measure the cutting heads of a boom-type roadheader with the diameter of ~750 mm and the length of ~500 mm. This is derived from the fact that the scanned surface had many areas with hard access by the scanner; however, with fewer scans, the mesh representing the scanned surface had many discontinuities (holes). By assuming the positioner disc rotation step of $\Delta\phi_T = 10°$, the number of scans used to build the model of a cutting head surface was more than 2400. Such massive amounts of data require high computational capacity of a computer used for processing and analysing measurement results.

In order to position the scanner correctly in relation to the scanned object, a scanner measuring field position is displayed on a virtual stage of the measuring station with the corresponding aperture value (**Figure 13**—green cuboid).

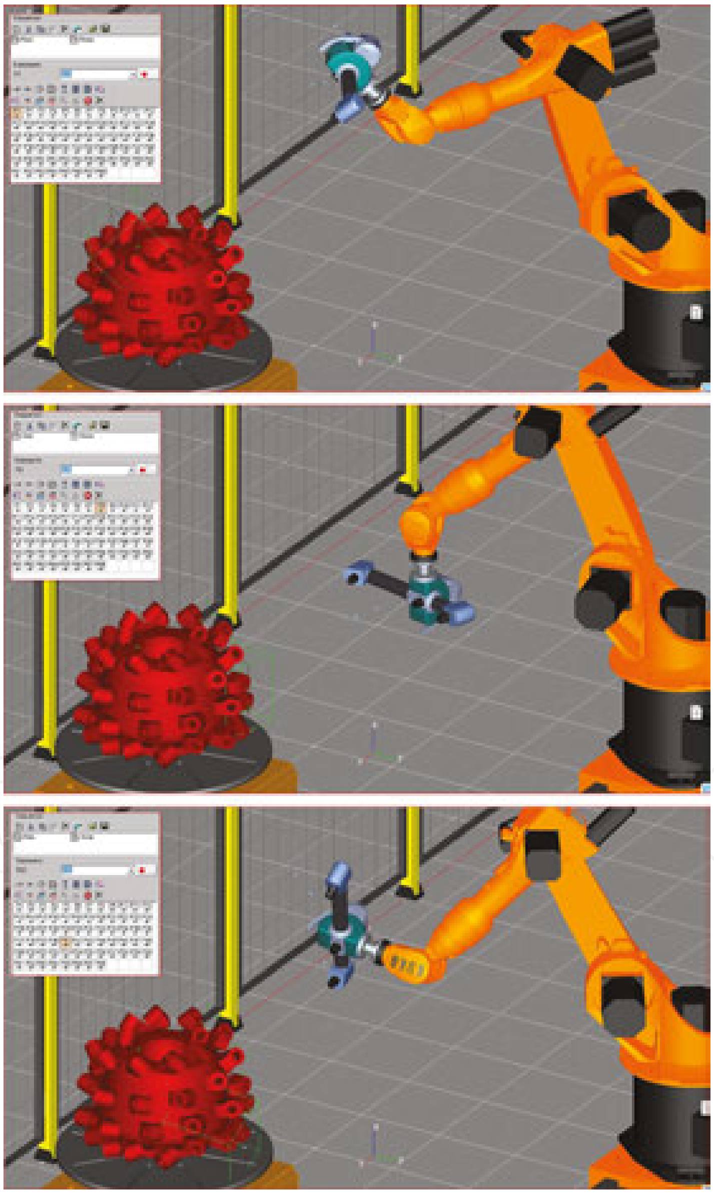

Figure 15. Simulation of the scanning process of boom-type roadheader cutting heads in *KUKA.SimPro* environment.

Three selected scanner positions are shown in **Figure 15**, resulting from the execution of the positioning instructions P1, P8 and P41. The whole sequence of the programmed instructions for positioning the successive scanner positions relative to the cutting head is shown in the left top corner, for which measurement is executed (the pictograms of the shown examples of positioning instructions are marked orange). After testing the created utility programme, it is converted into KRL language during transmission into a virtual control system of *KUKA. OfficeLite* environment (this is discussed in item 3 of this work). Using a virtual robot programming panel, scanning procedure calls are added after each positioning sequence to a subprogramme executing the scanning sequence. It is then transferred to a memory of the actual robot's control system using portable USB disc storage.

In the second stage of the stereometry measurement of the working units of mining machines in line with the discussed method, the measuring data obtained as a result of automatic scanning are processed in order to produce a measurement result. It is done using special computer tools—metrological programmes for, among others, analysing meshes representing the scanned object surface. The *GOM* environment of GOM mbH is an example of such software. It is worth noting that the basic version of the software is free. It also features a full metrological functionality. Scripts in Python language can be created in a paid version (Professional) and measuring procedure automation is available.

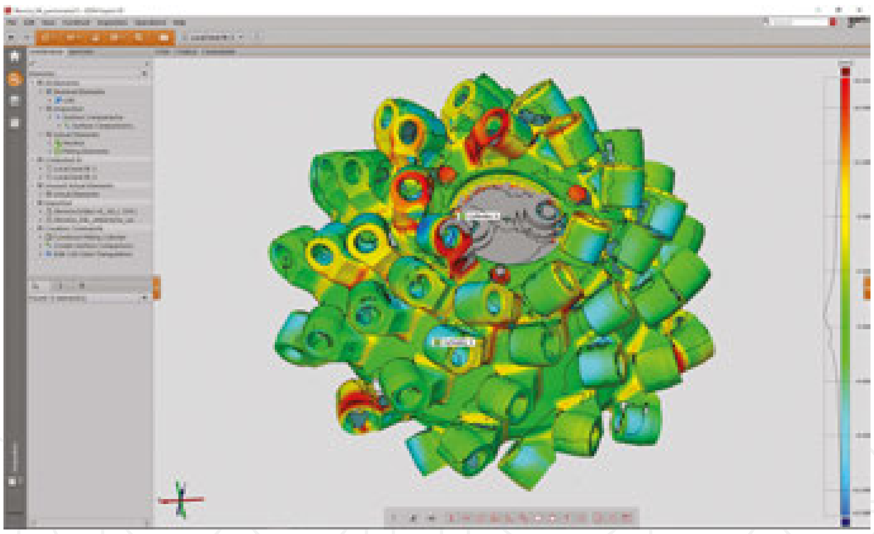

Figure 16. Analysis of measurement results of roadheader cutting head stereometry in *GOM Inspect* environment—distribution map of deviations of an actual surface from the nominal surface.

The software used for measuring data analysis allows to follow two measurement strategies of the working units of mining machines [1]. The shape of the scanned surface is compared with the nominal surface (CAD model) in the first of them. It is possible to make a quick inspection this way, the result of which is the determination of dimensional deviations in the actual surface area from the reference surface area. The measurement result in this case has the form of a colourful map with a distribution chart of values of such deviations (**Figure 16**). It is also possible to analyse deviations in the shape of section lines in the needed cross sections

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of the scanned object and to determine the values of deviations in the defined control points [23]. A mathematical measurement model has to be built in the second measurement strategy for each pickbox. The values of parameters describing the arrangement and spatial positioning of particular pickboxes and related picks are established on the basis of such a model according to characteristic geometrical features measured in a metrological programme. The consistency of the so-established measured values is determined in relation to the nominal values provided in technical documentation in order to assess whether or not the mining machine working unit has been executed correctly in this case. In particular, the work [1] describes the construction of a stereometry measurement model of the working units of mining machines.

In the example shown in **Figure 16**, the actual arrangement of some of the pickboxes clearly differs from that set in the design of the cutting head. In the map generated in *GOM Inspect* program, the areas of the minimal deviations of the actual surface from the nominal surface are marked green. The more red or blue the area is, the greater are the deviations (with respect to the absolute value). The degree of variation of the surface adaption of the individual pickboxes varies. The greatest deviations of the actual surface from the nominal surface were reported in case of the pickboxes arranged the closest to the face surface of the cutting head (in the upper part of the model). The surfaces of these pickboxes are marked red (the corresponding deviations are even greater than +18 mm). This proves that the arrangement of the pickboxes does not comply with the technical documentation. A similar effect is visible also in case of some of the pickboxes arranged near the base of the cutting head (in the lower part of the model). The production errors, which occurred at the stage of manufacturing of the measured head, result largely from the fact that the installation (attaching) of pickboxes to its side surface has been carried out at a manual assembly station. In such case, the quality of workmanship depends largely on the skills and conscientiousness of the operator.

5. Conclusion

This work discusses comprehensively the issue of manufacturing the working units of mining machines and the potential use of computer aid in particular phases of executing this process. Considering the efficient and effective work of mining machines, it is fundamental to optimise the construction of this type of working units, especially with regard to the way of arranging working tools and compliance of the final product with technical documentation. This is confirmed by practical experience and scientific investigations. They indicate that working units designed improperly for service conditions or constructed not in accordance with documentation may cause low-working capacity, considerable dynamic overloads of working machine's drives and its load-bearing system. This results in low-operating efficiency and low durability and reliability of such machines, especially when operated in difficult mining and geological conditions. This risk can be mitigated by using modern manufacturing techniques of the working units of mining machines based on computer-aided design and optimisation, computer-aided design of their manufacturing technology and production quality monitoring. A broad array of computer tools should be utilised in the successive steps of such a design, namely, standard CAD programmes, dedicated software aiding the design of mining machines working units and a computer simulation of the working process they execute, tool software for aiding the technology design and for simulating the manufacturing process, or metrological software allowing fast, automated inspection for quality control at the key stages of such units' production. The way how this issue can be solved practically has been presented with the example of boom-type roadheader working units. The usefulness of the computer tools presented in this work has been confirmed practically. Software for the aided design of pick systems is widely used by the manufacturers of mining machines for designing and selecting working units for particular service conditions. The capabilities of offline programming of robotised stations for the assembly of pickboxes and for measuring the stereometry of roadheader cutting heads were tested at a semi-industrial scale on a robotised assembly station and a robotised-measuring station created in the laboratory of the Institute of Mining Mechanisation, Faculty of Mining and Geology, Silesian University of Technology.

The use of computer aid is contributing to a significantly improved manufacturing quality of such important elements—considering the efficient operation of cutting machines—whilst reducing the time and work input of their production. Different configurations of picks are achievable by optimising the construction of working units and by applying robotised manufacturing technologies and this contributes to their enhanced service life. This, in turn, leads to the improved utilisation of technical potential of working machines, having a beneficial effect on the economical aspects of mining works carried out with such machines. A necessary condition critical to pursue this direction effectively is to minimise the design implementation time—starting with the formulation of technical assumptions to producing a final product. Such requirements can be successfully satisfied by using computer tools at each stage of such a process.

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