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Preliminary Failure Frequency Analysis of Receiving Bins in Retention Bunkers Operated in Underground Copper Ore Mines

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Abstract: Ore retention bunkers and receiving bins are important for continuous operation of transport system in a mine. Although the designs of the bins used in the KGHM PM S.A. mines have undergone modifications, their operating principle has remained unchanged since their initial commissioning. Their operation entails many problems, which are caused by the durability and functionality of the entire structure. Preventive actions and research into directions for possible modernizations require the type of damage and its reasons to be identified in the first place. This article presents an evaluation of the documented types of damage and an analysis of the repair works performed for the entire population of the receiving bins operated in one mine. The comparative evaluation of the bin failure rate is here proposed to be performed with the use of a number-based failure indicator and of a mass indicator. The key problem identified in the research was the wear and tear on steel elements due to abrasive processes. The linings of the bin elements were observed to undergo intensive abrasive wear. This abrasive wear of the analyzed bin elements is influenced by a combination of factors, the most important of which include variable physical and mechanical properties of the copper ore.

Keywords: retention bunker; receiving bin; underground copper mine; wear damage; failure analysis

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1. Introduction

The average production capacity of the analyzed underground copper ore mine is approximately 12 million Mg per year, which is approximately 33 thousand Mg per day [1]. The mined ore is transported from the working faces to the unit discharge points with the use of loading machines and haulage vehicles. It is subsequently transported to the surface with the use of a horizontal and vertical haulage system. Efficient haulage largely depends on retention bunkers. Their primary function is to enable the accumulation of the mined material, and as a result to facilitate continuous haulage and minimize ore flow fluctuations. Retention bunkers work in combination with belt conveyors or rail transportation systems and consist of two parts: a bunker and a discharge point, also referred to as a receiving bin. Figure 1 is a schematic diagram of a typical ore retention bunker. Depending on its capacity and location within the transportation system of the mine, a single bunker can work with one to eight receiving bins.

At the ore discharge and transfer points, as well as in the retention bunkers, the ore falls on steel elements or on a conveyor belt. Its impact force depends not only on the amount and speed of the material, but also on the geometry of the bunker. Publications [2,3] demonstrate that as the ore falls on and bounces off the belt, some irreversible damage may occur at the contact point between the belt and the material. Special attention should also be paid to a detailed analysis of the geometry of individual structural elements, on which the material bounces and slides. This issue is of great significance for the durability of the structural elements, as it leads to the loss of their physical properties and also increases the chances for ore congestion which may result in a limited transportation capacity of the entire ore haulage system. The problem of blockages may cause damage to the steel lining of reciprocating plate feeder. It happens when discharged opening is blocked and the trough reciprocates. Publications [4,5] provide a complex description of the issues related to the design and operation of retention bunkers with respect to their operating parameters and types of observed failures.

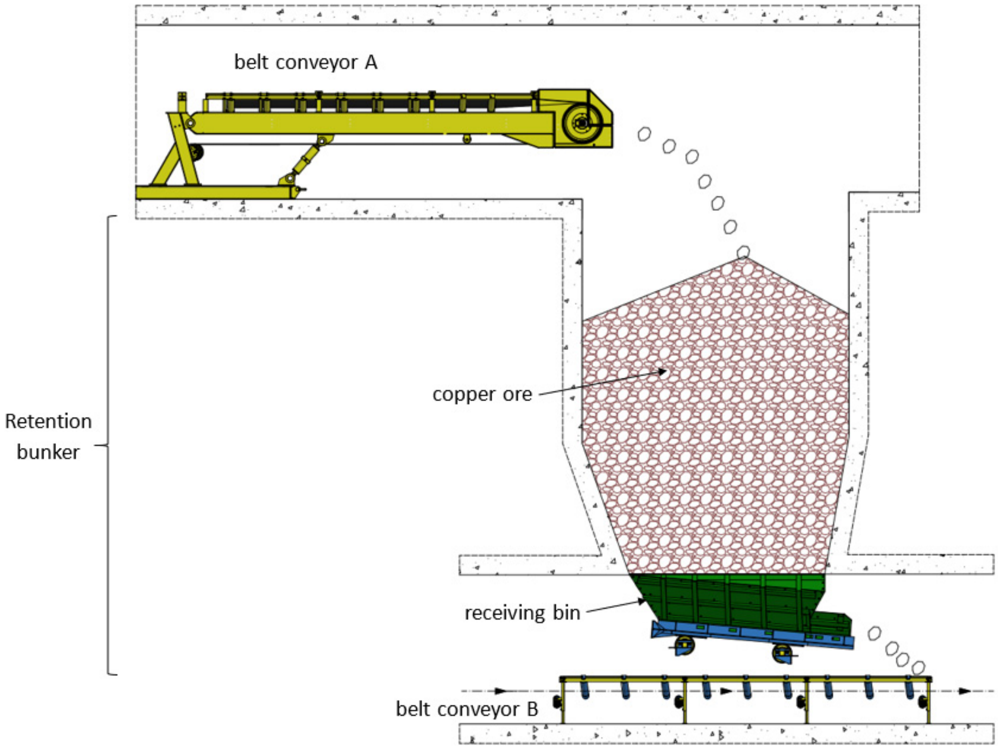


Figure 1. A representative design of a retention bunker with a receiving bin in its lower part, which enables the transfer of copper ore to the belt conveyor.

The design of a retention bunker should allow its effective, failure-free, and safe operation. Each prolonged downtime of a retention bunker which results in the downtime of the mining unit may cause the mine to incur financial losses due to the lost production [6]. The research discussed in the literature focuses mostly on the designs and strength-related analyses of the bunkers with respect to the loads from the surrounding rock mass [7,8], and to a lesser extent on the analysis of damage to the structure of or the wear and tear on the steel surfaces of the bunker elements due to the contact with the ore.

Problem Definition

Polish copper ore mines experience a number of maintenance problems related to the excessive wear of steel elements and friction linings, or to the loss of strength observed in structural elements. The solutions to these problems are temporary, and typically involve solidifying the structure or frequently replacing the worn elements. Copper ore receiving bins installed in retention bunkers are typical examples of elements subject to frequent failures. Therefore, bunkers for individual mining plants need to be designed on the basis of a set of guidelines which would allow for specific conditions in each mine, as suggested in [9]. Figure 2 shows the design of a typical receiving bin with a reciprocating plate feeder.

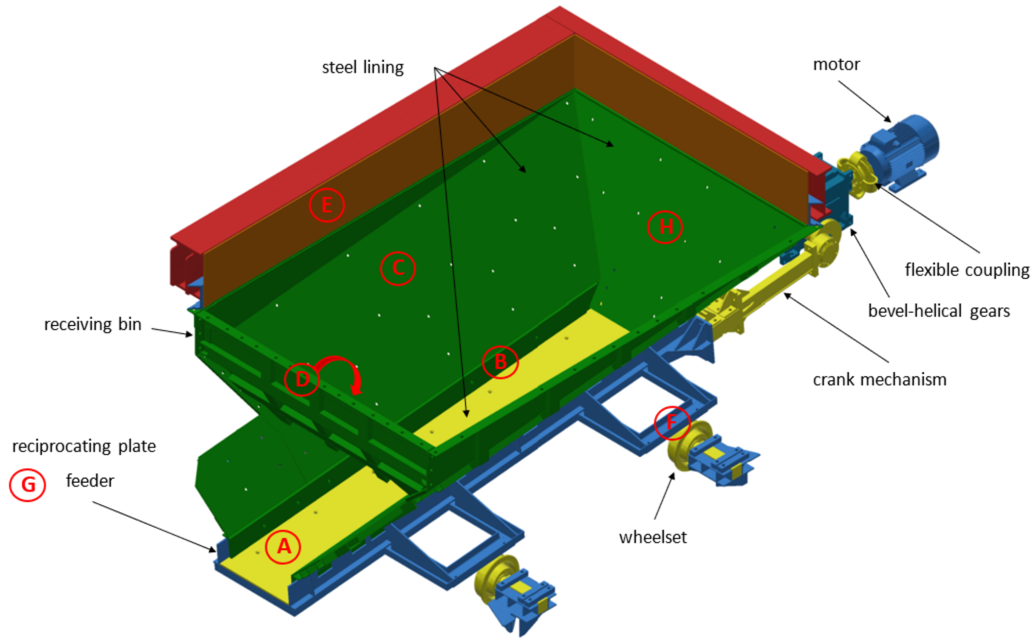


Figure 2. Construction of an ore receiving bin used in Polish copper mines: A—lining of the trough bottom in the reciprocating plate feeder, B—vertical sealing between the reciprocating plate and the fixed hopper, C—lining on the side walls of the hopper, D—lining on the front wall of the hopper, E—crown of the hopper, F—running rail of the feeder trough, G—feeder trough, H—lining on the back wall of the hopper.

In the device, copper ore passes by the force of gravity from the bunker to the hopper, which narrows in the direction of the material movement and which is limited on the four sides by inclined walls. The walls include two side walls C, a front wall D, and a back wall H. The surfaces of the walls in the hopper are lined with wear-resistant steel. A feeder trough G is installed in the bottom of the hopper. The trough is mounted on a reciprocating carriage powered by a crank mechanism. The bottom of the trough, which receives the ore, is also covered with a steel lining A. The trough is supported by a carriage with rails F, which in turn are supported on both sides with steel wheelsets typical of rail transportation systems. The trough together with the ore moves with respect to the hopper walls and this fact necessitates the use of vertical sealings B. The hopper is limited on the upper side with four vertical walls which form a crown E. The most significant maintenance problems result from permanent deformations (geometry changes) of the receiving bin due to the pressure from the ore mass accumulated in the bunkers. These deformations may lead to bunker downtime. The negative effects also include blockages in the hopper and in the feeder carriage (see Figure 3). Blockages necessitate longer downtime, as the repairs are potentially hazardous for the technicians who service these devices. The costs of such failure-related downtime events increase due to the need to perform appropriate preparation procedures, which are intended to ensure safety and consist in the removal of loose rock overhangs within the bunker prior to the service works in the receiving bin. Such procedures are performed by mining rescue teams, often with the use of blasting techniques.

From the perspective of load distribution, the stability of the bunker structure is another important issue, which includes an analysis of the loads on the basis of standardized calculations and numerical modeling, such as those presented in the example of the Boleslaw mine in [10].

Figure 3. Blockage in the feeder carriage.

Long operation in difficult conditions and constant movement of the ore also cause a number of problems related to the abrasion of some structural elements, such as linings. Publication [11] describes typical damage to the elements of retention bunkers operated in a hard coal mine, such as failures of bunker components or abrasive wear of linings, and offers methods for the evaluation of their technical condition. The phenomenon of abrasive wear on the surfaces due to contact between moving ore masses is a problem also in the case of other technical appliances. The authors of publication [12] discuss the results of abrasive wear simulations performed using the Archard model, which was implemented in the evaluation of the phenomena observed during the loading of a haulage truck. Publication [13], on the other hand, presents an integration of the finite element method (FEM) with the discrete element method (DEM) for the purpose of designing load-carrying bodies in self-propelled haulage trucks. A full-scale combination of numerical modeling and simulation tests with verified experiments and tests is a complex approach to optimization research, as demonstrated in [14,15] in an example of underground transfer points. This type of research provided information on the already mentioned flow characteristics of the ore, but also aided the definition of the scope of actual static and dynamic loads which cause damage to the receiving bins.

In the case of the Polish copper ore mine discussed in this article, additional attention should be paid to the fact that the ore extracted in different regions of the mine has different physical and mechanical properties [16]. Rock hardness definitely influences the rate of the abrasive processes which occur on steel surfaces. The majority of current research into the movement of ore and its contact with steel surfaces is performed at KGHM PM S.A. with the use of FEM tools [17,18]. The modeling of the ore flow, especially in the case when the flow is non-uniform, requires the parameters of both the contacting materials and the material interactions to be precisely identified. This information has a significant influence on the effectiveness of the device optimization activities supported by the results obtained from numerical tools [19,20]. Publication [15], on the other hand, demonstrates that the use of DEM allows a reconstruction of the phenomena which occur when the ore passes through the bunker, and as a result offers a possibility to locate blockages and find information on their reasons.

In reference to the above discussed issues, the integration of FEM and DEM may be used for comprehensive designing of an optimized construction of receiving bins while taking into account material flow. However, the modeling should be preceded by recognition of typical damage to the elements of retention bunkers and its analysis with special attention to type of specific mining conditions. Therefore, the design of receiving bins in KGHMs mines needs basic and fundamental research into the operating conditions and types of observed failures of bins, as their operation confirms that they are particularly prone to failure. It should be noted that problems connected to receiving bins in the analyzed mine are solved only on an ad hoc basis. Currently, neither is there a comprehensive approach nor developed methods to assess their technical condition. Regardless of rock properties and exploitation field characteristics, the shape and dimensions of retention bunkers; receiving bins are installed the same way without any analyses or simulation calculations. The only element which is calculated is a supporting structure of the receiving bin, while the whole process should include analyses of optimal bins geometry as well as optimal steel linings' thickness and properties.

Because the article is considered as an introduction to the presented issue, damage to the structure of bins, as well as the wear and tear on the steel surfaces of the bunker elements due to the contact with the ore, will be discussed and analyzed in the following parts. Initially, a qualitative evaluation of the observed failures was performed by identifying changes in the structure and surface of the materials. This was followed by a quantitative failure evaluation based on data describing repairs for the analyzed bunker population.

2. Materials and Methods

The properties of the surfaces of materials change during their work due to both the work itself and the working conditions. The operation of a device is accompanied by a number of degradation processes, which frequently entail material losses, and these result in a reduced cross-section of the element and subsequently in the loss of its strength properties. During the transfer of bulk materials, wear is observed mostly as a result of impacts and abrasion in situations when two bodies have different relative speeds. Research into and analyses of the operation of transfer devices indicate that the speed of the material has the greatest impact on its wear processes [21]. Among numerous wear evaluation methods provided in the literature [22], the Burwell classification seems useful, distinguishing the following types of wear: adhesive, abrasive, corrosive, surface fatigue mechanisms, and minor wear types.

The qualitative failure evaluation was performed on the basis of observations and photographic documentation. A visual inspection of the technical condition of individual elements and an inventory list of the observed surface changes allowed the identification of typical damage in the receiving bin and in the feeder carriage. The quantitative analysis of damage occurring in the operation of ore retention bunkers was performed on the basis of data collected and pre-processed for a 30-month period (between January 2018 and June 2020). The data concerned 41 receiving bins installed in 15 bunkers located in six units of a copper ore mine selected for the research. It provides information about the repairs and replacement of receiving bins' elements including the date, work shift, the name of mine unit, and the name of the retention bunker including number of receiving bins. The essential part of the research is that the analysis bases on the assumption that repair data reflects bunker failures. Furthermore, because the analysis is carried out for bunkers within the transportation system of the mine, Figure 4 schematically shows the locations of the bunkers (1–15). In the figure, blue color indicates smaller bunkers of a capacity up to 1000 Mg, and yellow color indicates larger bunkers capable of storing more than 1000 Mg of copper ore. Additionally, colors of belt conveyors define mining units (I–VI) and show the ore-flow routes.

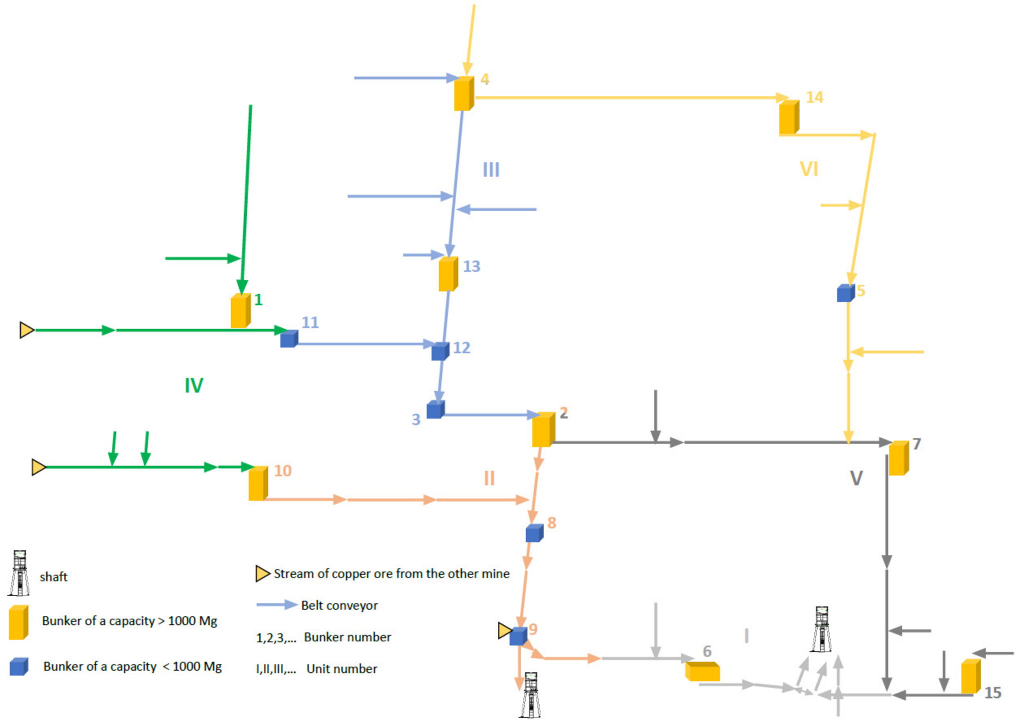


Figure 4. Locations of the bunkers within the transportation system of the mine.

The qualitative evaluation of the bunker failure rate was performed with the use of the suggested **number-based failure indicator (failure indicator)** which describes the number of repairs per one receiving bin and with the **mass indicator**, which describes the frequency of a particular type of failure in relation to the mass quantity of the flowing ore. The above indicators allow for a different number of receiving bins installed under the analyzed bunkers.

$$number - based\ failure\ indicator = \frac{number\ of\ repairs}{number\ of\ receiving\ bins} \tag{1}$$

$$mass\ indicator = \frac{mass\ of\ the\ flowing\ ore}{number\ of\ receiving\ bins} \tag{2}$$

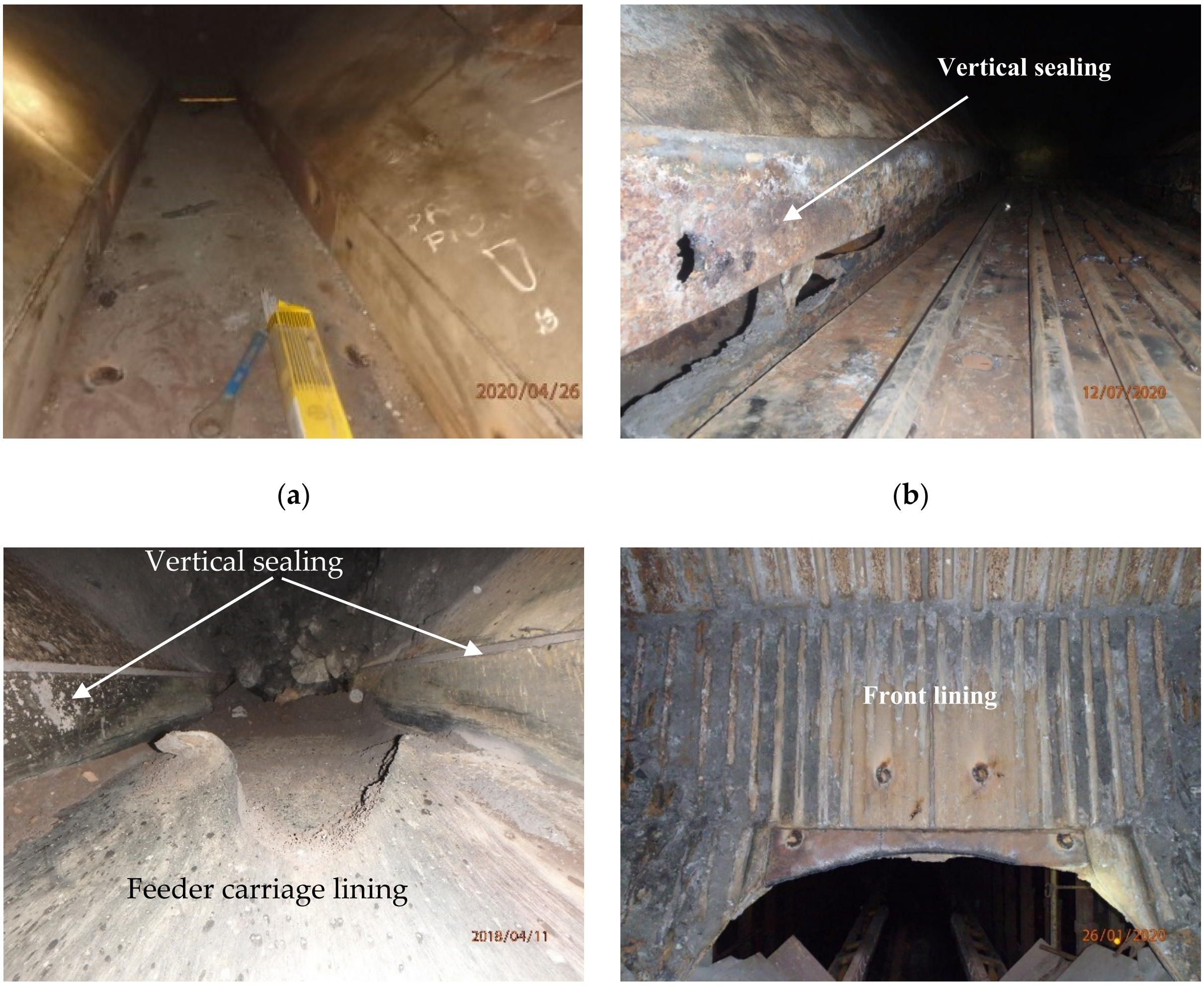
To calculate mass indicator value, total masses of ore passing through individual bunkers over the analyzed time period were identified on the basis of measurement data provided by scales installed in the conveyor belts. Strain gauges installed in the scales allow measurements of the instantaneous mass acting on a particular idler set. The data include instantaneous linear speed of the belt. The product of the instantaneous mass and of the instantaneous linear speed is equal to the instantaneous capacity of the belt conveyor, and if this value is integrated over a defined time period, the result is the total transported mass over a period of time. Publication [23] indicates that the instantaneous capacity measurement error is ±0.25%.

3. Results and Discussion

3.1. Qualitative Analysis

The most frequent changes observed for the surface structures and properties included abrasive and corrosive wear. Figure 5 shows an example of abrasive wear demonstrated in the removed upper layer of the surface of the steel element during contact with the transported material. This is the most frequent failure type found in ore transfer devices [24]. In order to enable the comparison of the wear level of steel elements in the receiving bin, the technical condition of these elements after repairs has been shown in Figure 5a. Further,

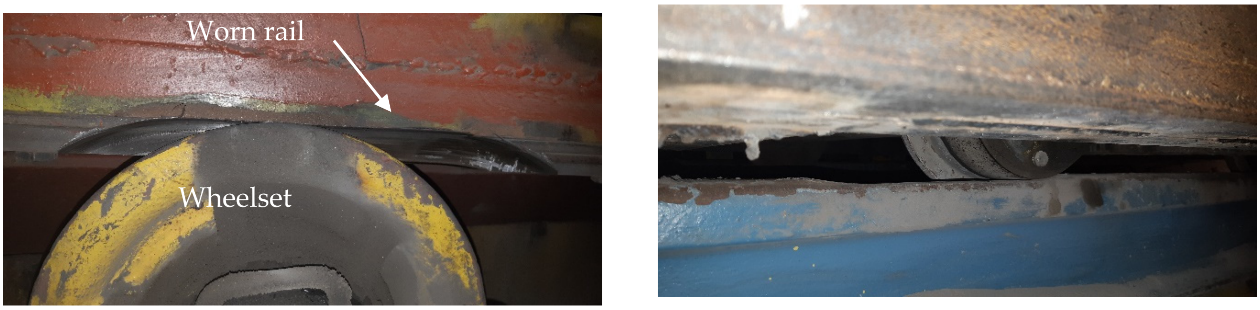
Figure 5b–d show the abrasive wear on the vertical sealings, the lining of the carriage trough and the lining of the front wall of the hopper, respectively. The movement of ore against the working device caused a drastic decrease in the thickness of the steel sheet, until it was perforated (Figure 5b,c) and as a result partially bent, which caused an ore blockage in the receiving bin (Figure 5c). In such case, repairs of the receiving bin consist in the replacement of linings made of ordinary quality structural steel sheets 20 mm in thickness. The use of linings allows only those elements to be replaced which are subjected to the most intensive wear, without the necessity to disassemble the entire device. This procedure significantly accelerates the replacement of worn elements and reduces the operating costs.



(**a**) (**b**) (**c**) (**d**)

Figure 5. Examples of abrasive wear observed in the receiving bin: (**a**) newly installed steel elements of the bin, (**b**) abrasive wear on the vertical sealings, (**c**) abrasive wear on the feeder carriage lining, (**d**) wear on the front lining of the hopper.

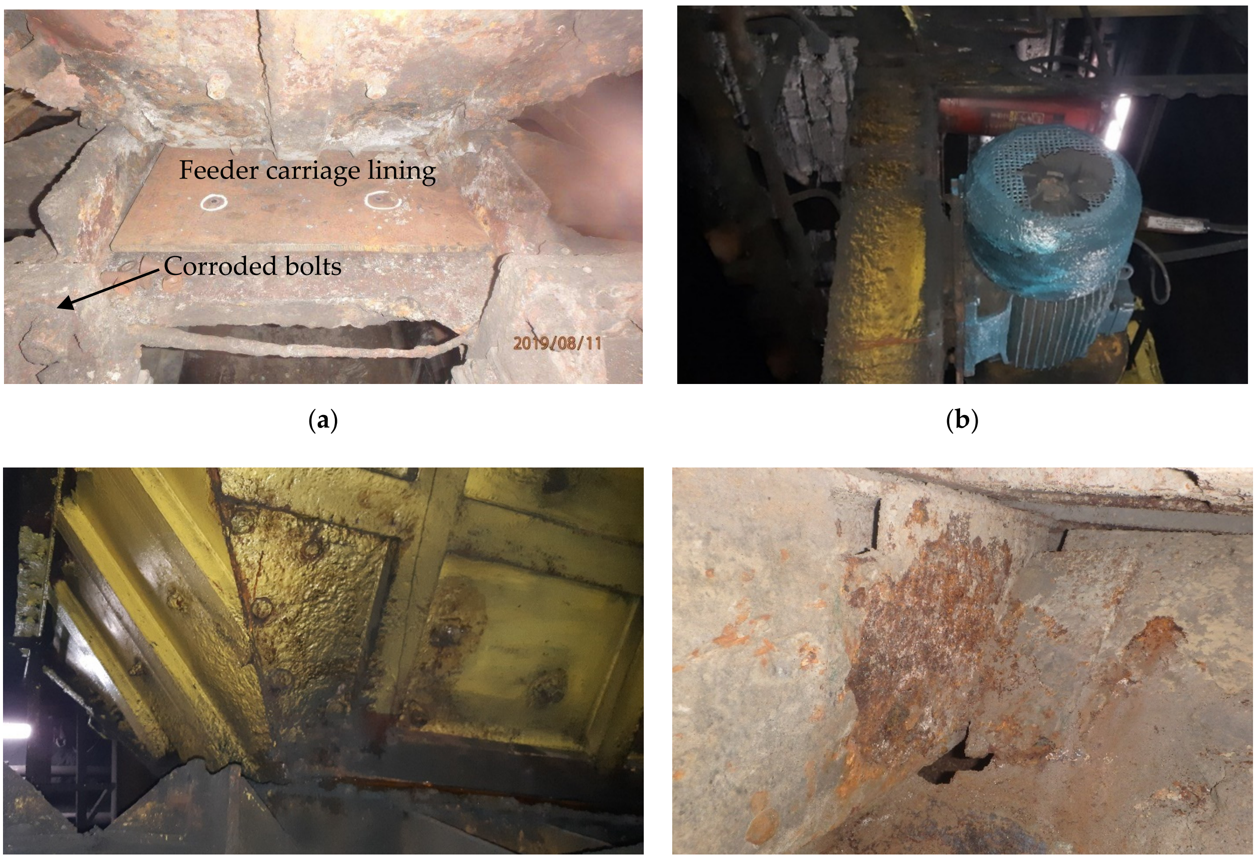
Figure 6 shows the wear on the running rail of the feeder carriage. In this case, the wear is due to rolling friction [24]. The rail, together with the entire feeder trough, reciprocates on the wheelsets. In the case of this element, the rate of the wear process is influenced not only by the aggressive operating condition, but also the pressure force exerted on the wheelsets by the trough. The wheelsets are typical for rail transportation systems. Therefore, they can be modeled and their behavior can be simulated on the basis of the solutions from the railway industry, which follow the Archard model [25].



(**a**) (**b**)

Figure 6. Example of the wear on the wheelset: (**a**) abrasive wear on the running rail in contact with the wheelset, (**b**) material loss in the running rail.

A bunker failure can also be due to corrosive wear, caused by subjecting the steel elements to a specific, highly humid microclimate, and to highly mineralized underground waters [24]. Figure 7a–d show examples of corrosive wear on the elements of the bunker. Figure 7a is a view of the back part of the hopper shown from the side of the feeder motor. The character of this surface damage is well visible in contrast with the newly installed lining of the feeder carriage. Corrosion which develops so fast causes the technical condition of the structure to be difficult to evaluate, and the corroded parts of the bolted joints are not easily replaced, thus extending the potential repair time.



(**a**) (**b**)

(**c**) (**d**)

Figure 7. Corrosive wear: (**a**) on the back wall of the receiving bin and on the feeder carriage, (**b**) on the motor of the feeder trough, (**c**) on the hopper, (**d**) on the linings in the bin.

The rate of the corrosion processes is also influenced by intensive venting of the excavations with forced oxygen supply (a normal mine ventilation process). Importantly, the majority of steel structures in mines is made of low-alloy structural steel. Despite additional anti-corrosion protection means (protective coatings), the corrosion advances at a significant rate [26].

Extreme loads from the mass of the transported material also result in a type of damage described as deformation wear. The changing geometry of the structural elements in the bin results in a number of downtime situations, as the entire device must be stopped to replace the worn elements or to solidify the structure.

3.2. *Quantitative Analysis*

The quantitative analysis was performed in two stages. In the first stage, a preliminary analysis of the basic repair-related data was performed in order to limit the area for further analyses. In the second stage, a detailed evaluation of the bin failure rate was performed on the basis of the determined indicators.

3.2.1. Preliminary Analysis

Over the analyzed period, a total of 147 service works were performed, consisting of 204 repairs. The preparatory and service works required 979 workers, and this number does not include rescue workers, who participate in the preparatory works. The most common repairs included replacements of the vertical sealings B, replacements of the through lining A, and replacements of hopper linings C. Less frequent repairs were required in the case of the feeder trough G, the running rails F and the lining on the back wall of the hopper H. The number of repairs made to individual elements is presented in Figure 8.

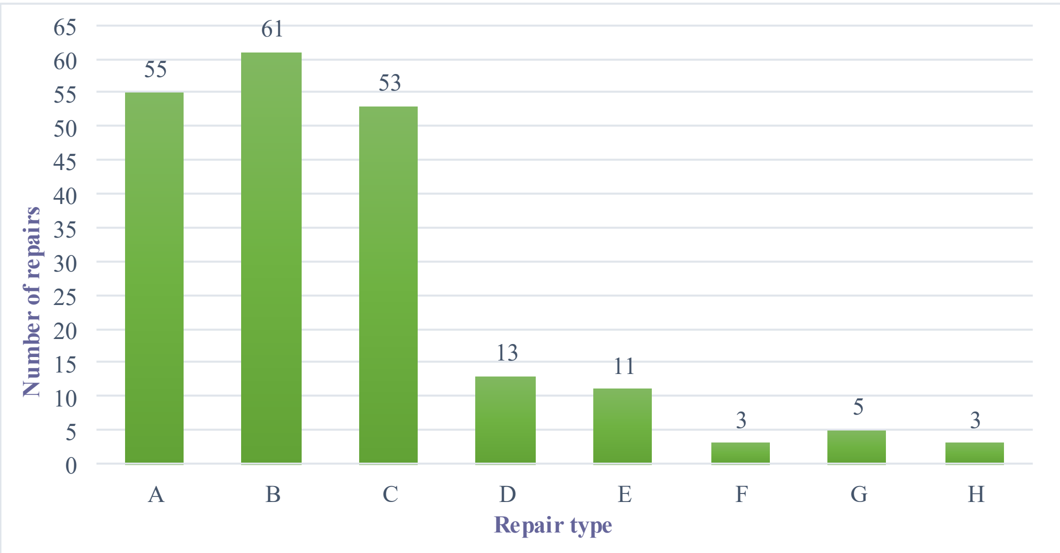


Figure 8. Total number of the A-H elements repairs.

Based on Figure 9 which presents what type of repair and how many of them were done on the specific shift, it is concluded that in the majority of cases, the replacement of the feeder trough linings A was accompanied by the replacement of the vertical sealings B, as dictated by the design of the receiving bin and the operation of the device. Moreover, this procedure is frequently preceded by the ripping of rock overhangs inside the bunker. Also, on multiple occasions the repairs of A and B were accompanied by the replacement of the hopper lining C. For this reason, similar wear rates of the three elements (A, B, and C) would represent an optimal scenario. To identify relations between A, B, and C repairs association rule mining was implemented. Results of metrics for different association rules are presented in Table 1.

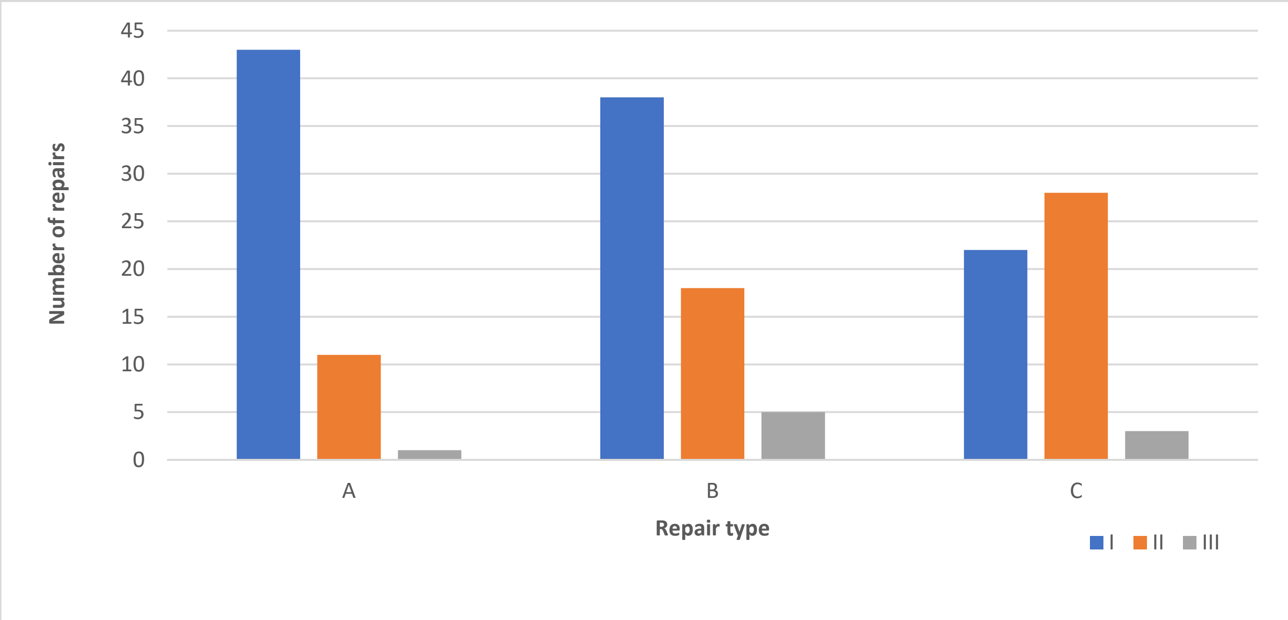


Figure 9. Repairs of A, B and C elements performed over the shifts (I, II, III).

Table 1. Results of association rule.

Rule \ Metrics	Support	Confidence	Lift
If A then B	24.49%	65.45%	1.58
If A then B and C	31.03%	52.94%	1.49

For rule if A then B, support value indicates that around 25% of analyzed repairs involved A and B element repair the same day in specific bunker. The confidence value means that out of all A repairs, around 65% of the repairs also contained B element repair. The last metric shows that repair of B element is 1.58 times more likely when A repair is done. If A then B and C are considered, the support value shows that 31% of analyzed repairs contained A, B, and C repairs the same day for specific bunkers. The confidence value means that out of all A repairs, nearly 53% of the repairs also contain B and C repair. Finally, the lift indicates that B and C repair is 1.49 times more likely to be done while A repair is carried out.

In view of above results, A, B, and C elements are crucial for bins maintenance from mining units management perspective. The repair or replacement of mentioned elements generates a considerable part of the cost, since more mining workers are needed than for regular repair. Therefore, the total number of repairs of A, B, and C elements were calculated and are presented in Table 2. Because results show that the highest number of works was done in II and III units, histograms of time between A, B, and C elements repair was prepared and showed in Figures 10 and 11.

Table 2. Sum of A, B, and C elements repair in I–VI mining units.

Mining Unit	Sum of Repairs
I	19
II	76
III	35
IV	15
V	15
VI	9

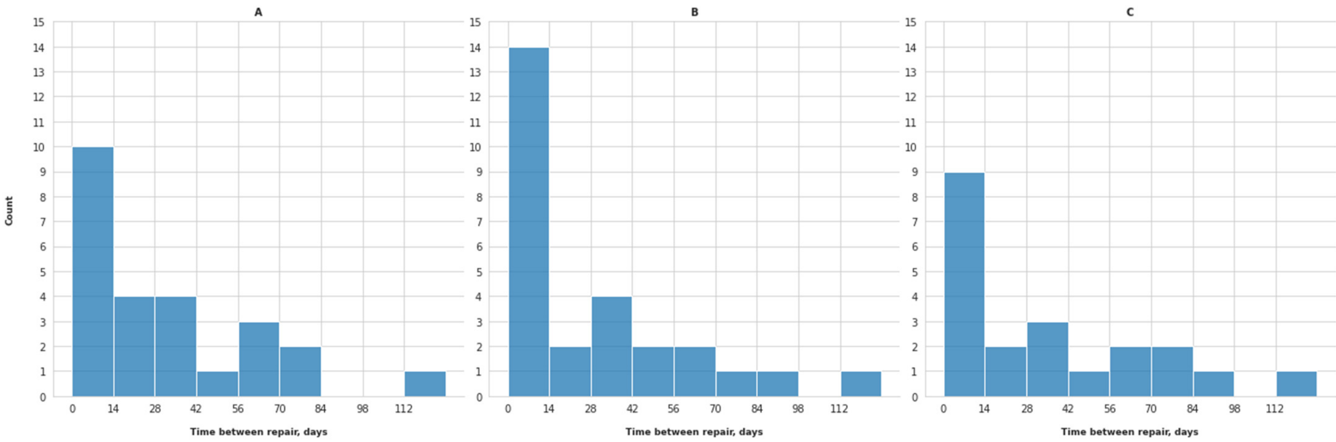


Figure 10. Histograms of time between repairs of (**A**–**C**) elements in mining unit named II.

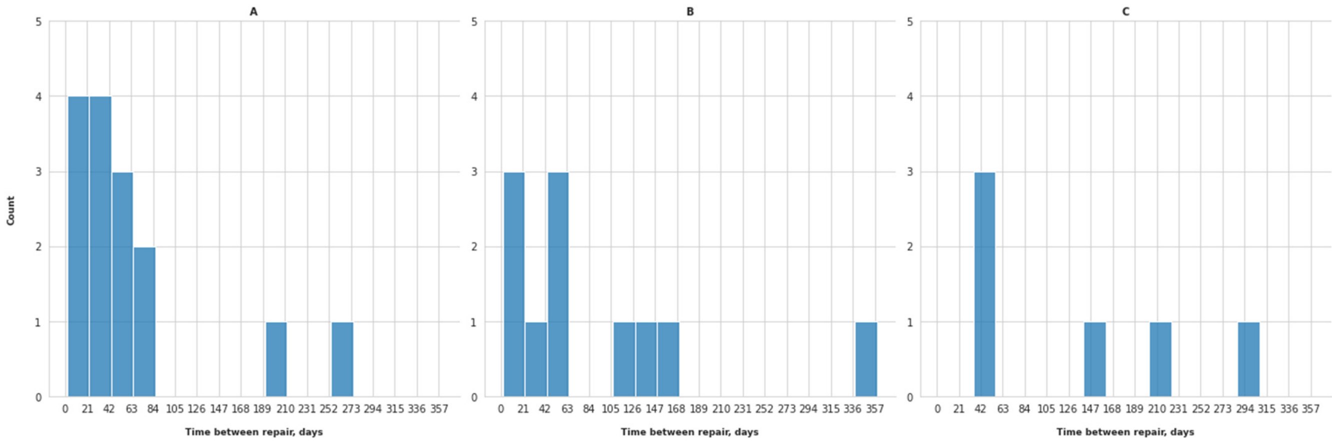


Figure 11. Histograms of time between repairs of (**A**–**C**) elements in mining unit named III.

The mean time between A, B, and C elements repair in II mining unit equals 31, 29, 35 days, respectively. In comparison, for III mining unit values increase to 65, 88, and 135 days, respectively. The difference in achieved results comes from the location of the mining unit in the transportation system and amount of transported material.

3.2.2. Detailed Analysis

The main objective of the analysis was to identify bunkers in which the receiving bins are most prone to failure. Therefore, durability analysis requires the receiving bins to be assigned to the individual bunkers. Figure 4 shows the locations of bunkers (1–15) within the structure of the ore transportation system, along with the indicated mining units (I–VI) and the ore-flow routes. Table 3 lists the repairs performed for bunkers 1–15 over the analyzed 30-month period. The last column in Table 3 contains number-based failure indicators per single receiving bin. The significant range of this indicator (1–17) results from different operating conditions, and justifies the durability analyses of the bin elements with respect to a particular receiving bin.

The number-based failure indicator provides information on the frequency of repairs for the entire receiving bin. From the perspective of managing repairs and maintenance, or planning modifications, it is very important to know which elements of the receiving bin and in which bin become most frequently worn. Such analyses were possible owing to the listing of repairs and replacements by individual bin elements (in accordance with Figure 2). Over the investigated period, the majority of service works, i.e., 28, 23, and 22, were performed on bins 2, 10, 9, and 6, respectively (Figure 12). These bins have a capacity exceeding 1000 Mg of copper ore. The trough linings A were most frequently replaced in bunker 10, the vertical sealings B—in bunker 6, linings in the hopper C—in bunker 8, and front linings in the hopper D—in bunker 13. This is due to the operating characteristics of the particular type of the receiving bin. The design of the receiving bin determines the flow of the ore through its front part, and therefore the element A becomes more worn up to half its length. The case is similar for the elements B and C. The ore also passes down the front wall D towards the discharge opening. Therefore, the elements A, B, C, and D are most prone to abrasive wear. Repairs of the elements E, F, and G were sporadic. The lining on the back wall of the hopper H was replaced only three times in bunker 11.

Table 3. Number of repairs in retention bunkers 1–15.

Bunker No.	**Replacement of Feeder trough Linings**	**Replacement of Vertical Sealings**	**Replacement of Hopper Linings**	**Replacement of Front Linings in the Hopper**	**Service Works on the Crown of the Hopper**	**Replacement of Running Rails in the Feeder**	**Replacement of Feeder trough**	**Replacement of Back Linings in the Hopper**	**Total**	**Number of Bins**	**Failure Indicator**
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**			
1	2	4	3	2	0	0	0	0	11	2	5.50
2	7	8	7	0	5	0	1	0	28	2	14.00
3	3	2	5	3	2	2	0	0	17	1	17.00
4	3	3	2	0	0	0	1	0	9	3	3.00
5	0	1	4	0	0	0	1	0	6	1	6.00
6	4	9	6	1	1	0	1	0	22	8	2.75
7	3	3	3	0	0	0	0	0	9	8	1.13
8	6	7	8	0	0	0	0	0	21	2	10.50
9	7	8	4	0	3	0	0	0	22	2	11.00
10	8	7	6	1	0	1	0	0	23	2	11.50
11	3	0	0	1	0	0	0	3	7	2	3.50
12	2	2	0	0	0	0	0	0	4	2	2.00
13	5	5	1	5	0	0	1	0	17	3	5.67
14	0	0	2	0	0	0	0	0	2	2	1.00
15	2	2	2	0	0	0	0	0	6	1	6.00

Analyses of the number of individual replacements together with the identified number-based failure indicator suggest that bunkers 3, 2, and 10 are most prone to failure. They show the highest number of repairs per one receiving bin. Importantly, the above-mentioned bunkers are located in the mining units in which the main haulage conveyors are also situated, and these have the highest daily capacities.

The smallest value of the number-based failure indicator is observed for bunkers 7 and 14. In the case of bunker 14, this fact is due to its location in the transportation system, and the resulting smaller amount of the ore transported on the unit conveyors. Importantly, despite one of the highest amounts of the passing ore, bunker 7 showed a very low failure indicator, which directly results from the fact that it has as many as eight receiving bins.

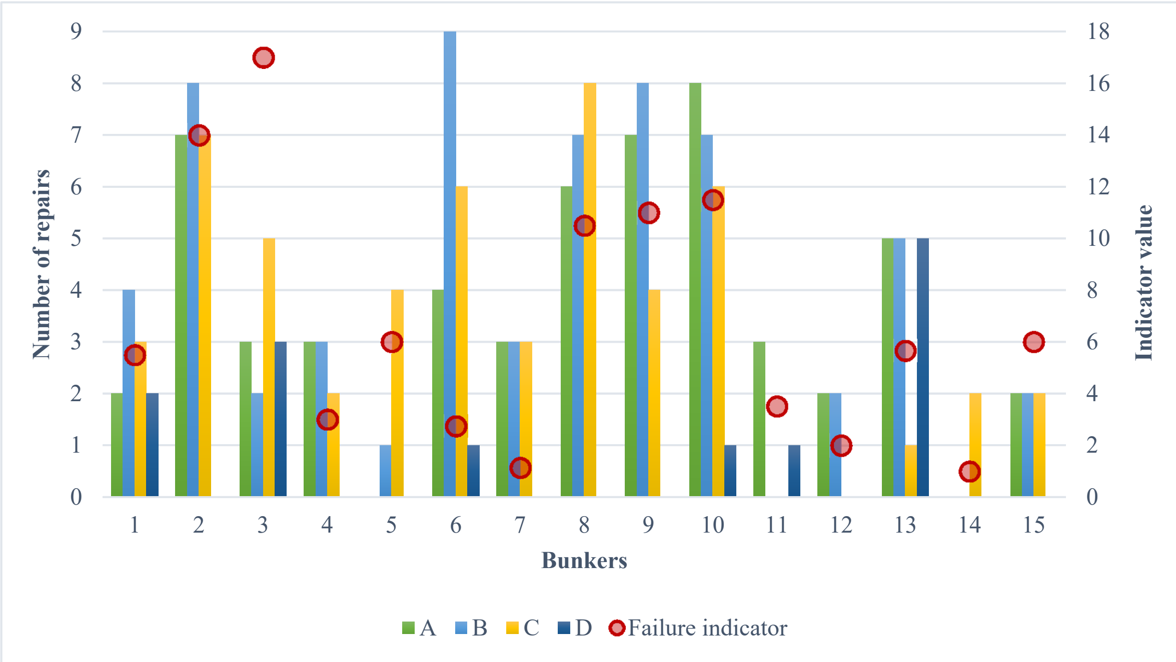


Figure 12. Number of repairs for the elements A, B, C, and D, and the daily failure indicator for the 15 receiving bins.

An additional analysis, which was conducted separately for each of the mining units indicated in Figure 4, focused on the service works performed in order to repair the operating failures. The greatest number of service works on the receiving bin was performed in unit II, which receives the cumulative stream of ore transported on the main haulage conveyors (Figure 13). Unit IV also showed a significant number of repairs per one bin. This case can also be accounted for by the amount of the transported ore mass, but most importantly by a significantly variable lithology and high moisture content (Figure 14). Importantly, very large amounts of ore pass through the bunker. The explanation in this case seems to lie in the lithology or high moisture content of the transported ore. The third analyzed unit is unit III, whose bunkers are partially located along the main conveyors, albeit the number of bins in the bunkers located in this unit is between one and three.

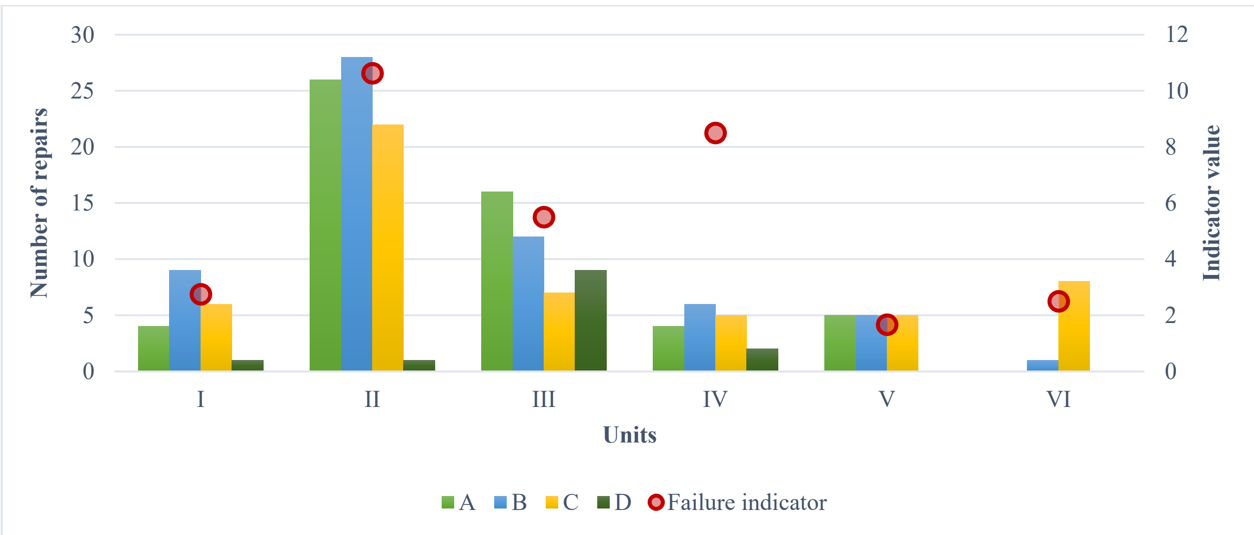


Figure 13. Number of repairs for the elements A, B, C, and D, and the daily failure indicator for the individual mining units in the mine.

(**a**) (**b**) (**c**)

Figure 14. Different types of the transported ore: (**a**) large rock lumps, (**b**) dry ore, (**c**) moist ore.

The analysis demonstrates that the mass of the ore passing through a bunker has a significant influence on its failure rate, and therefore a mass indicator was proposed in further research in order to describe what mass of ore determines the occurrence of a particular failure type in the elements A–D. For this purpose, total masses of ore passing through individual bunkers over the analyzed time period and number of repairs per bunker were calculated. The results of the measurements performed as part of this research are shown in Table 4 and in Figure 15.

Table 4. Values of the mass indicator in relation to the amount of the transported ore.

Bunker No.	**Replacement of Feeder trough Linings**	**Replacement of Vertical Sealings**	**Replacement of Hopper Linings**	**Replacement of Front Linings in the Hopper**	**Total Mass of Transported Ore, Thousands Mg**	**Mass Indicator A, Thousands Mg**	**Mass Indicator B, Thousands Mg**	**Mass Indicator C, Thousands Mg**	**Mass Indicator D, Thousands Mg**
	A	**B**	**C**	**D**					
1	2	4	3	2	-	-	-	-	-
2	7	8	7	0	9436	1348	1179	1348	
3	3	2	5	3	9436	3145	4718	1887	3145
4	3	3	2	0	-	-	-	-	
5	0	1	4	0	6290		6290	1573	
6	4	9	6	1	12,653	3163	1406	2109	12,653
7	3	3	3	0	10,720	3573	3573	3573	
8	6	7	8	0	10,729	1788	1533	1341	
9	7	8	4	0	16,396	2342	2050	4099	
10	8	7	6	1	5723	715	818	954	5723
11	3	0	0	1	-	-			
12	2	2	0	0	-	-	-		
13	5	5	1	5	4946	989	989	4946	989
14	0	0	2	0	4483	-		2242	
15	2	2	2	0	2421	1211	1211	1211	

Empty cells in the table indicate that no data are available.

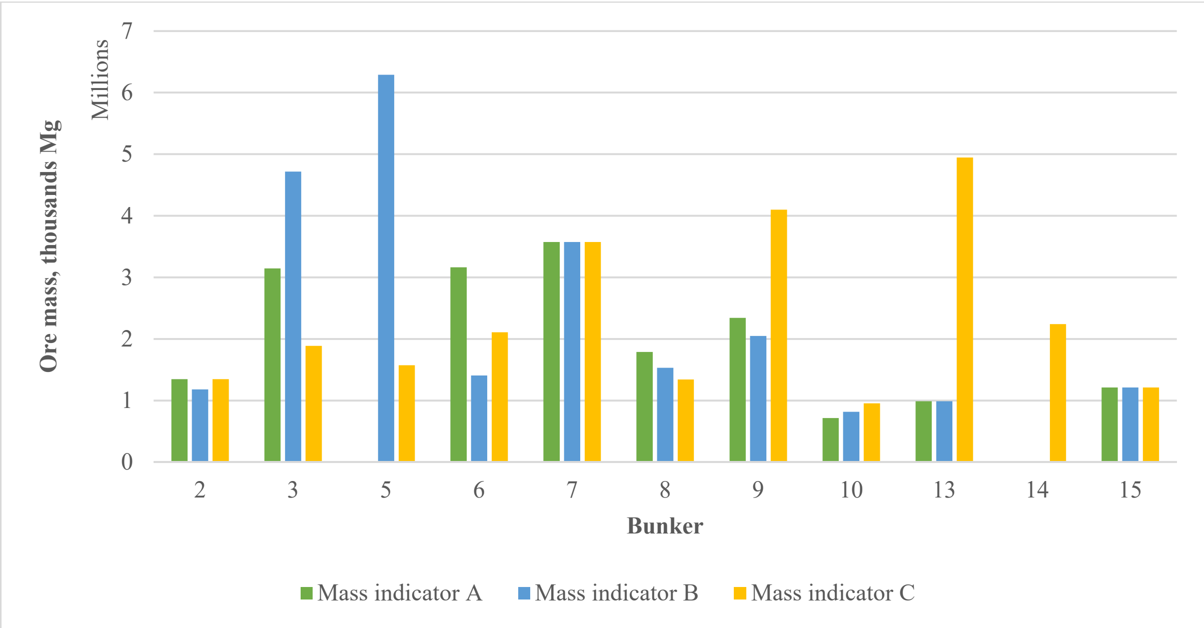


Figure 15. Mass indicator values for the elements A, B, C of the analyzed bunkers.

The greatest amounts of ore passed through bunker 9 (unit II), 6 (unit I), 7 (unit V), and 8 (unit II). Taking into account repairs for the elements A, B, C, and D, the indicators were calculated respectively for each of the bunkers. The results provided in the graph do not include the indicator for the element D, as its failures were occasional.

The mass indicators demonstrate that in bunkers 2, 7, 8, 10, and 15 the elements A, B, and C undergo wear at a comparable speed, but with intensity different for each bunker. Failures of the vertical sealings B dominate in bunkers 3 and 5, while in bunkers 9, 13, and 14 the majority of failures (critical wear) occur in the case of linings on the side walls of the hopper C. The most frequent repairs were performed for bunker 10—every 0.8 million Mg, on average. In the case of bunkers 2, 7, 8, and 15 the repair frequency is every 1.3 million Mg, 3.6 million Mg, 1.5 million Mg, and 1.2 million Mg, respectively. In bunkers 3 and 5, the vertical sealings are replaced rarely in comparison to other repairs (on average every 4.7 million Mg and 6.3 million Mg). A different scope of repairs is observed in the case of bunkers 9, 13, and 14, in which the linings on the hopper walls C are replaced at the greatest intensity, every 4.1 million Mg, 4.9 million Mg, and 2.2. million Mg, respectively. In general, the linings in the feeder trough A were replaced in all bunkers after approximately 2.0 million Mg of ore had passed through it, the vertical sealings B were replaced after 2.4 million Mg, and the hopper wall linings C—after 2.3 million Mg.

4. Conclusions

The analysis of wear levels was performed on the basis of data from 41 copper ore receiving bins installed in 15 retention bunkers. The results confirm previous observations which suggest that the character of the failures and the degradation processes are largely influenced by the bunker operating conditions and by the varying lithology of the transported material (copper ore). The varying physical and mechanical properties of copper ore and the varying parameters of its flow cause the pressures exerted on the hopper walls to vary, and this may be identified as the most significant reason behind the intensive abrasive wear.

Varying parameters of the transported ore and the specific character of the mining operation do not allow the identification of the influence of the grain size, moisture content, and lithology on the process and on the degree of wear on the elements of the receiving bin. Calculations can only be made with the use of quantitative measures related to average parameters of copper ore. Such measures of failure rates for receiving bins in retention bunkers may include a number-based failure indicator and the indicator per unit mass of the transported copper ore.

The analysis of the failures demonstrated that the element most prone to wear and tear is the lining in the bottom of the feeder trough, designated in Figure 2 with symbol A. This element is subject to loads from the falling lumps of ore, while the trough reciprocates simultaneously. The cyclically reversing direction of motion is the obvious reason behind the accelerated wear on this element. Other elements prone to wear include the vertical sealings designated with symbol B, which operate in a zone affected by great speed differences. The movement of ore along the side walls of the hopper at an increasing pressure is caused by the narrowing of the space inside and results in accelerated wear on the lining, i.e., the element C. The failure rate of the elements A, B, and C allows a conclusion that accelerated abrasive wear occurs in areas where relative speed differences are observed in combination with pressure or impact-related loads. Recommendations include the use of appropriate materials, with properties and geometries which would ensure not only increased durability but also similar wear rates of individual elements.

Based on the number of the observed failures, the design of the receiving bin was demonstrated not to be optimal for the transferring of the increased loads resulting from the current output potential of the mine, and the amount of the transported ore over a unit of time significantly affects the frequency of service works. The identified types of damage, along with the failure rates, indicate directions for the required modernization efforts. The obtained results may be used to verify simulation models. Further stages of this research include using the FEM and DEM tools in order to develop a model simulating the flow of ore through the bunker. The final result of the research will comprise a set of complex design guidelines for new solutions based on local operating conditions.

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References

1. Zintegrowany Raport KGHM Polska Miedź S.A. i Grupy Kapitałowej KGHM Polska Miedź S.A. za 2019 rok. 2020. Available online: file:///C:/Users/MDPI/AppData/Local/Temp/kghm_raport_zintegrowany_2019.pdf (accessed on 17 April 2021)
2. Fedorko, G.; Molnar, V.; Marasova, D.; Grincova, A.; Dovica, M.; Zivcak, J.; Toth, T.; Husakova, N. Failure analysis of belt conveyor damage caused by the falling material. Part I: Experimental measurements and regression models. *Eng. Fail. Anal.* **2014**, *36*, 30–38. [CrossRef]
3. Andrejiova, M.; Grincova, A.; Marasova, D. Monitoring dynamic loading of conveyer belts by measuring local peak impact forces. *Meas. J. Int. Meas. Confed.* **2020**, *158*, 107690. [CrossRef]
4. Stacey, T.R.; Swart, A.H. *Investigation into Drawpoints, Tips, Orepasses and Chutes*; 1997. Available online: https://www.mhsc.org.za/sites/default/files/public/research_documents/OTH%20303%20Report%20Vol%201.pdf (accessed on 17 April 2021)
5. Baral, S.C.; Daganzo, C.; Hood, M. Optimum bunker size and location in underground coal mine conveyor systems. *Int. J. Min. Geol. Eng.* **1987**, *5*, 391–404. [CrossRef]
6. Hastie, D. *Belt Conveyer Transfers: Quantifying and Modelling Mechanisms of Particle Flow*; University of Wollongong: Wollongong, Australia, 2010.
7. Koivisto, M. *Ore Pass Design and Placement*; Delft University of Technology: Delft, The Netherlands, 2017.

8. Esmaieli, K.; Hadjigeorgiou, J. Selecting ore pass-finger raise configurations in underground mines. *Rock Mech. Rock Eng.* **2011**, *44*, 291–303. [CrossRef]
9. Bunker, K.; Campbell, A.; O'Toole, D.; Penney, A. Guidelines for orepass design in a sublevel cave mine. In *Proceedings of the International Seminar on Design Methods in Underground Mining*; Potvin, Y., Ed.; Australian Centre for Geomechanics: Perth, Australia, 2015.
10. Wiewiórka, D.; Sepiał, J. *Analysis of Storage Bunker Stability in the Region of the Shaft "Chrobry" ZGH Bolesław*; Wydawnictwa AGH: Kraków, Poland, 2010.
11. Bock, S.; Rotkegel, M.; Szymała, J. Underground coal storage bunkers. Typical damages and methods of assessment of technical condition. *Przegląd Górniczy* **2016**, *27*, 39–51.
12. Rojas, E.; Vergara, V.; Soto, R. Case study: Discrete element modeling of wear in mining hoppers. *Wear* **2019**, *430–431*, 120–125. [CrossRef]
13. Forsström, D.; Jonsén, P. Calibration and validation of a large scale abrasive wear model by coupling DEM-FEM: Local failure prediction from abrasive wear of tipper bodies during unloading of granular material. *Eng. Fail. Anal.* **2016**, *66*, 274–283. [CrossRef]
14. Beus, M.J.; Iverson, S.R.; Stewart, B.M. Design Analysis Of Underground Mine Ore Passes: Current Research Approaches. In Proceedings of the The 100th CIM Conference, Montreal, QC, Canada, 3–7 May 1998.
15. Nazeri, H.; Mustoe, G.G.W.; Rozgonyi, T.G.; Wienecke, T.J. Implementation of a discrete element methodology for the modeling of gravity flow of ore in ore passes. In *Proceedings of the North American Rock Mechanics symposium*; University of Toronto: Toronto, ON, Canada, 2002.
16. Bardziński, P.J.; Doroszuk, B.; Kawalec, W.; Król, R. Investigation of Grain Size Distribution of Conveyed Copper Ore for Modelling Ore Flow through a Bunker. In *Proceedings of the IOP Conference Series: Earth and Environmental Science*; IOP: London, UK, 2020.
17. Ilic, D.; Roberts, A.; Wheeler, C.; Katterfeld, A. Modelling bulk solid flow interactions in transfer chutes: Shearing flow. *Powder Technol.* **2019**, *354*, 30–44. [CrossRef]
18. Ilic, D.; Roberts, A.; Wheeler, C. Modelling bulk solid interactions in transfer chutes: Accelerated flow. *Chem. Eng. Sci.* **2019**, *209*, 115197. [CrossRef]
19. Walker, P.; Kawalec, W.; Król, R. Application of the discrete element method (DEM) for simulation of the ore flow inside the shaft ore bunker in the underground copper ore mine. In *Proceedings of the Advances in Intelligent Systems and Computing*; Springer: Berlin/Heidelberg, Germany, 2019; Volume 835, pp. 633–644.
20. Bardzinski, P.J.; Walker, P.; Krol, R.; Kawalec, W. Simulation of random tagged ore flow through the bunker in a belt conveying system. *Int. J. Simul. Model.* **2018**, *17*, 597–608. [CrossRef]
21. Ilic, D.; Hicks, T.J. TOWARDS THE DEVELOPMENT OF DESIGN CRITERIA FOR REDUCED WEAR IN IRON ORE TRANSFERS. In *Proceedings of the ABM Proceedings*; Editora Blucher: São Paulo, Spain, 2016.
22. Varenberg, M. Towards a unified classification of wear. *Friction* **2013**, *1*, 333–340. [CrossRef]
23. Bardzinski, P.J.; Król, R. Quantitive ore assessment for the purpose of simulation of the ore flow distribution in the mine's transport system. *Transp. Przem. iMaszyny Rob.* **2018**, *1*, 2–5. [CrossRef]
24. Dobrzański, A.L.; Dobrzańska-Danilkiewicz, D.A. *Obróbka Powierzchni Materiałów Inżynierskich*; International OCSCO World Press: Gliwice, Poland, 2011; ISBN 83-89728-93-1.
25. Chudzikiewicz, A.; Góra, I. Dynamic properties of railway wheelset with innovative self-lubricating coatings–modeling and concept of simulation analysis. *Pr. Nauk. Politech. Warsz. Transp.* **2017**, *118*, 75–84.
26. Głuszko, M. Problems of anticorrosion protection of steel structures and electro energetic equipment exploited in atmospheric conditions. *Prace Inst. Elektrotechniki* **2008**, *235*, 1–173.