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Environmental footprints caused by the operation of open-pit mines and the possibility of multifunctional use of the occupied space

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Abstract: Open-pit mines of mineral raw materials play a key role in the development of society and economy. However, their construction and operation often have a significant environmental footprint, which includes physical, chemical and biological changes in the natural environment. This paper investigates the environmental impacts of open-pit mining and emphasizes the importance of integral use of the affected area in order to minimize negative impacts and at the same time promote their beneficial functions. The paper presents examples of rehabilitation and repurposing of open-pit mines and the possible multifunctional use of space.

Key words: open-pit mining, environmental footprints, integral use of space, rehabilitation and repurposing

Otisci u okolišu uzrokovani radom površinskih kopova te mogućnosti multifunkcionalnog korištenja zahvaćenog prostora

Sažetak: Površinski kopovi mineralnih sirovina igraju ključnu ulogu u razvoju društva i gospodarstva. Međutim, njihova izgradnja i eksploatacija često imaju značajan otisak u okolišu, što uključuje fizičke, kemijske i biološke promjene u prirodnom okruženju. Ovaj rad istražuje utjecaje površinskih kopova na okoliš te naglašava važnost integralnog korištenja zahvaćenog prostora kako bi se minimizirali negativni učinci, a istodobno potakle njihove korisne funkcije. U radu su prikazani primjeri sanacije i prenamjene površinskih kopova i mogućeg multifunkcionalnog korištenja prostora.

Ključne riječi: površinski kopovi, okolišni otisci, integralno korištenje prostora, sanacija i prenamjena

1. INTRODUCTION

In their original form, mineral raw materials are a non-renewable natural resource that is found primarily in an uneven natural environment, and secondarily and even tertiarily in different transformed forms such as energy sources, housing construction, infrastructure facilities (roads, bridges, railways), cars, vessels, aircraft, pharmaceutical and cosmetic products, and plastic and other consumer products that form an indispensable part of human civilization. Man achieves everything based on mineral raw materials or products obtained from them. Therefore, mineral raw materials are necessary not only for development but also for the survival of society as a whole. The issue of energy and mineral raw materials must not and cannot be viewed unilaterally, but comprehensively according to the principle of sustainable development [1,2]. The World Commission on Environment and Development (WCED) published its report in 1987 and presented a new concept of sustainable development, which is defined in the following way: "Sustainable development is a development that meets the needs of the present, without compromising the needs of future generations to meet their own needs" [3].

At a time of great population growth and shrinking living space, it is clear that spatial planning and highly effective environmental protection must be taken into account. Since mining operations are predetermined by the place of occurrence of mineral raw materials, and limited by the real possibilities and wishes of the social community, experts, miners and geologists must be actively involved in spatial planning and point to the potential activation sites in order to be able to make a decision on the priority of their use based on this [2,4,5,6]. It is necessary to determine the realistic possibilities of exploitation, because mining operation at any price is a past that must not be forgotten, but it cannot be repeated any more. Trends in the development of society that will encourage only humane, economically and environmentally friendly exploitation also strive towards this [7]. The exploitation of mineral raw materials is carried out in surface and/or underground mines. Surface exploitation, and sometimes underground mining, consequently leads to changes in the landscape, which represents one of the main footprints in the environment. However, in addition to mining operations, numerous energy, hydraulic engineering and infrastructure facilities leave a large footprint in the environment, or a footprint on the surface part of the lithosphere, by changing the landscape. Changing the landscape also results in other environmental impacts, such as the impact on biodiversity.

The carbon footprint, which takes place by the emission of carbon dioxide when generating energy from fossil sources (fuels) and other technological processes, also represents a large environmental impact. Despite the efforts of scientific, economic, social and ecological organizations, the production of carbon dioxide is constantly increasing, whether we are talking about stable plants, most often thermal power plants, or means of transportation. The needs of the consumer society and the increase in population result in higher energy demands, which leads to an imbalance with the efforts to reduce the emission of greenhouse gases, predominantly carbon dioxide.

Open-pit mines play a key role in the development of society and economy. However, their construction and operation often have a significant environmental footprint, which includes physical, chemical and biological changes in the natural environment. Therefore, this paper aims to investigate the environmental impacts of open-pit mining with an emphasis on the importance of integral use of the affected area in order to minimize negative effects and promote beneficial functions.

As places where mineral raw materials are extracted to obtain building materials, open-pit mines and infrastructure facilities (roads, public networks, etc.) are interconnected. The construction of infrastructure facilities is impossible without the extraction or use of mineral raw materials. During the construction of infrastructure facilities, open-pit mines from which crushed stone aggregate or construction sand and gravel are extracted are located as close as possible to the location of placement due to the significant share of transportation costs in the total cost of the facility construction [8]. Such open-pit mines can be characterized as places (deposits) of primary extraction of mineral raw materials for construction materials (concrete, asphalt, embankment, road base, etc.).

In the area of Dinarides, there are numerous open-pit mines covering more than 10,000 ha, where the exploitation of bauxite, a mineral raw material used for obtaining aluminum, improving the properties of cement, obtaining cleaning agents, rare chemical elements, etc., was primarily carried out. Deposits of karst bauxite types are often covered by carbonate rocks and they need to be removed or disposed of in order to excavate the bauxite ore. Therefore, as a consequence of the exploitation of bauxite deposits in Dalmatia and Herzegovina, smaller or larger deposits of overlying rocks, which represent a secondary mineral raw material for obtaining construction material, are often found next to open-pit mines [9]. It is especially interesting that such places have not been rehabilitated in an appropriate way and therefore cannot be converted to other useful functions. Therefore, a landscape footprint without valid justification is recorded on such open-pit mines.

The principle of sustainable development obliges civilization to conscientiously treat all areas. Therefore, each area must be evaluated integrally, which means that the possibility of multifunctional use of the affected area (open-pit mine and disposal site) should be considered, in order to minimize the landscape footprint, or make it necessarily acceptable for society as a whole [10]. The idea of using open-pit mines to obtain renewable energy sources and attractive and functional facilities that would contribute to the quality of life should be considered as a justified possibility. Precisely for the purpose of a demonstration model of multifunctional use of the space affected by mining operations (open-pit mines and disposal sites), this paper examines the example of exploitation of bauxite deposits in Western Herzegovina.

2. ANALYSIS OF IMPACTS AND FOOTPRINTS ON THE ENVIRONMENT AND POSSIBILITY OF MULTIFUNCTIONAL USE OF PLANNED OPERATIONS

Construction of infrastructure facilities, primarily roads, is correlated to the construction materials supply source, or open-pit mines where mineral raw materials are extracted for the production of construction materials. The Dinarides area is mainly hilly terrain where there are predominantly carbonate rocks that are excavated and mostly used as crushed stone aggregate. According to rock excavation methods, road construction and open-pit mining of crushed stone aggregate have approximately the same environmental impact and can therefore be put under the same denominator up to a certain stage of development. However, they differ significantly in terms of purpose and lifespan, since the function of an open-pit mine is limited to the time of construction of the facilities, while roads have a much longer lifespan, or they are used for many times longer than the time of construction. Environmental impact assessment is conducted according to state regulations related to the environment, in the form of legislative and non-legislative acts (rules and regulations) and based on the assessment of the environmental impact study of the planned project. The environmental impact study of the planned project analyzes individual impacts as well as expected environmental consequences and protection measures [11, 12]. According to the expected environmental impacts, their footprints can be modeled in measurable values and possibilities for reducing the impact on the ecosystem can be determined both through protection measures and by planning the multifunctional use of planned interventions. Therefore, the remainder of this paper discusses the environmental impacts of open-pit mines and other excavations, the ecological footprint as a collective indicator, individual environmental footprints, and the application of the principle of multifunctional use of planned interventions for the purpose of reducing the analyzed environmental footprints.

2.1. Environmental impacts of open-pit mines

In a broader sense, the biosphere is the space where the organisms of our planet live, and along with the lithosphere (the surface part of the rock plate), the hydrosphere (all water) and the atmosphere (troposphere), the biosphere makes up the environment. According to Article 4 of the Law on Environmental Protection (Official Gazette 78/15, 12/18, 118/18) the following is defined: "The environment is a natural and any other environment of organisms and their communities, including man, which enables their existence and their further development: air, sea, water, soil, the Earth's crust, energy and material resources and cultural heritage as part of the human-made environment; all in their diversity and totality of interaction. The components of the environment are: air, water, sea, soil, landscape, flora and fauna and the Earth's crust" [13].
For this reason, open-pit mining operations can have different impacts on people, biodiversity (flora and fauna), water, soil, air and landscape, and the influence of these factors is described in detail hereinafter.

Impact on people

Any impact, including the impact on people, can be observed as a direct or indirect impact. Indirect impact on people results from other impacts, during a shorter or longer period of operation. However, the emphasis here is on the direct impact on people in the environment, and is reflected in the direct threat to people's lives from the technological process of work, such as from blasting, loading and transport means, etc.

Impact on biodiversity

The impact on biodiversity is one of the biggest environmental impacts of mining and other related works, such as geotechnical works and road construction, which, due to the excavation of soil and rocks, result in the loss of natural habitats of wild species. Practically there is a complete biodiversity loss on the affected surface, which can have long-term consequences for local ecosystems, including the loss of habitat for many species and changes in the structure of the ecosystem. The impact on biodiversity can also be reflected outside the operation area, through contamination of surface water and groundwater with heavy metals.

Impact on water

During the works, and sometimes after cessation of the works, open-pit mines can have a significant impact on water resources, including surface water and groundwater. When sulfide ores are excavated, they are dissolved in water, thus creating acidic mine waters that contain sulfide ions and metal ions, which leads to contamination of surface water and groundwater. Precipitation and surface runoff carry contaminated soil particles into rivers, lakes and other watercourses, thus further reducing water quality.

Impact on soil

During the exploitation of mineral raw materials, soil pollution is most often caused by heavy metals such as lead, copper and zinc that come from ore residue and mine wastewater. These heavy metals change the chemical properties of the soil and can have harmful effects on plants and animals living in that environment. Soil erosion can also be a significant problem during mining operations, and is caused by natural processes such as rain and wind, but also by activities that include the excavation and movement of earthen material. Erosion leads to soil loss and reduces its fertility, and causes permanent environmental degradation.

Impact on air

During open-pit mining operations, various pollutants are released into the atmosphere, including dust, suspended particles, gases such as sulfur and nitrogen oxides (SOx, NOx), and other harmful chemicals. Such pollutants contribute to the reduction of air quality, but also have a long-term impact on climate change and human health. Acid rain, resulting from long-term SOx and NOx emissions, causes acidification of soil and water, and also negatively affects vegetation, which can result in the degradation of forests and crops. Suspended particles containing heavy metals and other harmful chemicals are deposited near the emission source, but can also be transported to more distant areas depending on atmospheric conditions. Such pollutants can seriously endanger human health because the particles are inhaled and deposited in the lungs. Long-term exposure to such substances is associated with respiratory problems, but also with a decrease in biodiversity in surrounding areas due to habitat damage. The main sources of air pollution during excavation include drilling, blasting, transportation of raw materials and refining processes using dry processes that increase dust emissions [14].

Noise and vibrations

Drilling, blasting, loading and transportation can result in high levels of noise that interfere with human activities, and also negatively affect ecosystems. Animal species can abandon their habitats or change their natural behavior due to the constant presence of noise. During the detonation of an explosive charge, a large amount of energy is released, which is converted into the kinetic energy of seismic waves and air shocks. Such impacts can cause damage to nearby structures as well as disturbance to the population near the source [14].

Impact on landscape

The development of an open-pit mine directly affects the landscape and all environmental components located in the affected area. Depending on the surface and volume of excavated material, the operations can more or less disrupt the natural environment, and in this case, the aesthetic value of the landscape. Unrehabilitated mines do not fit into the original landscape and reduce its aesthetic value, but also prevent the restoration of biodiversity functions or the regeneration of wild species, which makes the affected area useless [15,16]. In landscape evaluation, watercourses with their associated vegetation belt and the valley or canyon through which they flow are considered a single spatial and structural unit. Therefore, in such areas, it is necessary to coordinate and implement the intended interventions by taking into account landscape values and characteristics. Natural water landscapes and aquatic ecosystems should be preserved to the maximum extent possible as exceptionally valuable and as bearers of the recognizability and identity of the area, in which process geometric watercourse regulation should be avoided. It is necessary to prevent landscape degradation in the energy use of watercourses (low water levels), or to establish a trade-off between energy and landscape uses, and thereby also tourism and recreational arguments. Forests are of particular importance and value for the landscape and should be preserved to the maximum extent possible as one of the most important and visually dominant parts of the landscape. Existing forests should be protected and preserved to the maximum extent possible, so their conversion and clearing are not permitted [16].

2.2. Environmental footprints

Changing the landscape consequently affects all other environmental components. Therefore, the landscape footprint can be shown in a simple model as a quantitative indicator of the relationship between the goods that are generated by a certain activity and the coverage area (m^3/m^2 or kg/m^2, etc.). On the other hand, air quality is assessed by quantitative indicators of the emission of harmful and climatically adverse gases (kg/equivalent unit measure). In recent research, special attention is paid to the emission of greenhouse gases, primarily carbon dioxide, due to the consequent threat to the ozone layer and climate change. The emission of carbon dioxide is expressed as a carbon footprint in the environment. The ecological and carbon footprint in the environment will be defined hereinafter.

Ecological footprint in the environment

Ecological footprint is a method that determines how dependent humans are on natural resources. It is a measure that indicates how much resources from the environment are required to support a specific way of life or business. In simpler words, the ecological footprint indicates the amount of pressure that humans put on the natural resources available to them in their surroundings. It is generally expressed in global hectares (gha), and allows professionals to determine the land area required by each human to sufficiently meet their needs. This can be expressed as the demand required by humans and the supply offered by nature. The ecological footprint is used commonly to calculate sustainability of an entity, such as a region, an individual, or a business. It can also be expressed as the amount of resources consumed. First introduced in 1992 by William Rees, the idea of calculating ecological footprints is designed to evaluate the environmental impact of activities conducted by humans [17]. It allows analysts to determine the rate at which humans consume resources and generate waste [18]. The ecological footprint is an accounting measure that evaluates the demand and supply of nature. To determine demand, the footprint tallies all the productive elements for which populations usually compete. This includes all biological and ecological assets that a functioning population would require to produce natural resources for sustenance. It includes all natural resources such as livestock and fish, timber and other wood products, plant-based food and space for building infrastructure. The ecological footprint can be calculated for regions, countries, cities, individuals, businesses, and as a whole, for the entire planet. For calculating the supply, the ecological footprint aggregates the total biocapacity available, including any land and sea area, forest lands, crops, fishing regions, and any land on which construction has been completed. On a personal level, the ecological footprint determines how much you consume, and how sustainably certain products are being manufactured, and as such, plays a very important role in helping organizations and nations determine how much productive land is available to them.

The biocapacity of each individual is calculated based on the productive area available (expressed in hectares), the productivity of each area, and the number of people who share it. However, if a population's ecological footprint is greater than the biocapacity to service it, that region risks running a biocapacity or ecological deficit [18]. Simply put, the demand for goods and services exceeds the speeds at which the region's ecosystems are capable of regenerating. In this case, a region may consider servicing demand by importing goods, overconsuming its own ecological assets, or partaking in activities that harm the environment in one way or another. Without evaluating the ecological footprint, it can be difficult for governments and organizations to monitor the consumption of ecological resources and to take steps towards a sustainable future. The total ecological footprint of humanity is considered to be more than 50% of the Earth's capacity. According to these data, for the needs of humans, another planet is already needed for life.

There are several variables that are taken into account when calculating the ecological footprint, and the equation that is often used in the calculation is shown below [19]:

$$EF = \Sigma Ti/Yw \times EQFi \quad (1)$$

where:

Ti is the annual consumption (in tons) of product i by a nation;
Yw is the world average yield for product i;
EQFi is the equivalence factor for product i.

It is important to note that there are several models for determining the ecological footprint today. The ecological footprint standards, introduced in 2006, state that the ecological footprint calculates the amount of biologically productive area needed to produce resources that the human population would require, while also absorbing greenhouse gas emissions. For instance, to calculate the ecological footprint of an individual or a company, we would calculate all of their demands, such as their need for land to grow crops, or the need for forestland to use wood and absorb carbon emissions. Then, all materials and waste generated must be translated into a figure, expressed in global hectares (gha). Consequently, the ecological footprint of a nation, a group of people in a city, is just the sum of all ecological footprints of all the residents or members within the group [18]. The ecological footprint is an indicator of the sustainability of an organization. There is an increasing need for businesses to take the necessary steps to focus on sustainable development. Therefore, many businesses are increasingly investing in processes and revamping their infrastructure to reduce their ecological footprint. Understanding the organization's ecological footprint is the first step to taking steps to improve it. Moving towards a resource-efficient business model also helps build trust and makes organizations more transparent amongst stakeholders. And, more importantly, it ensures that the organization plays its role to improve the future.

Carbon footprint

The carbon footprint emerged from the broader concept of ecological footprint [20]. As, according to [21], carbon dioxide (CO_2) emissions were recognized as the main driver of global warming, or negative environmental impact, the carbon footprint soon became a key component in discussions on sustainable development and climate change. Therefore, measuring and identifying the main sources of emissions is exceptionally important for developing a strategy to reduce negative environmental impacts [14]. The carbon footprint is defined as the total amount of CO_2 emissions and other greenhouse gases generated directly or indirectly by human activity. It is used to quantify the environmental impact of different activities, from production and transportation to everyday activities such as household energy use. By measuring it, it is possible to determine how much an individual, organization or industry contributes to global greenhouse gas emissions and to identify key points where this impact can be reduced [14,22].

Greenhouse gas quantification is determined by a calculation based on activity data, such as the amount of diesel fuel consumed, with the application of appropriate emission and conversion factors. All greenhouse gas emissions can be presented as equivalent carbon dioxide emissions (CO_{2eq}) because they originate from the same sources. In order to take into account the different impacts that individual gases have on the greenhouse effect, the emissions of each gas are multiplied by its greenhouse potential. In this way, total emissions can be summed up and presented as equivalent carbon dioxide emissions (CO_{2eq}) [14,23].

CO_{2eq} emissions are calculated as follows:

$$E_{sp} = P_{dg} \times FE \tag{2}$$

where:

E_{sp} is the greenhouse gas emission, kg CO_{2eq};
P_{dg} is the diesel fuel consumption, GJ;
FE is the emission factor, kg/GJ CO_{2eq}.

The greenhouse gas emission calculation uses the emission factor FE = 84.728723 kg/GJ CO_{2eq}, which is taken from the methodology of the Ministry of Economy and Sustainable Development [14,23].

Current state of the planet (biodiversity)

The Living Planet Report warns that huge collective effort will be needed over the next five years to tackle the dual climate change and biodiversity loss crises [24]. According to the Living Planet Report, there has been a catastrophic 73% decline in the average size of monitored wildlife populations over just 50 years, from 1970 to 2020 [24]. The report was released worldwide on 10 October 2024, and warns that a huge collective effort will be needed over the next five years to tackle the dual climate change and biodiversity loss crises as the Earth approaches dangerous tipping points posing grave threats to humanity.
The Living Planet Index, produced by the Zoological Society of London, includes nearly 35,000 population trends for 5,495 species from 1970 to 2020. The heaviest declines were recorded in freshwater ecosystems (85%), followed by terrestrial (69%) and marine populations (56%). Habitat loss and degradation, driven primarily by the human food system, pose the greatest threat to wildlife populations worldwide. It is followed by overexploitation, invasive species and disease. Climate change poses an additional threat to wildlife populations in Latin America and the Caribbean, where an astonishing average decline of 95% has been recorded. Declines in wildlife populations can serve as an early indicator of increased risk of extinction and potential loss of healthy ecosystems. Once ecosystems are damaged, they cease to provide the benefits we depend on – clean air, water and healthy soil for food – and become more vulnerable to tipping points. A tipping point occurs when an ecosystem is pushed beyond a critical threshold, resulting in substantial and potentially irreversible change [25].

3. POSSIBILITIES OF MULTIFUNCTIONAL USE OF SPACE TO REDUCE THE ENVIRONMENTAL FOOTPRINT OF PLANNED OPERATIONS

Sustainable management

Sustainable management implies the integration of ecological, economic and social factors in the process of planning and exploitation. The first step in this direction is proper spatial planning that ensures the minimization of environmental impact, and includes careful selection of mining locations, reduction of affected areas and implementation of technologies that reduce harmful emissions into air, water and soil.
Space must be viewed in an integral way, which implies the development of such spatial development plans of the municipality/city/county that will determine the possibilities for multifunctional use of space to reduce environmental footprints.
For the purpose of multifunctional use of space, it is necessary to adopt and implement the following activities:

1. spatial planning of the supply chain of mineral raw materials with the priority of using abandoned and/or unrehabilitated mines from which it is possible to obtain raw materials for the production of construction materials (savings rule, not to increase the ecological and carbon footprint);
2. integral evaluation of deposits of mineral raw materials and the surrounding space;
3. exploitation of all types of mineral raw materials from deposits based on the principle "without the rest";
4. rehabilitation (technical and biological) of all locations where there are craters and disposal sites, whether it is legal or illegal exploitation of mineral raw materials;
5. conversion of rehabilitated spaces (open-pit mines and disposal sites) into acceptable and useful facilities (power plant for renewable energy sources, facilities for sports and recreation, amusement park, scenic area, warehouse, etc.).

The implementation of these activities must be coordinated between public administration bodies (municipality/city, county and state), economic entities and other participants in procedures for approving interventions in space in order to satisfy economic and general interests. Partial interests must not be an end in themselves, but part of a complementary solution offering to meet interests of all stakeholders in the space ("win-win" situation). This will significantly reduce the ecological footprint and achieve the common goal, which is sustainable management and care for the environment.

Rehabilitation of space

Acceptable rehabilitation is only the one that involves mandatory technical improvement and, if necessary, biological reclamation. The execution of rehabilitation works must be included in the initial documentation, projects and solutions [5]. Every area, including the one where mining operations are carried out, must be viewed integrally [16]. It is also important to emphasize the previously mentioned importance of spatial planning documentation, which must include the appropriate conversion of rehabilitated spaces for socially beneficial uses. The possibilities for this are great and can include any facilities, from sports and recreation centers, outdoor cinemas, catering facilities, parks, bicycle paths, economic and commercial activities, and so on. Repurposing, or targeted rehabilitation, can not only improve the space, but also influence the decision on the acceptability of exploitation at a particular location. The design of an open-pit mine in the rehabilitation phase must be economically justified. In addition to economic feasibility, the most important factors are the stability of the space obtained through rehabilitation and the resolved water drainage system. All of the above mainly applies to technical rehabilitation. Biological rehabilitation is performed at the end of technical rehabilitation and primarily refers to the procedure in which soil suitable for the development of plants, or flora and fauna, is placed on the rock material. Biological rehabilitation and its quality, and thereby its success, will largely depend on the type of rocks on which it is carried out.

Repurposing of open-pit mines after exploitation

Repurposing the space of the mineral raw materials exploitation fields, after ending the exploitation of mineral raw materials and conducting a regular rehabilitation, must be harmonized with the interests of the wider social community. The process of repurposing these spaces is a key step in reducing the negative consequences of mining and in encouraging sustainable development, which represents a great opportunity for environmental regeneration and the development of new functions in the community.

Repurposing of open-pit mines basically means carrying out certain technical interventions, with which excavated areas and ore residue disposal sites are converted for the uses and facilities specified in the spatial planning documentation after exploitation. What type of facility the excavated space will be used for upon completion of exploitation depends on its size, appearance, position in space, distance from urban, agricultural, forest, sea or river areas, travel routes and the like.

The most common models for the conversion of open-pit mines include reclamation and restoration of agricultural or forest functions, tourist and recreational facilities, industrial and commercial zones, and the generation of energy from renewable energy sources, and these are discussed further in this paper.

Reclamation and restoration of agricultural or forest functions is a traditional conversion method that includes soil rehabilitation, restoration of native plant species and restoration of ecological balance. It is often applied in rural areas where there is a need for additional agricultural land (Fig. 1).

Figure 1. An example of conversion of a landfill to agricultural and other uses, Tyrone Cooper Mine, New Mexico [26]

Some former mining areas can be transformed into nature parks, recreation centers, or even industrial heritage museums [27]. Such conversion not only contributes to environmental conservation but also creates new economic opportunities through tourism (Fig. 2).

Figure 2. An example of conversion into tourism and recreational facilities: Eden Project Cornwall, England [28]

In urban areas, abandoned bauxite mines can be converted to industrial or commercial uses. However, in this case it is important to ensure implementation of all necessary rehabilitation measures to prevent risks to human health (Fig. 3).

Figure 3. An example of conversion of industrial zones into agricultural and other facilities: Morlacco Jasenica, Croatia [29]

Existing mining areas can be used to install solar or wind power plants, which can be an environmentally sustainable solution in terms of space conversion (Fig. 4).

Figure 4. RWE Indeland solar plant Inden, Germany [30]

4. MODEL OF MULTIFUNCTIONAL USE OF SPACE ON THE EXAMPLE OF SURFACE BAUXITE MINES IN THE COUNTY OF WEST HERZEGOVINA

In the County of West Herzegovina in Bosnia and Herzegovina, there are tens of localities where the landscape and ecosystem of the surrounding areas have been disrupted due to the exploitation of bauxite deposits. No rehabilitation procedure was carried out on these mines, even though the rehabilitation of the locality after completion of the mining works is prescribed by law, and they are left in the condition caused by the exploitation of mineral raw materials [9]. Unrehabilitated mines contain numerous craters and often large amounts of excavated overburden that have been deposited nearby. Their quantities range from several hundred tons to several hundred thousand tons. The landscape views are disrupted in this way to a greater or lesser extent depending on the scope of the work carried out, but the lack of rehabilitation has certainly drastically reduced its aesthetic value. Slopes with critical inclinations, which pose a risk of collapse and, together with pits pose a threat to human life, but also to wildlife, are often present in such locations [6]. The karst relief drains water easily due to the presence of numerous cracks and is an exceptionally sensitive system, largely due to the widespread groundwater. In some abandoned and unimproved open pits, waste is disposed of without control, from municipal and bulky waste to dead livestock and hazardous chemicals. As mentioned earlier, as this is a karst terrain with underground watercourses, the risk and impact on biodiversity is multiplied.

In the wider area of Posušje and Široki Brijeg, some of the more significant examples of unrehabilitated and dangerous mines are Tribošić, Studena Vrila, Crne Lokve, Zagorje, Tribistovo, Mratnjača and Vir. In addition to these, there are also tens of other mines and it is exceptionally difficult to list all of them [31]. The significance of these areas, or bauxite exploitation fields, lies in the geologically favorable formations in which they are located, or carbonate rocks that can be used as a mineral raw material for obtaining crushed stone aggregate or carbonate raw material. Therefore, based on the principle of an integral approach, they can be used for the construction of infrastructure facilities. Surface bauxite mines together with overburden disposal sites are located on bare land, in significant areas, and are suitable for installing solar power plants or other facilities. As an example of the possible multifunctional use of space, two bauxite-bearing areas, Crne Lokve and Tribošić, are analyzed hereinafter (Fig. 5).

Figure 5. Significant bauxite exploitation areas in Crne Lokve and Tribošić

The open-pit mines of Orašnica and Tribošić are located right next to the Ugrovača canyon. Immediately next to the mines, there are disposal sites the fill slopes of which end on the slopes of the canyon. Heavy rains cause torrential flows that spread smaller pieces from the fill, which end downstream from the open-pit mines. Due to their specifics, variant solutions for rehabilitation and repurposing of the observed open-pit mines are presented below.

4.1. Variant solutions for rehabilitation and conversion of the Orašnica open-pit mine

The Orašnica open pit is located in Crne Lokve and, together with the disposal sites, covers an area of about 10 ha (Fig. 6). It is about 15 km away from the center of Široki Brijeg. Mining operations, or bauxite exploitation, are still being carried out at the open-pit mine. The estimated amount of overburden at the disposal site is about 500,000 m^3. The overburden was crushed by blasting and is suitable for improving crushed stone aggregate. Since the overlying rocks are of carbonate composition, they are considered as moderately hard rocks and there is a possibility of using them to obtain construction materials for the construction of roads and other facilities [32]. This would allow maximum use of the deposit and the implementation of technical rehabilitation of the entire coverage, or open-pit mine and disposal site. Also, the prerequisites for the conversion of the rehabilitated area would be created.

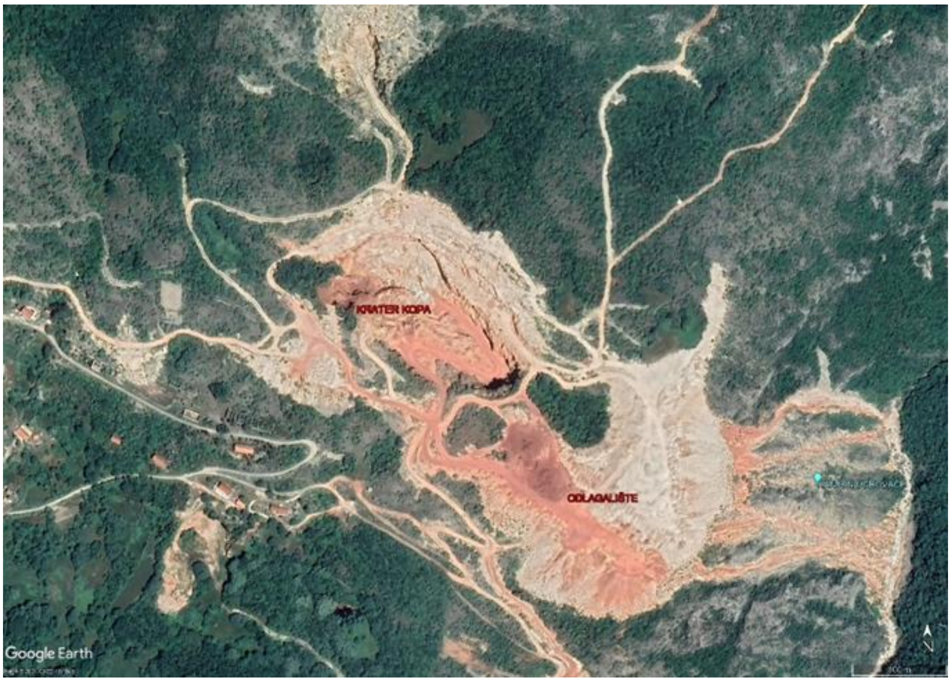

Figure 6. Open pit mine Orašnica (Crne Lokve)

When it comes to optimization, the usual method of selecting the optimal solution in mining is the method of variants, which implies the creation of multiple conceptual solutions and selection of the optimal one. Two variant solutions for the rehabilitation of the Orašnica open-pit mine are presented further in this paper.
The first variant solution for the rehabilitation and conversion of the Orašnica open-pit mine according to [33] is shown in Figure 7.

Figure 7. The first variant solution for the rehabilitation and conversion of the Orašnica open-pit mine deposit [33]

According to this conceptual solution, the technical rehabilitation assumes developing the contours of the pit, which would be carried out by forming floors 10 m high and 7 m wide and an inclination of the floor slope of 60°. The deep part of the pit would be filled to the level of the surrounding terrain so as to achieve a continuous transition from the base plateau of the pit to the external disposal site. The external disposal site will be developed in the form of several terraces.

After technical rehabilitation, biological reclamation is proposed in the form of planting low shrubs on the floors, creepers and grasses on the slopes, and native trees on the peripheral parts of the terrain. Several possible types of conversion are specified, such as planting plants for the market, developing a lookout point, and building a sports and recreation center.

The second variant solution for the rehabilitation and conversion of the Orašnica open-pit mine was created for the purposes of this paper, and is shown in Figure 8.

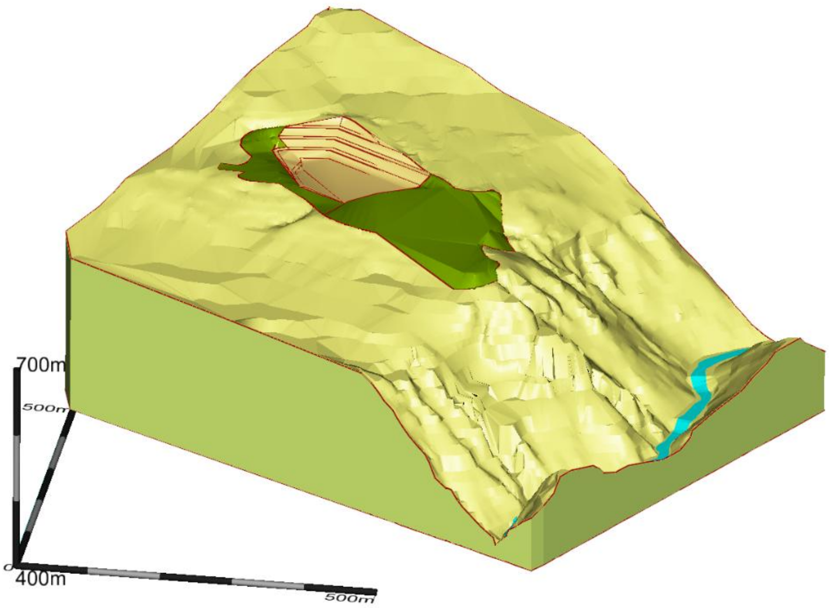

Figure 8. Second variant solution for the rehabilitation and conversion of the Orašnica open-pit mine deposit

The second variant solution for the rehabilitation of the Orašnica open-pit mine partially coincides with the first proposed solution, and so in the part of the development of the mine crater. However, in the part of the rehabilitation (shaping) of the external disposal site, this solution differs significantly from of the first solution. According to Figure 8, it is visible that the plane of the external disposal site continues to the base plane of the open pit, thus creating a significant single surface that is suitable for economic purposes. An area of about 10 ha where a solar power plant could be installed would be prepared by developing the contour of the open pit and disposal site. The power of the power plant depends on the reception capacity of the public network, but part of the energy could be used for business facilities that could also be located in the vicinity. Optimization of the final solution for rehabilitation and conversion can be carried out on the basis of numerical analysis, which will be the subject of further research.

4.2. Variant solutions for rehabilitation and conversion of the Tribošić open-pit mine

The Tribošić open-pit mine is located in Donja Britnica and covers a total area of about 5 ha, together with the disposal sites (Fig. 9). It is about 10 km away from the center of Široki Brijeg. No mining operations are conducted at the open pit. The estimated amount of overburden at the disposal site is about 200,000 m^3. The characteristics of the overburden are the same as at the Orašnica open-pit mine, therefore the crushed stone can be used as a construction material.

Figure 9. Tribošić open-pit mine

According to [34] three variants of conceptual solutions were treated, and a numerical analysis was performed and the optimal variant for the rehabilitation and conversion of the Tribošić open-pit mine was selected (Fig. 10).

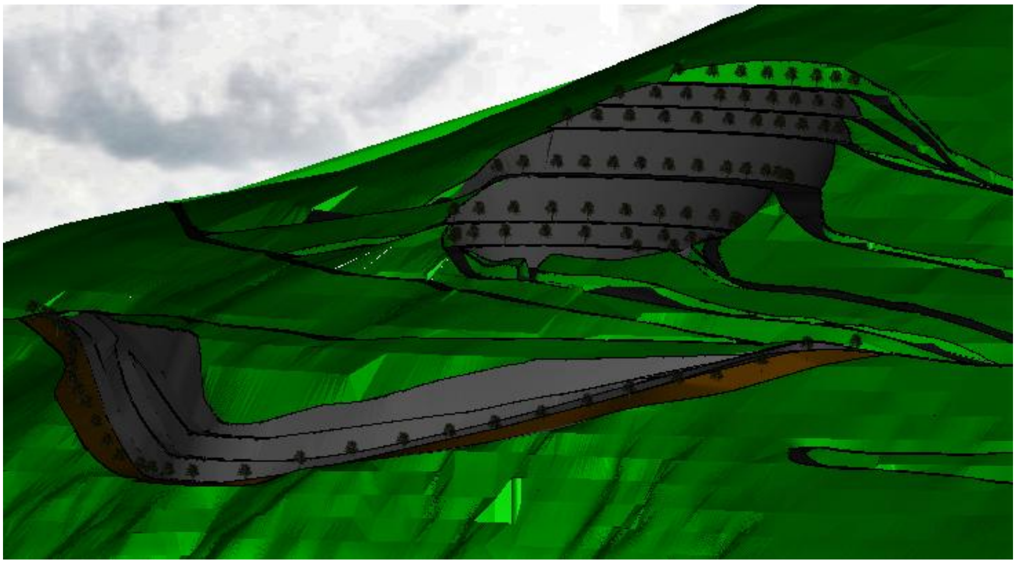

Figure 10. Selected model of rehabilitation and conversion of the Tribošić open-pit mine, view from the southeast

According to the selected model, the entire area will be rehabilitated in two parts. In the upper part, there is a crater that will be rehabilitated by developing five floors, of which there will be four high floors with a width of about 7 meters and a base floor with a width of 22 meters. The three lower floors are 10 m high, and the two upper floors are 20 meters high. The inclination of the floor slope is 60°.
In the lower part of the open pit, immediately next to the asphalt road, three floors 10 meters high and 8 meters wide will be developed. The inclination of the floor slope is 70°, while the final slope is 38°, which is exceptionally favorable in terms of safety. There are many possible solutions for repurposing the Tribošić open pit, and some of them are an amusement park and recreation zones, agricultural or forest areas, etc. Figure 10 shows a variant of biological reclamation of rehabilitated areas, which involves planting trees and grass on the floor surfaces, which would significantly improve the image of the existing landscape. There is a possibility of using the open pit for further exploitation of limestone and dolomite, which can be placed on the market as carbonate raw materials or crushed stone aggregate, considering the planned construction projects in the vicinity (construction of roads, residential buildings, etc.).

4.3. Proposed procedure and expected results

In order to implement the proposal for the multifunctional use of the space of open-pit mines in Crne Lokve and Tribošić, it is necessary, following the previously stated principles, to adopt implementing measures in the spatial planning documentation. After that, it is necessary to create technical documentation in which the data on the types, quantities and quality of mineral raw materials at the respective locations would be treated in detail, and implementing solutions for the rehabilitation and conversion of the space would be created.

Applying the model of multifunctional use of space on the example of surface bauxite mines Orašnica and Tribošić would achieve significant economic, ecological and social interests. In the process, it should be pointed at the fact that significant infrastructure facilities will be constructed in the vicinity of these projects, which will require the supply or exploitation of a certain quantity of crushed stone aggregate, and this means the opening of new open-pit mines (if they do not already exist) or the use of existing resources that are described in this paper. The opening of new open-pit mines represents a new ecological and carbon footprint, which is unjustified because a major environmental impact has been made by already existing mines. Therefore, using existing resources can significantly reduce the new ecological footprint. The model of construction of a highway and low-level roads can certainly be presented here as a good example. Open pit mines for crushed stone aggregate are opened at a maximum distance of about 30 km from the placement location, which means that for a total length of roads of 600 km (example A1 in the Republic of Croatia) it is necessary to open 20 open-pit mines near the route. With an average surface area of 20 ha, this represents a new ecological footprint of 400 ha. The use of previously opened and often unrehabilitated mines would significantly reduce the need for, or the number of, new open-pit mines, and thus the ecological footprint. If the carbon footprint is valued, then it should be pointed out that previous mining operations have already left a certain carbon footprint through mining, loading and transporting the rock located in the disposal sites. Therefore, the failure to use existing resources creates a double footprint on the environment, which is completely needless. In the end, it can be determined that the issue of rational use of existing resources is the level of responsibility of the competent administrative bodies and society as a whole.

5. CONCLUSION

The environmental impacts caused by unrehabilitated open-pit mines are significant, but their negative consequences can be reduced with the application of multifunctional use of space and an integral approach. Examples of conversion of open-pit mines and integration of rehabilitated areas into urban environments show that sustainable spatial management can be implemented with the aim of preserving the environment and improving the quality of life of local communities. Through education, community participation and innovative solutions, it is possible to build a sustainable future that balances the development and conservation of natural resources.

Carrying out rehabilitation would not only integrate the rehabilitated mines into the landscape, but, as in the case of the Orašnica and Tribošić open-pit mines, would bring economic and socially beneficial and attractive locations for the local and wider community. Solving this problem would prevent further impact on the environment and adopt a behavioral model for sustainable resource management, which would help preserve the entire ecosystem, or the living environment of plants, animals and humans. Ultimately, that should always come first, regardless of cost.

Future research will be focused on analyzing and applying the methods of optimizing proposed variant solutions in order to find the optimal solution from different ecological, social, economic, technical and other aspects of the open-pit mining problem.

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