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RISK ASSESSMENT OF FLOODED EQUIPMENT REVITALIZATION ON OPENCAST COAL MINE TAMNAVA-WEST FIELD

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Unprecedented floods in 2014 caused huge consequences on Serbian lignite opencast mines, such as halt of coal production and damages of the mining equipment.

Three equipment revitalization options were urgently assessed to continue with coal production on opencast mine Tamnava-West Field. This paper compares the economic risks of the three investment options for lignite mine Tamnava-West Field mining equipment revitalization, based on this experience and probable risk of a repeated event. The results of the detailed quantitative risk analysis should verify the urgent decision and ranked with a multiple-criteria decision analysis.

Key words*: risk assessment, opencast mine, quantitative analysis, floods, mining equipment, revitalization.*

1. Introduction

The largest producer of coal in the Republic of Serbia is the opencast mine Tamnava-West Field. It has nine continuous systems, from which eight have bucket wheel excavators and one has a bucket chain excavator. According to the provided coal production information, opencast mine Tamnava-West Field is essential for the power generation in the most important thermal power plant and overall energy stability in the country [1].

However, heavy rainfall caused major floods in 2014. All opencast mines were flooded, along with the continuous mining equipment. An expert team had to be assembled quickly to develop a plan for mine rehabilitation and minimizing the negative consequences of the floods. Despite efforts to swiftly return the mine to normal operation, a report from December 2014 shows that the most important power plants TENT (Termoelektrane Nikola Tesla) generated 16,322 GWh of electricity for the Serbian power system in 2014, which is 1,362 GWh less than planned in the year of the flood [2]. The halt of coal mining due to the floods caused a significant delay in coal production. Figure 1 shows that in 2013, coal production was at 14,661,219 tonnes before a significant decrease to 5,965,306 in 2014 due to the temporary delay. It can also be observed that the rehabilitation and equipment revitalization were successful because the mine recovered fast and coal production rose to 11,419,040 tonnes in 2015.

The sudden implementation of the Tamnava-West Field opencast mine rehabilitation plan indicated the need to verify the made decisions and to establish a methodological approach for continuous equipment revitalization risk assessment for production in increasingly complex internal and external mining conditions. A detailed analysis of the revitalization options should be carried out in terms of potential losses, which includes determining the probability and time of failure. In terms of risks, a flood of this magnitude should be considered as an uncontrolled ecological risk.

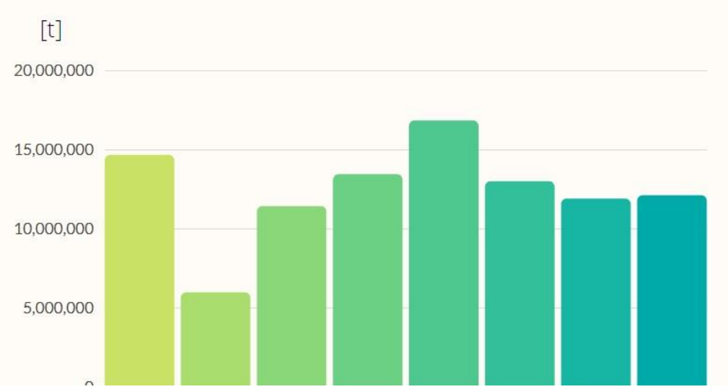

Figure 1: Tamnava-West Field coal production 2013-2020

2. Methodology

2.1. Tamnava-West Field flooded equipment risk analysis

The problem of submerged mining equipment shouldn’t be analyzed only from the economic side of equipment revitalization. The approach to this issue should be multidisciplinary because it’s necessary to take a number of factors into account for the final choice of investment options for mining equipment revitalization. Authors have dealt with the reconstruction, revitalization and maintenance of mining equipment on opencast mines in previous research, as well as the assessment of the level of risk for equipment used in the mining industry [3][4][5]. However, flooded equipment revitalization risk assessment from the aspect of the observed problem is not a topic present in a lot of scientific papers in the Republic of Serbia or worldwide [6].

There are many techniques and models for the selection and optimization of mining equipment, which are partly related to the economics of equipment selection and optimization. The general project management concept is presented in the research of the author Semolic, et al [7], where significant direct and indirect savings resulting from adequate resources management are given. In Celebi's research, two models for equipment selection and cost analysis system were developed and proposed [8].

There are very few research papers dealing with the reconstruction and revitalization of mining equipment with reference to the economic effects of these procedures. Most papers which can be found in domestic and international research are about reconstruction and revitalization of mining equipment without taking the economic effects of the reconstruction and revitalization of equipment into account [9][10][11]. Research on the economic effects of equipment maintenance on opencast coal mines, as well as the economic and financial effects of reconstruction and revitalization and the risk of investment are extremely rare [12]. There’s mostly individual research in the field of investment risk, hence it's obvious that more research in this area is necessary [13][14][15][16][17][18][19].

After this disaster, five continuous mining systems were flooded on Tamnava-West Field: systems for overburden, coal and interburden (Fig. 2). Those continuous systems included the following main equipment: four bucket wheel excavators, a bucket chain excavator, five spreaders and many conveyors. In addition, the following auxiliary equipment was flooded: four draglines, a bulldozer, seven pipelayers, six hydraulic excavators and two cranes. The value of the flooded equipment, if it was procured as new, would amount to approximately €250 million [1]. Since €250 million would have been an impossible investment, it was concluded that equipment revitalization was the best solution.

The equipment revitalization plan after the catastrophic floods in the Republic of Serbia had three possible options of investment.

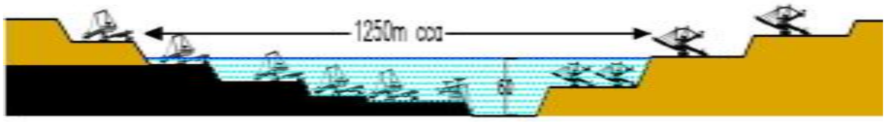

Figure 2: Submerged Tamnava-West Field excavators

Discussions were focused on three levels of repair works and revitalization of continuous mining equipment according to the following criteria [1]:

- ***Option 1***: The minimum investment and minimum time for bringing mining equipment to operating condition; these imply activities such as dismantling only the flooded basic equipment, washing and cleaning, the necessary replacement of critical parts, service for all parts, assembly of tested and cleaned equipment, as well as functional trials.
- ***Option 2***: Investments that will eliminate all the negative effects of the flooded main and auxiliary mining equipment; these imply activities such as complete refurbishment/replacement of flooded segments, service for other parts, assembly of repaired and new equipment, as well as functional trials.
- ***Option 3***: Investments that include complete refurbishment and modernization of the mining equipment, with functional trials after the assembly.

Every option was considered for all the equipment. In all cases, the investments in the electric parts are the same. After careful consideration, repairs were applied according to Option 2. The assessment of all the equipment was made based on the state of the equipment – certain excavators were completely submerged, some were partly, hence not all parts needed to be replaced or fixed (Fig. 3).

Figure 3: Partially submerged Tamnava-West Field overburden excavator

Another big factor was the possibility of finding certain parts on the market, because acquiring parts for enormous mining equipment is complex and takes a lot of time. The estimated value of the damaged electric equipment was €28.57 million, while the actual costs amounted to €28.43 million. There was a similar ratio of estimated and actual damage of the mechanical equipment, and it amounted to €17.5 million.

The modernized equipment might also face sudden failures due to many reasons, which represents a technical risk. Technical risk is the possible impact changes could have on a project, system, or entire infrastructure when an implementation does not work as anticipated [20]. These are the risks caused by the use of new or untested technologies or technical equipment or means of production [21].

Another thing that should be taken into consideration is that an event of this magnitude might repeat itself in the recent future. That risk should be considered alongside the before mentioned technical risk in a serial connection.

Risks in relation to costs increasingly require special attention. Risks can be divided into controlled risks, which are predictable and could have short-term planned control in the opencast mine area, and uncontrolled risks, which are related to external influences whose occurrence cannot be predicted short-term and as a rule relate to the contour of the mine. Uncontrolled risks, which are particularly related to ecological hazards like in this case, may have catastrophic consequences on mining and lead to a prolonged suspension of work, as well as a complete closure of the opencast mine with great losses [22].

Reducing the probability of failure is the most effective way of managing risks, rather than analysing and subsequently removing the consequences of unwanted events. Risk is essentially an unreliability, and its value is the probability of complementing the reliability up till value one [22].

Total risks are divided into technical, environmental controlled (which can be managed by timely and careful work and a maintenance plan, operational measures and investments) and uncontrollable environmental risks associated with ecological disasters. In this case, the technical risks are influenced by the uncontrollable environmental risk. The total estimated risk is verified by comparing the eligibility criteria for the elements of the subsystem, such as the minimum permissible values of reliability, risk of failure and present value of losses.

2.2. Risk probabilities

For mutually exclusive individual events of technical and environmental failures, the proper risks should be assessed and accumulated to the total risk [23] [24]. According to the classic definition, the risk of technical and environmental failure is practically the possibility of occurrence of a situation or event that can have negative consequences on the function and operation of an opencast mine, and it's defined as:

$$R = P_f \cdot C \tag{1}$$

Where: P_f - probability of any failure (exceedance probability) and C - losses caused by failure.

Total failure losses in opencast mines are usually expressed in monetary units.

Any individual risk of failure (Fig. 4) could be acceptable, while the overall (aggregate) risk might be unacceptable.

The mean operating time to failure of system elements (i = 1,…, n) is [25] [26]:

$$T_{oi} = \int P_{oi}\,(t)dt = \int exp(-a_i \cdot t)\,dt = {}^{1}/_{a_i} \tag{2}$$

The mean renewal time of the system elements is:

$$T_{ri} = \int P_o\,(t)dt = \int exp(-b_i \cdot t)\,dt = {}^{1}/_{b_i} \tag{3}$$

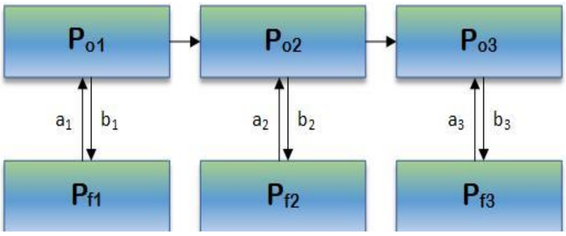

Figure 4: Operational and failure probabilities of technical (P_{o1}, P_{f1}), controlled (P_{o2}, P_{f2}) and uncontrolled (P_{o3}, P_{f3}) environmental elements in a serial system connection

The values of a_i and b_i are attained from the average failure and renewal times of the continuous excavators before and after the flood. The data before the flood would remain identical for Option 1 because in this case the excavators wouldn't have been modernized. The data after the flood is based on the current working state of the excavators, because Option 2 was selected. It is apparent that the modernized excavators of Option 2 have a lower average failure time compared to the excavators before the revitalization. In this sense, Option 3 would have had even more optimistic working results.

When $t \rightarrow \infty$, the limited stationary operation probabilities of elements (P_{oi}) and the renewal probabilities of elements after failure (P_{fi}) of the serial technical and environmental mining subsystem are:

$$P_{oi} = {}^{b_i}/_{(a_i + b_i)}, \qquad P_{fi} = {}^{a_i}/_{(a_i + b_i)} \tag{4}$$

Opencast mine production systems, as a rule, have extremely high losses due to failures of elements. It is customary to estimate losses due to failure through the availability (the ratio of realized and largest possible production) [27]. However, when considering that the failures occur at different times, the financial impact on production losses and the cost of regenerating system elements are important, so it's helpful to use the present value of total losses at a given time t in risk assessments, through the known present value equation:

$$PV_i = {}^{C_i}/_{(1 + r)^{ti}} \tag{5}$$

where r is the discount rate.

The probability that a catastrophic event will not occur during the analysed period of the project of n years is:

$$P_o = (1-p)^n \tag{6}$$

On the other hand, the legally anticipated return period of such rainfall is 100 years, so p = 0.01. From here it is clear that n = 10 years since (6): $P_{o\,min} = (1 - 0.01)^{10} = 0.9$. The risk or probability that the event will occur in this period is 10%.

The risk or the probability that the catastrophic event will happen at least once during the analysed period of the project is:

$$P_f = 1 - (1 - p)^n \tag{7}$$

The structural schemas that represent the graphical display of elements in the system can define unambiguously operation or failure of the system [28]. System elements are connected in series. If the system consists of (n) elements connected in series, the system operation probability $P_{so}(t)$, for the operation probability of each element $P_{oi}(t)$, is:

$$P_{so}(t) = P_{o1}(t) \cdot P_{o2}(t) \cdot \ldots \cdot P_{on}(t) = \prod_{i=1}^{n} P_{oi}(t) \tag{8}$$

Probability of the system failure equals:

$$\mathrm{P_{sf}} = 1 - \mathrm{P_{so}}(\mathrm{t}) \tag{9}$$

For i mutually independent failures in serial systems, the total risk of failure is [22]:

$$\mathrm{R_t} = \mathrm{P_{f1}} \cdot \mathrm{C_1} + \cdots + \mathrm{P_{fn}} \cdot \mathrm{C_i} \tag{10}$$

Where: R_t - total risk of technical and environmental failure, P_{fi} - probability of failure of the i-th element (i = 1,…, n), C_i - expected losses due to the failure of the i-th element.

2.3. Tamnava-West Field equipment investments

The estimated investments for each option are shown in Tab. 1. These values originate from the emergency expert study of the neccessary equipment repairs after the flood, which were estimated in euros.

Table 1. Investment costs for all options

Equipment revitalization options	Amount [€]
Option 1	32,360,000
Option 2	40,942,000
Option 3	46,771,000

The repair costs for every machine were estimated in detail. Since continuous excavators, spreaders and conveyors are the most expensive and important mining equipment, they will be shown separately in Tab. 2.

Table 2. Investment amounts for the basic equipment

Equipment	Option 1 [€]	Option 2 [€]	Option 3 [€]
SchRs 1600	2,178,500	2,413,500	3,413,500

SchRs 630 G1	2,361,000	2,995,000	3,995,000
SchRs 630 G4	2,361,000	2,995,000	3,995,000
SchRs 900	2,461,000	3,095,000	6,427,000
ERs 1000	2,126,000	2,673,000	6,454,000
Spreaders (four)	5,143,050	5,691,150	5,721,000
Conveyors	15,730,000	16,960,000	16,766,000

As shown in Tab. 2, the amounts needed for revitalizing the opencast mine Tamnava-West Field excavators are enormous. This clearly warrants a detailed risk analysis.

Other crucial parameters for probability assessment are failure and renewal intensities.

Tab. 3 shows the duration of equipment revitalization for each option and machine, which is crucial for determining the losses in production until the excavators are operational. Due to the necessary revitalization time of certain machines (shown in bold), that has to be the minimum revitalization time in total for each option as a whole.

Table 3. Duration of equipment revitalization per Option

Equipment	Option 1 [days]	Option 2 [days]	Option 3 [days]
SchRs 1600	60	60	60
SchRs 630 G1	**90**	**90**	90
SchRs 630 G4	**90**	**90**	90
SchRs 900	**90**	**90**	**180**
ERs 1000	**90**	**90**	**180**
Spreaders (five)	60	60	60
Conveyors	60	60	60
Necessary total time	**90**	**90**	**180**

In addition to the time necessary for continuous equipment revitalization, the time needed for mine rehabilitation should be included in the analysis. The average time of dewatering the flooded mine for each level of excavators is 3 months, because first and foremost the mine had to be dewatered to liberate the excavators. That time must be added to the duration of equipment revitalization for uncontrolled risk.

Tab. 1 shows the total investment costs of the possible three equipment revitalization options. However, investment costs are not the only costs that should be taken into consideration. The halt of production due to the flood also caused huge losses. Mine rehabilitation lasted for 6 months, and in that time the production loss was 15 million euros, which is 2.5 million loss per month or rather 500,000 per excavator monthly [22]. That loss also has to be added to the uncontrolled risk, in addition to the costs of fixing the mechanization from Tab. 1.

Furthermore, loss due to halt has to be considered in technical risks, as every failure causes the continuous system to stop. When an excavator isn't operative for a month, it makes a loss in production worth 500,000 euros. Even if maximum repair (renewal) time takes up half a month, when adding repair costs, it amounts to a 1,000,000 euros loss.

2.4. Quantitative risk probability assessment

The quantitative probability assessment analysis of the options provides precise and realistic results, both for risk failure probabilities and for losses depending on the moment of investment based on net present value (NPV).

The following Tab. 4, 5 and 6 show the probability assessment parameters for Option 1.

Table 4. Parameters and analysis of technical and environmental risks for Option 1

Parameter	Technical	Environmental controlled	Environmental uncontrolled
Failure intensity (year^{-1}) Eq. (2)	2.44	3	0.10
Renewal intensity (year^{-1}) Eq. (3)	5	25	2
Nonexceedance probability Eq. (4)	0.67	0.89	0.95
Exceedance probability Eq. (4)	0.33	0.11	0.05
Losses (M euros)	11.6	11.25	47.36
Risk Eq. (1)	3.8	1.21	2.26

As a result, total risk of failure according to Eq. (10) equals:

$$\mathrm{R_{tO1}} = 0.33 \cdot 11.6 + 0.11 \cdot 11.25 + 0.05 \cdot 47.36 = 7.26 \tag{10}$$

The present value of total losses according to Eq. (5) at a planned time of exceedance *t* = 10 years in risk assessments, where r is the discount rate equalling *r* = 8% is (5):

$$\mathrm{PV_{O1}} = {}^{70.21}\!/_{1.08^{10}} = 32.52 \tag{5}$$

Table 5. Parameters and analysis of technical and environmental risks for Option 2

Parameter	Technical	Environmental controlled	Environmental uncontrolled
Failure intensity (year^{-1}) Eq. (2)	1.7	2.38	0.10
Renewal intensity (year^{-1}) Eq. (3)	10	25	2
Nonexceedance probability Eq. (4)	0.82	0.91	0.95
Exceedance probability Eq. (4)	0.18	0.09	0.05

Losses (M euros)	7.5	7.5	55.94
Risk Eq. (1)	1.31	0.65	2.66

For Option 2, the total serial non-exceedance system probability (P_{os}) in Eq. (8) is 0.74, the exceedance probability of the system (P_{fs}) in Eq. (9) is 0.26, and the total losses are C_{O2} = 70.94 M euros.

As a result, total risk of failure according to Eq. (10) equals:

$$\mathrm{R_{tO2}} = 0.15 \cdot 7.5 + 0.09 \cdot 7.5 + 0.05 \cdot 55.94 = 4.41 \tag{10}$$

The present value of total losses according to Eq. (5) at a planned time of exceedance t = 10 years in risk assessments, where r is the discount rate equalling $r = 8\%$ is:

$$\mathrm{PV_{O2}} = {}^{70.94}\!/_{1.08^{10}} = 32.86 \tag{5}$$

Table 6. Parameters and analysis of technical and environmental risks for Option 3

Parameter	Technical	Environmental controlled	Environmental uncontrolled
Failure intensity (year^{-1}) Eq. (2)	1.5	2	0.10
Renewal intensity (year^{-1}) Eq. (3)	12	25	1.34
Nonexceedance probability Eq. (4)	0.89	0.93	0.93
Exceedance probability Eq. (4)	0.11	0.07	0.07
Losses (M euros)	5	6	69.27
Risk Eq. (1)	0.56	0.44	4.81

For Option 3, the total serial non-exceedance system probability (P_{os}) (8) is 0.77, the exceedance probability of the system (P_{fs}) (9) is 0.23, and the total losses are C_{O3} = 80.27 M euros.

As a result, total risk of failure according to Eq. (10) equals:

$$\mathrm{R_{tO3}} = 0.11 \cdot 5 + 0.07 \cdot 6 + 0.07 \cdot 69.27 = 5.81 \tag{10}$$

The present value of total losses according to Eq. (5) at a planned time of exceedance t = 10 years in risk assessments, where r is the discount rate equalling $r = 8\%$ is:

$$\mathrm{PV_{O3}} = {}^{80.27}\!/_{1.08^{10}} = 37.18 \tag{5}$$

The present values for the three revitalization options should be ranked with a multiple-criteria decision analysis for an easier overview of most favourable results. TOPSIS would be an apt decision analysis for this case.

3. Result analysis and discussion

Tab. 7 shows the final results of the quantitative probability risk assessment.

Technical risks would be considerably lowered in Option 3 due to the modernized equipment, but the bigger investment makes it a significant economic risk since there is a serious chance such a devastating event will happen again.

Table 7. Quantitative risk assessment and losses present value of the revitalization options

Option	Risk	Present value [€]
Option 1	7.26	**32.52**
Option 2	**4.41**	32.86
Option 3	5.81	37.18

Option 1 obviously has the lowest present value of losses, due to the lowest investment. But the investments for Option 2 reduce the risks to the lowest possible value. Therefore it's proven that Option 2 was the best possible investment; eliminating all the negative effects of the flooded main and auxiliary mining equipment, with the shortest possible time. The choice the expert team made was justified, despite the urgency.

The attained results are ranked with the multiple-criteria decision analysis TOPSIS, based on equal preferences of risk value and present value from the quantitative risk analysis. The ranking is shown in Tab. 8.

Table 8. TOPSIS ranking of the assessed options

TOPSIS	Closeness to ideal solution	Rank
Option 1	0.22	**3**
Option 2	0.98	**1**
Option 3	0.47	**2**

TOPSIS reaffirms the conclusion that Option 2 is most suiting, and grants it rank #1.

4. Conclusion

Catastrophic events like floods will start happening more frequently because of climate change. They can cause devastating damages, especially when it comes to mining. In the case of the Republic of Serbia's opencast coal mine Tamnava-West Field, the enormous flood ceased production completely, flooded most of the equipment and caused many dewatering issues. Due to the halt of mining, coal production was alarmingly reduced and it influenced the energy stability of the country. The mine was succesfully rehabilitated and the equipment was revitalised, which resulted in returning to the neccessary coal production the next year.

A detailed risk probability assessment of the options for equipment revitalization showed that the decision of the expert team for Option 2 was justified. The analysis showed that Option 2 has the lowest total risk out of the three.

This method of determining and managing risk probabilities should be used because of the serial connection of all risks that threaten the functionality of the system, not just one independent possibility of failure. This enables objective decision-making with the help of net present value in realistic situations where mining businesses are faced with many risks at the same time.

Nomenclature

R – risk of technical and environmental failure

P_f – probability of any failure (exceedance probability)

C_i – expected losses due to the failure of the i-th element [€]

T_{oi} – mean operating time to failure [year^{-1}]

T_{ri} – mean renewal time [year^{-1}]

a_i – average failure time [year]

b_i – average renewal time [year]

P_{oi} – operation probabilities of elements

P_{fi} – renewal probabilities of elements after failure

PV_i – present value of total losses [€]

r – discount rate [%]

p – return period

P_{so} – system operation probability

P_{oi} – operation probability of each element

P_{sf} – probability of system failure

R_t – total risk of failure

P_{fi} – probability of failure of the i-th element

C – losses caused by failure [€]

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