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Optimization test of operation of URB/ZS-3 automatic machine for breaking oversized lumps under conditions of Polkowice-Sieroszowice mine

This article presents the experience from the first stage of the optimization tests of an automatic machine for breaking oversized lumps. The tests took place between December 2017 and March 2018 at the O/ZG Polkowice-Sieroszowice mine. The URB/ZS-3 automatic machine was developed as part of the second competition of a joint venture financed by NCBR and KGHM Polska Miedź S.A. under the name of CuBR. The adopted methodology of carrying out the operational tests of the URB/ZS-3 machine was discussed, which had to take into account the specific requirements and operating conditions of the mining department in the Polkowice-Sieroszowice mine. The reference point for evaluating the effectiveness of the new solution was the cleaning times of the grate by a machine working in remote mode. The results of clearing the grate of excavated materials by a machine working in automatic mode were presented for various algorithms and scenarios included in the control software. The influence of the degree of ore fragmentation (including the number of oversized lumps) on the time of the grate cleaning was taken into account. The influence of the changes introduced in this software on the obtained grate discharge times was initially evaluated. The article also presents the impact of loading the grate with the use of loaders and haul trucks on the effectiveness of the automatic machine for breaking oversized lumps. Also, the driver elements of the machine were assessed in terms of their reliability, and the directions for possible structural changes were proposed. In conclusion, the directions for further activities aimed at optimizing the machine and increasing its efficiency and reliability were proposed.

Key words: *optimization, mining, breaking oversized lumps*

1. INTRODUCTION

The tests of the URB/ZS-3 automatic lump breaker under the conditions of the Polkowice-Sieroszowice mine took place as part of the research and development work carried out as a portion of the CuBR II project entitled "Type URB/ZS-3 automatic rock crushing machine for underground copper mines "–" co-financed by the National Center for Research and Development and KGHM Polska Miedź S.A. The project is carried out in a consortium whose members are KGHM ZANAM S.A., KGHM CUPRUM Sp. z o.o. CB-R, and AGH University of Science and Technology.

Prior to the in-house testing, a methodology was developed to determine the criteria necessary to be analyzed in order to assess the correct operation of the lump breaker as well as the performance of the automatic control system.

A prototype of the machine was installed on a discharge point in the Polkowice-Sieroszowice mine in drift T-210/crut P-13 with an R-120/1 discharge grate onto a Legmet L-120 conveyor. The discharge point was subjected to optimization tests with excavation materials during the period of December 2017 to March 2018.

During the measurements, the times when the machine cleared the grate of oversized material were recorded, and the effectiveness of its operation was evaluated. The mechanical solutions of the automatic lump breaker and control software were also evaluated.

2. URB/ZS-3 AUTOMATIC LUMP BREAKER

The prototype of the URB/ZS-3 lump breaker was developed in response to the growing needs of KGHM Polska Miedź SA in connection with the need to increase the level of automation during the excavation of copper ore [1]. These needs result from the deteriorating mining conditions – increased air temperature, humidity, and the risk of bumps [2].

In addition, the automation of the process of breaking lumps would enable the optimization of the URB operators' working time and, thus, reduce the costs of copper ore excavation. In order to achieve these objectives, the machine must ensure that the grate is cleaned without intervention from the operator who would perform a control role and would get involved in the cleaning process remotely in specific cases [2].

The attempt to automate the process of crushing lumps was based on the existing equipment for breaking lumps (URB, manufactured by KGHM ZANAM), which was dictated by the need for an optimal conversion (from the point of view of the costs) from the currently applicable system of breaking oversized lumps (manual breaking with the operator directly on the grate and remote breaking) into a system operating in the automatic cycle [1].

The operation of the URB/ZS-3 is based on scanning the grate with a laser scanner that determines the commencement of the process of grate cleaning by assessing the degree of occupancy of the grate with excavated material. Coordination between the boom-mounted hammer, scanner, and control program are achieved by installing sensors and positioning angle and distance transducers [1].

3. LOCATION

The prototype of the URB/ZS-3 automatic lump breaker was installed on the discharge point in the Polkowice-Sieroszowice mine in drift T-210/crut P 13 with an R-120/1 discharge grate onto an Legmet L-120 conveyor. The installation of the machine is shown in Figure 1, and a diagram of the discharge point is shown in Figure 2.

Fig. 1. Method of installation of URB/ZS-3 in Polkowice-Sieroszowice mine

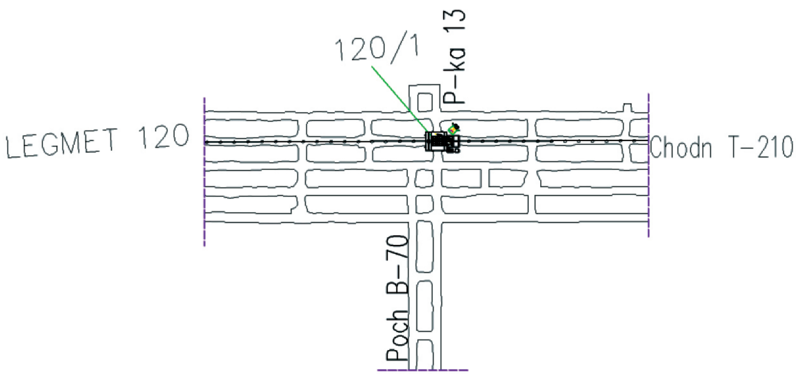

Fig. 2. Location of URB/ZS-3 in Polkowice-Sieroszowice mine

At the same time, the URB/ZS-3 control station equipped with a remote-control console and control cabinets enabling remote work on the grate were installed in the SK-2 control room on the shaft bottom of the SW-1 shaft. The method of installation in the control room is shown in Figure 3.

The control room has access to the monitoring of the R120/1 grate, allowing for control of the entrance signaling (thanks to which, it is possible to cooperate with an operator of a haul truck).

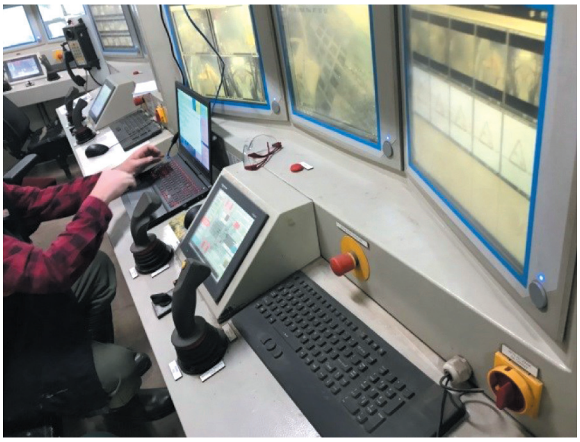

Fig. 3. Remote control console in SK-2 control room on shaft bottom of SW-1 shaft

4. ASSESSMENT CRITERIA

The tests were preceded by the preparation of the appropriate rules for assessing the correctness of the operation of the URB/ZS-3 automatic lump breaker. The correctness of the operation of the machine itself and the operation of the control algorithm were assessed.

The basic parameters for determining the working capability of the lump breaking machine are as follows [2]:

- correct operation of the hydraulic system of the boom with an impact hammer,
- no leaks in the hydraulic system,
- correct settings of the safety valve,
- correct operation of the automatic lubrication system,
- correct operation of the laser scanner,
- correct operation of the drawer-like feeder system,
- possible taking over of remote control of the machine from the SK-2 control room on the shaft bottom of the SW-1 shaft.

The basic parameters to be checked during the operation of the control algorithm are as follows [1]:

- the duration of the self-cleaning cycle of the discharge grate,
- the degree of cleaning the grate after the end of the operating cycle,
- the impact of the type of excavation material (degree of fragmentation, dampness, etc.) on the duration of the self-cleaning cycle of the discharge grate,
- the effect of the type of excavated material on the degree of cleaning the grate at the end of the machine cycle,
- the correctness of the assessment of the distribution of excavated material on the discharge grate by the laser scanner,
- the ability of the machine to search for excavated material and skip the empty areas of the discharge grate,
- the ability of the machine to search for and break down oversized lumps,
- the ability of the machine to search for and rake fine excavated material,
- the correctness of the operation of the entry gates that automatically turn on the machine.

5. OPTIMIZATION TESTS

Five optimizing bottom tests were carried out to improve the algorithm's performance in terms of the efficiency and speed of the grate cleaning. The tests were carried out with the use of LKP-0903 bucket loaders manufactured by KGHM ZANAM, each with a load capacity of approx. 7 Mg of excavated material. The planned optimization works with the WO CB4 haul trucks (each with a capacity of 20 Mg of excavated material) were carried out on a partial basis due to the failure of the machine in March 2018.

The material used in the tests covered the full range of grain found in the mines of KGHM Polska Miedź S.A. The aim was to adapt the algorithm to the changing conditions on the discharge grate depending on the type of excavated material, location of the mining unit, and general variability of the grain size resulting from the application of the method of mining faces with explosives in a room-and-pillar mining system.

The tests were aimed at developing the appropriate parameters and settings in the control algorithms, improving the operating time of the URB/ZS-3 and ensuring the appropriate ratio of the duration of the cleaning cycle to the level of clearing the grate of excavated material [1].

The optimization tests were based on the definition of the necessary modifications to the software and on the determination of an acceptable grate occupancy level in order to maintain the continuity of haulage, which allows machines to pass through the grate if necessary [1].

An example of a grate before cleaning is shown in Figure 4. About 7 Mg of excavated material with fine characteristics was delivered to the grate. Figure 5 shows the grate after cleaning with the URB/ZS-3 automatic lump breaker. The degree of clearing the grate was considered satisfactory.

Fig. 4. Grate after LKP-0903 loader has unloaded excavated material

Fig. 5. Grate after URB/ZS-3 has automatically cleaned it

As a result of the optimization tests, three modes of operation were introduced to the cleaning algorithm:

- the breaking of lumps in the meshes of the grate (chiseling mode),
- the raking of excavated material on the grate (spreading mode),
- the breaking of lumps at their geometric centers determined by scanning ("single" mode).

After the optimization process, the cleaning modes were significantly simplified in order to shorten the cleaning program time. In the initial phase of the tests, the chiseling mode consisted of the preliminary raking of excavated material from the mesh bars of the grate and then breaking a lump in the middle of the mesh of the grate. As a part of the tests, the program has been simplified; in its current version, it consists in the hammer running over the geometric center of the grate mesh. The machine is then lowered, and the impactor in the hydraulic hammer is activated as soon as the resistance of a lump is encountered.

The raking mode has been simplified to angular runs in place of the initial run along the grid bars. This significantly speeds up the cleaning of the grate from fine excavated material when compared to the previous solution.

The "single" mode was introduced in a late stage of the tests. It is used to break up lumps in the last phase of the algorithm's operation after the execution of the raking and spreading modes.

The modes are arranged in scenarios depending on the type of excavator (haul truck/bucket loader) and the degree of occupancy of the grate.

The occupancy rate of the grate was determined on the basis of the scanning performed before and during the implementation of the cleaning scenario. The lump breaker should continue the cleaning process until the set value is reached, after which it should allow the next machine to enter the plant after reaching the set parameter. The optimization tests resulted in a satisfactory limit value of 17% occupancy of the grate. The height of the excavated material (which allows free passage of the machine) was determined at 150 mm above the grate as a result of the optimization tests.

When the excavated material is unloaded onto the grate, the control system reads the occupancy rate and activates the URB/ZS-3 when the supplied excavated material fills the grate to more than 17% of the occupancy rate. The cleaning work continues until the occupancy rate is below 17%.

During the measurements, the duration of the individual cycles from the moment of switching on the automatic self-cleaning mode to the return of the URB hydraulic hammer to its base point was recorded, and the efficiency and degree of the cleaning of the grate after each measurement was determined. Additionally, in order to ensure the best possible reproduction of the operating conditions, 15 s before the URB/ZS-3 start-up, the R-120/1 drawer-like grate feeder was switched on, which enabled the fine excavated material to be pre-poured – grate self-cleaning.

During normal operation, it is planned to ensure control of the movement of the dumping machines in the area of the grate by the URB/ZS-3 system. This is achieved by controlling the traffic light, which draws information (among other things) from special gates installed at the entrances to the grate. During the optimization tests, the operator's entry signaling was not tested. The green light and permission to enter the grate were given by the supervising operator from the SK-2 control room [2].

The times of the individual measurements and results of the tests are presented in Table 1 for the optimization tests and Table 2 for the algorithm-verification tests. The grate was considered cleaned if, after the completion of a test, the state of the occupation of the grate made it possible to reload excavated material.

The URB/ZS-3 optimization tests were carried out at 5 mining shifts, during which 39 measurements were made using approx. 280 Mg of excavated material (40 buckets of the LKP-0903 loader), of which 8 ended with the cleaning of the grate. The mean duration of a positive test from the moment of activation to the moment of deactivation of the URB/ZS-3 was126 s.

The tests verifying the URB/ZS-3 were carried out at three working shifts; however, due to the failure of the machine during the first tests with haul trucks on the second day of the tests, it was necessary to discontinue the tests.

Eleven measurements were made during the first shift, using approx. 105 Mg of excavated material (15 buckets of the LKP-0903 loader), of which nine ended with the cleaning of the grate. The mean duration of a positive test from the moment of activation to the moment of deactivation of the URB/ZS-3 was 293 s.

During the tests on March 15, 2018, the machine malfunctioned. The fastening of the piston rod position sensor of the swivel actuator of the URB/ZS-3 was damaged, causing the machine to decalibrate and the hydraulic hammer to lose its zero point. Due to the design of the measuring system (a sensor installed in the piston rod), the entire swivel actuator had to be replaced. After the analysis, it was found that the failure of the piston rod position sensor fastening in the rotary actuator occurred as a result of the incorrect sensor securing in the fastening socket. Polyurethane resin was used, which was ultimately destroyed by the temperature of the working medium. The unprotected sensor under the influence of impact work of the URB/ZS-3 started to move, which caused the machine's decalibration.

Since the distance sensors are installed in all four actuators of the lump breaking machine, consideration should be given to changing the adopted concept of securing the sensor and recording the piston rod extension.

The failure made it impossible to carry out full haulage tests with the CB4 haul trucks and optimize the algorithm accordingly. The optimization tests with a haul truck were carried out in parallel to the repairs of the decalibrated URB/ZS-3.

Table 3 shows the general results for the tests carried out at the discharge point using the URB/ZS-3 automatic lump breaker. The optimization tests were conducted on eight mining shifts from December 2017 to March 2018. A total of 55 tests were carried out, of which 21 ended with the cleaning of the grate, which results in a 38% efficiency. The average cleaning time was 4.8 minutes. Fifty tests were carried out with the use of a bucket loader, of which 17 were completed with the cleaning of the grate. The average cleaning time was 3.4 minutes. The table also includes statistics for the tests using a haul truck. Five tests were carried out, four of which ended with the cleaning of the grate. The average cleaning time was 10.7 minutes.

It should be noted that the tests conducted during the optimization period were of a research and verification nature. There were interruptions during the measurements and changes in the algorithm parameters. Hence, a low level of success of the tests and low shift use of the URB/ZS-3 were observed. The optimization of the software was additionally hampered by the changing nature of the excavation material – finer material requires a higher share of the raking mode than material with a higher share of oversized lumps.

Table 1

Results of optimization tests of URB/ZS-3 automatic lump breaker

Date of tests	Number of tests	Number of positive tests	Additional information	Excavated material		Operating time duration of URB [min]	Positive test	
				loader [bucket]	truck [truck]			
December 19, 2017	4	1	optimization tests	3	0	5.0	no	0
				1	0	8.0	no	0
				1	0	4.0	yes	1
				3	0	8.0	no	0
January 12, 2018	2	0	optimization tests	5	0	no test	no	0
				4	0	no test	no	0
January 31, 2018	8	6	optimization tests	2	0	1.5	yes	1
				1	0	1.7	yes	1
				1	0	1.5	yes	1
				1	0	1.8	yes	1
				1	0	1.7	yes	1
				1	0	3.5	no	0
				3	0	3.0	yes	1
				3	0	2.8	no	0
February 2, 2018	17	1	optimization tests	1	0	1.7	no	0
				prev. test	0	1.7	yes	1
				1	0	1.7	no	0
				prev. test	0	2.8	no	0
				1	0	1.5	no	0
				1	0	3.3	no	0
				prev. test	0	3.8	no	0
				prev. test	0	3.7	no	0
				1	0	3.0	no	0
				prev. test	0	5.5	no	0
				prev. test	0	2.0	no	0
				prev. test	0	1.0	no	0
				prev. test	0	6.3	no	0
				prev. test	0	2.5	no	0
				prev. test	0	1.3	no	0
				prev. test	0	0.8	no	0
				1	0	2.0	no	0
February 28, 2018	8	0	optimization tests	1	0	1.0	no	0
				prev. test	0	7.0	no	0
				prev. test	0	6.0	no	0
				1	0	3.0	no	0
				1	0	3.9	no	0
				prev. test	0	3.1	no	0
				1	0	7.0	no	0
				prev. test	0	1.5	no	0

Table 2

Results of verification tests of URB/ZS-3 automatic lump breaker

Date of tests	Number of tests	Number of positive tests	Additional information	Excavated material		Operating time duration of URB [min]	Positive test	
				loader [bucket]	truck [truck]			
March 9, 2018	11	9	tests testing algorithm	3	0	6.0	yes	1
				1	0	4.0	yes	1
				1	0	11.0	no	0
				1	0	6.5	no	0
				1	0	10.7	yes	1
				2	0	4.0	yes	1
				2	0	3.0	yes	1
				1	0	4.0	yes	1
				1	0	4.3	yes	1
				1	0	3.3	yes	1
				1	0	1.5	yes	1
March 15, 2018	2	1	machine malfunction	0	1	14.7	yes	1
				0	1	8.0	no	0
March 16, 2018	3	3	machine malfunction	0	1	3.0	yes	1
				0	1	6.5	yes	1
				0	1	18.5	yes	1

Table 3

General results of testing URB/ZS-3 collected during tests at Polkowice-Sieroszowice mine

General statistics for tests of URB/ZS-3	
Operating time of URB [min]	228
Material delivered with bucket loader [Mg]	385
Material delivered with haul truck [Mg]	100
Material delivered in total [Mg]	485
Handled material to URB operating time [Mg/min]	2
Number of shifts worked [change]	8
Average of material handled per shift [Mg/shift]	61
Shift duration time [min]	240
Average of material handled per minute [Mg/min]	1
Average test duration time [min]	4.2
Total number of tests carried out	55
Number of positive tests carried out	21
Degree of positive tests [%]	38
Average positive test duration time [min]	4.8

Table 3 cont.

General statistics for tests of URB/ZS-3	
Statistics for bucket loader LKP-0903	
Number of tests carried out with bucket loader	50
Number of positive tests carried out with bucket loader	17
Degree of positive tests with bucket loader [%]	34
URB operating time with bucket loader haulage [min]	178
Material delivered with bucket loader to URB operating time [Mg/min]	2
Average test duration time with bucket loader haulage [min]	3.6
Average positive test duration time with bucket loader haulage [min]	3.4
Statistics for WO CB4 haul truck	
Number of tests carried out with haul truck	5
Number of positive tests carried out with haul truck	4
Degree of positive tests with haul truck [%]	80
URB operating time with haul truck haulage [min]	51
Material delivered with truck to URB operating time [Mg/min]	2
Average test duration time with haul truck haulage [min]	10.1
Average positive test duration time with haul truck haulage [min]	10.7

In the initial phase of the tests (in December and January), very fine excavated material was delivered to the grate, which resulted in the optimization process focusing to a large extent on the raking of material, which did not prove to be the main mode of operation at the time of the appearance of the oversized material in February and March. It was necessary to extend the share of the lump breaking mode and to introduce an additional "single" mode. As a result of the longer cleaning times, simplifications were applied in the operation of the particular modes. Following further optimization, a satisfactory compromise was reached on March 9, 2018.

Table 4 presents the results of the tests of March 9, 2018. Eleven tests were carried out, nine of which ended with the cleaning of the grate. The average cleaning time was 4.5 minutes.

The analysis of the data from the table shows that the progress of the optimization work is at a promising level. Significant progress has been observed in the area of grate cleanliness efficiency. The testing was to be continued on March 15, 2018, in a continuous manner; however, due to the failure, it was necessary to stop the work and start the diagnostics of the defect.

The most common problems noted during the automatic operation of the URB/ZS-3 were related to the operation of the laser scanner.

Problems with the location of the excavated material due to the lack of real-time scanning on the grate were noted. This meant that the machine was not able to correct the path when implementing the set algorithm after scanning the grate until the grate was scanned again. This created problems due to the movement of excavated material on the grate during its cleaning, which resulted in the hammer operating on empty meshes of the grate or the omission of lumps. This problem remained unresolved during the optimization tests and contributed to the deterioration of the results obtained during the tests.

Fixing the scanner at an angle had a negative effect on the cleaning results and times. Oversized lumps or piles of excavated material covered the next row of meshes of the grate. The scanner interpreted such cover as excavated material in a subsequent row, which caused movements to empty meshes of the grate and an increases in the time taken to clean the grate. This problem remained unresolved during the optimization tests and contributed to the deterioration of the results obtained during the tests.

Table 4

Results collected during testing of algorithm of URB/ZS-3 on March 9. 2018

Statistics of testing performed on March 9, 2018	
Operating time of URB [min]	58
Material delivered with bucket loader [Mg]	105
Material delivered with haul truck [Mg]	0
Material delivered in total [Mg]	105
Handled material to URB operating time [Mg/min]	2
Number of shifts worked [change]	1
Average of material handled per shift [Mg/shift]	105
Shift duration time [min]	240
Average of material handled per minute [Mg/min]	0.4
Average test duration time [min]	5.3
Total number of tests carried out	11
Number of positive tests carried out	9
Degree of positive tests [%]	82
Average positive test duration time [min]	4.5

The scanner was not able to distinguish the grain of the excavated material on the grate. This pointed to problems in selecting the algorithm path and carrying out the cleaning process correctly; i.e., raking oversized lumps and breaking down fine excavated material. A partial solution to the problem was the introduction of the "single" mode to the algorithm, during which the device started to break oversized material in the middle of the mass of a lump after scanning as opposed to the earlier breaking down in the middle of the meshes of the grate. Despite providing a better cleaning of the grate, the "single" mode extends the operating time, which negatively affects the measurement results.

Significant problems observed during the tests were the idle movements and the need to return the hammer to a fixed point in order to scan the excavated material again, which prolonged the operating time. An optimization was made consisting of scanning the grate at the hammer's standstill without any unnecessary additional movement, which reduced the time it took to clean the grate. An optimization was also carried out with regard to the movement of the machine on the grate during operation. Further improvements in the performance require the continuation of tests with excavated material.

Problems with the coverage of the URB/ZS-3 arm were also noted. The machine had difficulties in breaking up the lumps in the last row of meshes – the hammer used the impactor at an angle to a lump, which resulted in longer operating time and the frequent suspension of the cleaning algorithm. It was decided to reduce the scanner's field of vision by masking the last row of meshes in the grate. This resulted in a significant improvement in the operating times.

During the tests, the material supplied was occasionally contaminated with metal elements, which posed a threat to the rubber belt of the conveyor. When cleaning the grate with the operator, the operator is responsible for checking the condition of the excavated material and intervening in dangerous cases. In the case of automatic cleaning, the appearance of such elements forces a manual emergency shutdown of the program and human intervention.

The optimization tests have also shown that the design of the boom joints and swivel is very important for the proper operation of the control system. Constant and low-motion resistances at the joints and swivel make it significantly easier to determine the correct operating parameters of the control software. Therefore, it is necessary to use a central lubrication system. During the tests, however, it was found that the load values exceeded safe levels at certain points of the kinematic system, and excessive bearing wear occurred, which resulted in the increased displacement resistance of individual boom members. Therefore, it was necessary to frequently correct certain parameters adopted in the control software. For this reason, it seems advisable to redesign the joints and swivel in order to increase their load capacity and durability. After using a more efficient hydraulic power supply, this would increase the speed of the hammer's movement and, thus, reduce the cleaning times of the grate.

6. SUMMARY

The optimization tests of a prototype of the URB/ZS-3 lump breaker were aimed at adjusting the control algorithm and testing the machine under the underground conditions of the KGHM Polska Miedź S.A. mine. The optimization was based on a specific method of tests whose main aim was to ensure the shortest possible time of cleaning the grate, to a point which enabled unloading next bucket loader.

During eight mining shifts, 55 tests with excavated material were carried out in the Polkowice-Sieroszowice mine using the LK3 LKP-0903 bucket loaders (50 tests) and the WO CB4 haul trucks (5 tests), 38% of which were successful (the grate was cleaned). The average cleaning time was 4.8 minutes. During the shift on March 9, 2018, tests were carried out to check the algorithm for the bucket loaders. As a result of the verification measurements, 11 tests were carried out, 82% of which were successfully completed (with an average cleaning time of 4.5 minutes). During the verification measurements, the machine broke down the oversized material and raked the fine material in a satisfactory way.

The cleaning algorithm is based on putting the subprograms in the modes in the right order:
- chiseling – breaking lumps in the middle of the grate meshes,
- spreading – the raking of the excavated material on the grate,
- single – breaking lumps in the middle of the mass recognized by the scanner.

Significant time savings have been made by eliminating the unnecessary idle movements during scanning – the scanning of the grate takes place while the machine is at the starting point of the URB/ZS-3. Further improvements to the algorithm should include real-time scanning, whereby the lump breaker can react depending on the current distribution of excavated material on the grate.

In addition, grate scanning should provide information on the grain size of the excavated material on the grate. Fine-grained excavated material requires more raking movements, while oversized excavated material should be broken down by the hydraulic hammer. In addition to information on the nature of the excavated material, the scanning should inform the operator about undesirable metal elements on the grate.

The tests with haul trucks were carried out with the URB/ZS-3 machine malfunctioning. As a result of the failure of the piston rod position sensor in the swivel actuator, the machine was decalibrated. The malfunction was caused by the incorrect choice of fastening to protect the sensor in the socket. As the URB/ZS-3 has four actuators with displacement sensors, similar failures are likely to occur in the future.

The tests showed that it is advisable to redesign the joints and swivel of the URB boom in order to increase their load capacity and durability.

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