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Hybrid Model for Optimisation of Waste Dump Design and Site Selection in Open Pit Mining

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Abstract: Waste management is an unavoidable technological operation in the process of raw material extraction. The main characteristic of this technological operation is the handling of large quantities of waste material, which can amount to several hundred million cubic metres. At the same time, this operation must comply with all administrative and environmental standards. Therefore, optimising waste rock management (particularly haulage and dumping) has the potential to significantly improve the overall value of the project. This paper presents a hybrid model for the optimisation of waste dump design and site selection. The model is based on different mathematical methods (Monte Carlo simulation, genetic algorithm, analytic hierarchy process and heuristic methods) adapted to different aspects of the problem. The main objective of the model is to provide a solution (in analytical and graphical form) for the draft waste dump design, on the basis of which the final waste dump design can be defined. The functioning of the model is verified using an example of an existing open pit. In the case study, 2250 members of the initial population (different waste dump variants) were generated, and a total of 110 optimised solutions were obtained using 15 optimisations. The solution with the best value of the objective function is adopted, and the final waste dump design is created.

Keywords: waste dump design and site selection; hybrid model; optimisation; genetic algorithm

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1. Introduction

Mining is a complex activity, and the success of a mining project depends on a variety of factors. Certainly, cost management is an important component necessary for the project to realise its full potential. Material handling (particularly haulage) is the largest contributor to the cost of open pit mining, as confirmed using several studies and scientific papers [1–6]. Lately, clean energy transition has been the focus of the modern mining industry. This is recognised as a policy in many countries around the world. Clean energy transition tends to define strict CO_2 emission limits as a form of combat against climate change by integrating more green and renewable energy technology [7]. Many authors have published papers on this topic in the area of coal [8] and metal ore [7,9,10] processing.

Large volumes of waste must be removed in open pit mines in order to expose ore [11]. Waste material is very low in content or, more often, barren material, and it is disposed of in waste dumps or in a much smaller amount used to construct roads, dikes, etc [12].

In general, the majority of these costs are incurred in the excavation, haulage and dumping of waste. This can be explained using the stripping ratio, which is usually greater than one (there are larger quantities of waste than ore), and the fact that capacities and haulage distances for ore are approximately constant. On the other hand, unlike ore, when waste rock is hauled to a dump, the volume in the dump accumulates, resulting in higher costs due to increasing haulage distance and height as the waste dump expands horizontally and vertically [13]. The impact of waste management on total costs is likely to increase given the decline in ore grades in deposits and the trend towards decreasing cut-off grades, resulting in an increase in stripping ratio [14–17] and the need to mine larger quantities of waste per unit of ore. Therefore, optimising waste management (particularly haulage and dumping) has the potential to significantly improve the overall value of the project and is highly desirable. Although this is widely recognised, many authors agree that waste management has not received sufficient scientific and practical attention. Li et al. [13,18,19] argue that current mine planning practice is ore-centric and that little attention is paid to waste dumping. This is further emphasised by Fu et al. [20], who state that the waste management planning process is usually reduced to manual selection of the dump location based on the current shortest route (attention is focused on the short-term haulage cost-saving objective, but long-term objectives are neglected) while ensuring that the waste rock from the pit does not exceed the waste dump capacity. In this way, the importance of waste management is highly underestimated. All this suggests that there is a great need to improve waste management planning, both from a scientific and practical point of view.

There are many papers related to waste management in mining that address specific problems. The optimal location of waste dumps is probably the most frequently analysed. Kumral and Dimitrakopoulos [11] developed a taboo search algorithm for the selection of optimal waste dump sites. The authors take into account financial, environmental and safety considerations to optimise the possibility of dumping waste at five potential sites from six predefined mines. Hajarian and Osanloo [21] have identified the effective factors in selecting the waste dump sites and have developed a linear mathematical model for finding a suitable waste dump site, minimising the haul road construction cost. The authors emphasise that the waste dump site with the shortest haul route is not inevitably the optimal solution, as earthworks and construction costs should be taken into account. In recent years, the selection of a preferred waste dump site has often been based on multi-attribute decision-making (MADM) methods [22–25], and GIS methods have also been popular [26,27]. The focus of these studies is mostly on the correct selection of factors that influence the selection of a waste dump site and its management. In the mentioned papers, different mathematical methods and different sets of criteria are used for selecting the optimal solution. However, the analysed locations for waste dumps are mostly predefined (the best one is chosen from a set of several locations). In this research, there are no predefined locations, but the entire area of interest is divided into sub-zones. This approach is a novelty because all influential factors can be analysed at a much more discrete level (for each sub-zone), which, as a result, increases the precision of the solution.

Many studies recognise the problem of waste scheduling as particularly important to the overall project optimisation process. Li et al. argue that current practice focuses mainly on ore recovery scheduling and subsequently neglects waste scheduling in long-term planning [19]. Mixed-integer programming (MIP) is a commonly used method that has been successfully implemented in several waste scheduling optimisation studies. As expected, minimising the total transport distance is the basic objective function in these studies. Minimisation of the required truck deviation between adjacent years [19] and prevention of undesired environmental impacts such as acid mine drainage [13,18,20] are additional objective functions or constraints used to generate the optimal waste placement schedules. It is important to note that in the mentioned studies, the waste scheduling problem is considered for the case of a defined final waste dump design; that is, the problem of the design and location of the waste dump is not considered. These problems are the focus of the study presented in this paper. Keeping this in mind, this study represents a complementary extension of the existing research.

Internal waste dumping is also an interesting possibility, which has been addressed in many studies [28–31]. Due to the specific geological conditions (shape and location of the deposits) as well as the mining methods used, internal waste dumping is most often, but not necessarily, limited to open-pit coal mining. Sari and Kumral [32] developed an MIP-based model to maximise the Net Present Value (NPV) of the mining project, which, in addition to external dumping, supports a waste dumping option within the same pit. Peng and Zhang [33] developed a mathematical model to determine the optimal height of the internal waste dump and minimise costs.

It is noticeable that among the studies related to waste management, there are very few papers related to the design of waste dumps. This may be unusual, especially considering the amount of attention given to the design and optimisation of pit boundaries. Even some papers related to waste management include the word design in the title, they only partially address the actual overall design components and mostly focus only on the height of the waste dump or on the selection of the optimal one from a set of predefined dump designs based on economic, geotechnical or environmental conditions [34–36]. A particularly interesting study has been carried out by Ortiz [37], who uses linear programming to optimise waste dump design. More specifically, he optimises the ratio between the number of benches and the base area of the waste dump (more dump benches mean a smaller waste dump base area and vice versa) for a given volume, i.e., waste dump capacity. However, the described research does not consider the shape of the waste dump itself (waste dump shape and location are predefined), which is one of the basic components of the design. Precisely, these shortcomings have been addressed in the model presented in this paper.

Summarising the above, it is clear that the majority of studies carried out have focused on optimising waste dump site selection and the problem of waste scheduling, while relatively little attention has been paid to the overall aspects of waste dump design.

This paper presents a hybrid model for the optimisation of waste dump design and site selection. Environmental conditions and constraints are considered using the criteria used in the model, while the waste scheduling issue was not the subject of interest in this research. The goal of the proposed model is to provide a solution for the draft design of the waste dump, based on which an experienced engineer can develop the final waste dump design (similar to the way the final pit design is developed based on the optimal pit shell).

In order to make the paper more understandable, the general structure is shown in Figure 1.

Figure 1. General structure of the paper.

In the introductory part, the significance of the problems related to the waste dump design and site selection is described. In the next chapter, the hybrid model development procedure is described from the aspect of the methods used and with a detailed description of the algorithm steps. In the third chapter, the application of the developed model is shown in the example of the active open pit mine Buvač. In the fourth chapter, the results of the analysis are presented. Additionally, in the conclusion (last chapter), the practical and scientific contributions of the developed model are discussed and highlighted.

2. Hybrid Model Development

To solve many different complex problems related to waste dumps, a hybrid model combines various mathematical methods adapted for individual aspects of the problem.

2.1. Methods

The developed model uses the following mathematical methods:

- Random selection (Monte Carlo simulation)—to simulate the geometry of potential solutions,
- Genetic algorithm—to optimise solutions,
- Multi-criteria decision making—AHP method—for defining variable values,
- Heuristic method—for expert interpretation and finalisation of solutions

2.1.1. The Monte Carlo Method

The Monte Carlo method was first introduced by Metropolis and Ulam [38]. There is evidence of earlier applications of this method, but these applications were not published, so these earlier contributions went unnoticed [39]. Monte Carlo methods are numerical methods for solving mathematical problems using random variables and statistical evaluation of their properties. In Monte Carlo algorithms, so-called random numbers play an important role and, strictly speaking, exist only as the result of random processes [40]. In general, the Monte Carlo method consists of 4 steps [41]:

1. Generation of a static model (process functions),
2. Defining input parameters using probability distribution functions,
3. Generation of random variables from the set of distribution of input parameters,
4. Analysis of the obtained results.

The benefits of the Monte Carlo method have been recognised in many different industries over time. In mining, Monte Carlo has found application in risk analysis and as the accompanying method in the analysis of various problems [42–44].

2.1.2. Genetic Algorithm

The Genetic Algorithm (GA) was introduced by Holland in the early 1970s [45] and belongs to the group of optimisation algorithms whose main goal is to find the minimum or maximum of a function (global optimum). In practice, genetic algorithms should produce an exact or approximate solution to an optimisation or search problem. The result can be a numerical value, a mathematical function, a path in a graph, etc. [46].

GA was developed on the basis of natural selection, i.e., the principle that only the strongest/highest-quality individuals in a population survive to reproduce and form new generations of individuals [47]. Using these basic ideas of evolution and the basic genetic transformations of selection, crossover and mutation, GA solves optimisation problems. Each possible solution to the optimisation problem is represented by a single chromosome or genotype. The parameters of the problem are encoded as genes in the chromosome [48].

It's well known that natural reproduction can lead to certain drawbacks, such as degeneration in the population. A similar can occur when GA is used for optimisation. In such situations, individuals from the offspring generation will not have better characteristics than individuals from the parent generation. The value of the objective function for this type of individual will be worse (far from the optimal solution), so they will be excluded from the selection process. In addition to the appearance of such solutions, one of the most common problems encountered during the work of the GA is early convergence. Early convergence occurs when the GA population reaches a suboptimal state. This means that the genetic operators can no longer produce offspring with better performance than their parents. Thus, evolutionary algorithms remain trapped in the domain of local optimum [49]. The basic flowchart of a GA is presented in Figure 2 [50].

Figure 2. The basic flowchart of genetic algorithm [50].

The first shape of the flowchart (parallelogram in Figure 2) defines the input data, i.e., the initial population. The other shapes represent the basic operations of the genetic algorithm. The method implies an iterative procedure, i.e., the creation of the next generation.

The use of GA in various scientific fields remains very common. It's similar in mining, where GA is most commonly used for production and equipment scheduling optimisation [51–53], cut-off optimisation [54,55], and grade and quality control [56,57].

2.1.3. Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a decision-making method developed by Thomas L. Saaty in the 1970s. It provides a structured approach to dealing with complex decisions by breaking them down into a hierarchical structure and evaluating the relative importance of different criteria and alternatives [58]. AHP is widely used in various fields, including business, engineering, health care and environmental management [59].

The general schematic display of the AHP method structure is shown in Figure 3. The goal (zero level) of the AHP method structure is at the very top. After the goal, level 1 contains the criteria, after which comes the sub-criteria. The last level of the structure (level 2) contains the alternative choices, which are analysed according to the defined criteria and sub-criteria. The number of criteria and sub-criteria in the model is unlimited. On the basis of the defined criteria and sub-criteria, the dependency between them and the qualities of the considered alternatives is established, and they are evaluated in comparison, after which we obtain the final solution in the form of the best choice [60].

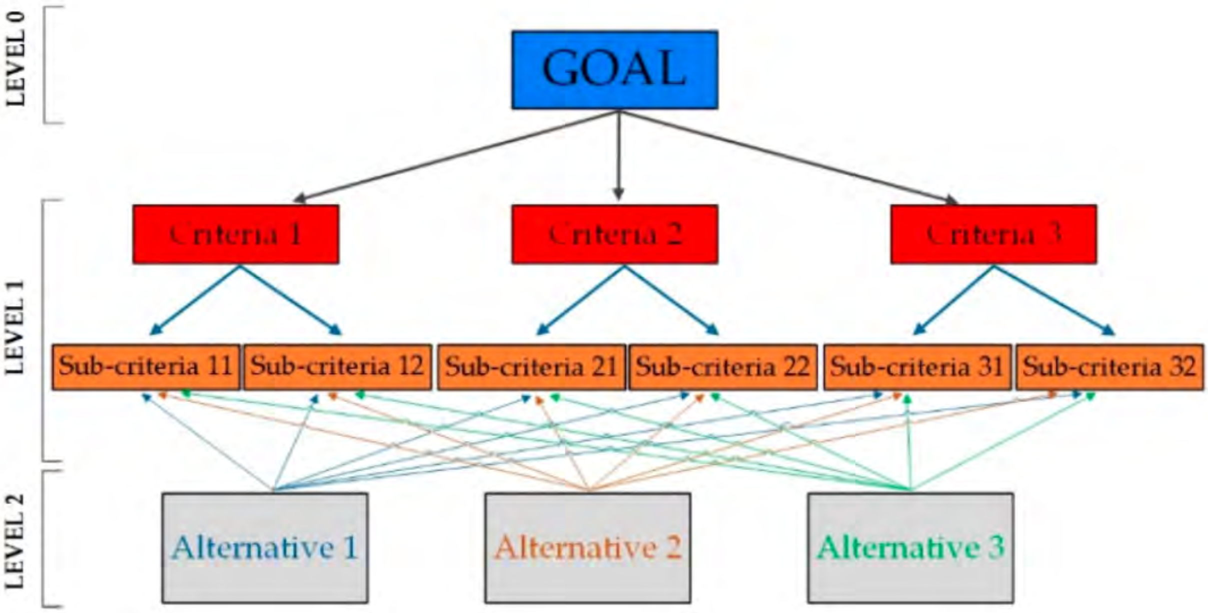

Figure 3. The schematic display of the structure of the analytical hierarchy process (AHP) method [60].

The AHP method consists of the following steps [61,62]

1. Define the unstructured problem and clearly state the objectives and outcomes.
2. Decompose the complex problem into a hierarchical structure with decision elements (criteria, detailed criteria and alternatives).
3. Pairwise comparisons—assess the relative importance of criteria and alternatives using pairwise comparisons (using a scale that reflects their relative preference or importance).
4. Derive priority weights—based on pairwise comparisons; the AHP calculates priority weights for each element in the hierarchy (these weights quantify the relative importance of each element in achieving the goal).
5. Consistency check—evaluates the consistency of the pairwise comparisons to ensure their reliability.
6. Aggregation and ranking—combine the priority weights to obtain a comprehensive ranking of the alternatives.

As the AHP method provides a systematic and structured approach to decision-making, it has found significant application.

2.2. Model Algorithm

The proposed hybrid model algorithm can be roughly divided into three steps and is shown in Figure 4.

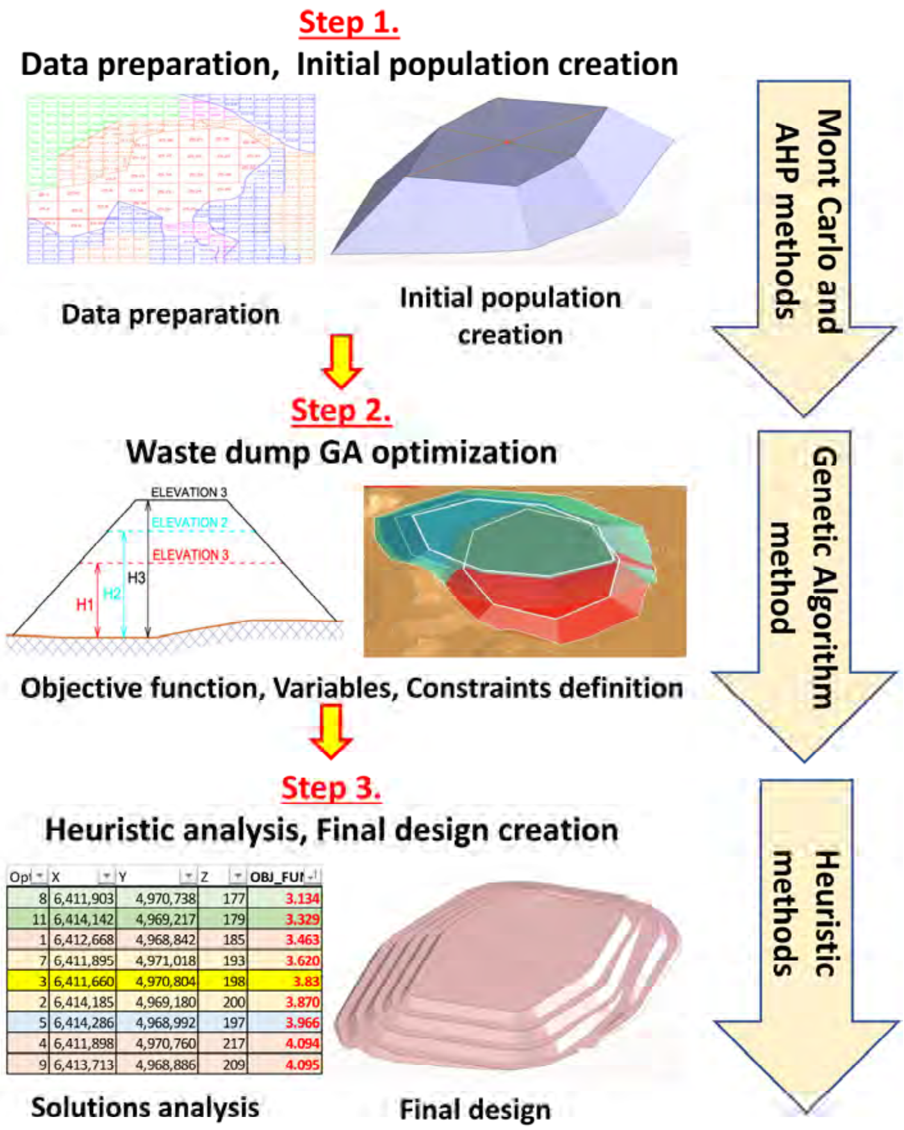

Figure 4. Hybrid model algorithm.

All three steps are characterised by a significant set of operations, which must be performed in order to ensure the functioning of the model and the generation of results (optimised draft design of the waste dump).

In the first step, the input data and the initial population are defined, i.e., elements necessary for the subsequent optimisation process. The entire area of interest is divided firstly into zones and then into sub-zones, and by using the AHP method, coefficients are defined that increase the costs of forming waste dumps along some specific sub-zone. These coefficients represent all the additional factors (various risks, administrative obstacles, environmental impact, etc.) that are characteristic of each sub-zone. Additionally, in the first step, Monte Carlo simulation is used for the generation of the initial population (for the genetic algorithm). Members of the initial population are represented by randomly generated waste dump designs.

In step two, defined input data and initial population are further used for the genetic algorithm optimisation process. In this step, all necessary optimisation parameters (objective function, variables, constraint functions) are defined and set. In the optimisation process, a standard set of genetic algorithm operations (evaluation, selection, crossover, mutation) is executed. After multiple iterations, a set of optimised solutions (set of optimised waste dump designs) is generated. The solutions are ranked and generated in analytical and graphical form.

In step three, a solution that has the best objective function result, in this case, the lowest cost of waste dump formation (EUR /m^3 of waste material), is used for further processing (detailed engineering). This last step is done manually in some specialised 3D mining software, where from the generated waste dump draft design, the final, detailed waste dump design is produced. Due to their importance and ease of understanding, the mentioned steps are described in detail in the text below.

2.2.1. Step 1—Data Preparation and Initial Population Creation

The first step in the algorithm is mainly related to data preparation, constraints definition and initial population generation (for the next step, i.e., GA optimisation). All the required data are part of the standard data set that is usually found during the design of waste dumps. According to the algorithm, it is necessary to define:

- Waste dump capacity,
- Overall slope angle of the waste dump,
- Basic geometry (shape) and elevation of waste dump top area,
- Definition of terrain zones to be analysed using the model and zone evaluation.

The capacity of the waste dump is determined by the planned amount of waste material from the pit, increased by the swell factor. The overall slope angle of the waste dump depends on the properties of the waste material.

Geometry and elevation of waste dump top area are characteristics of each waste dump, and in this case, shape and elevation range (minimum and maximum elevation) are necessary elements of the initial population creation for further optimisation (GA). Basically, waste dump design can be controlled by waste dump top area (elevation and shape), overall slope angle and topography (defines waste dump base area). If we generate a waste dump top area with a random shape and elevation and expand the top area boundary according to the overall slope angle to the intersection with the terrain, we will obtain a randomly generated waste dump. The same methodology is used to generate the initial population in the presented model.

More specifically, the generation of the initial population in the proposed hybrid model starts with the generation of a point with randomly selected X, Y and Z coordinates (Figure 5). The selected coordinates (X and Y) must be within the terrain zone in which we consider waste dump creation, while the Z coordinate (elevation) is selected from the range of minimum and maximum elevations of the future waste dump. The elevation range is created empirically, and in practice, the set of possible values is often constrained by existing administrative restrictions (e.g., the maximum elevation of an object in a certain zone may be limited by some administrative rule).

By generating several axes using a randomly selected point (at the same elevation as the point), the upper area of the waste dump is obtained. The process starts by drawing the first axis (k-axis, Figure 5) with a chosen length and direction relative to the north. Both the length and direction of the first axis can be specified by the user, and they can be randomly selected from the range of values created. It is recommended that the direction of the first k-axis coincides with the longest axis of the terrain zone. To obtain a feasible top of the waste dump, at least two other axes should be generated (axis-u and axis-s, Figure 5). The directions of the axes can (but do not have to) be equally divided (360°/two times the number of axes). The lengths of all other axes are partially controlled by the length of the first axis in the sense that the lengths between the axes cannot be too different in order not to generate technologically unfeasible (concave) shapes of the waste dump top. By connecting the ends of the generated axes, the waste dump top area is created. By expanding the top area boundary, according to the overall slope angle, to the intersection with the terrain, a randomly generated waste dump design is obtained. This provides an initial population for further optimisation. It is important to note that not all randomly generated members of the initial population will be good candidates for further optimisation, in which case they will be discarded as unfit in the first step of the genetic algorithm.

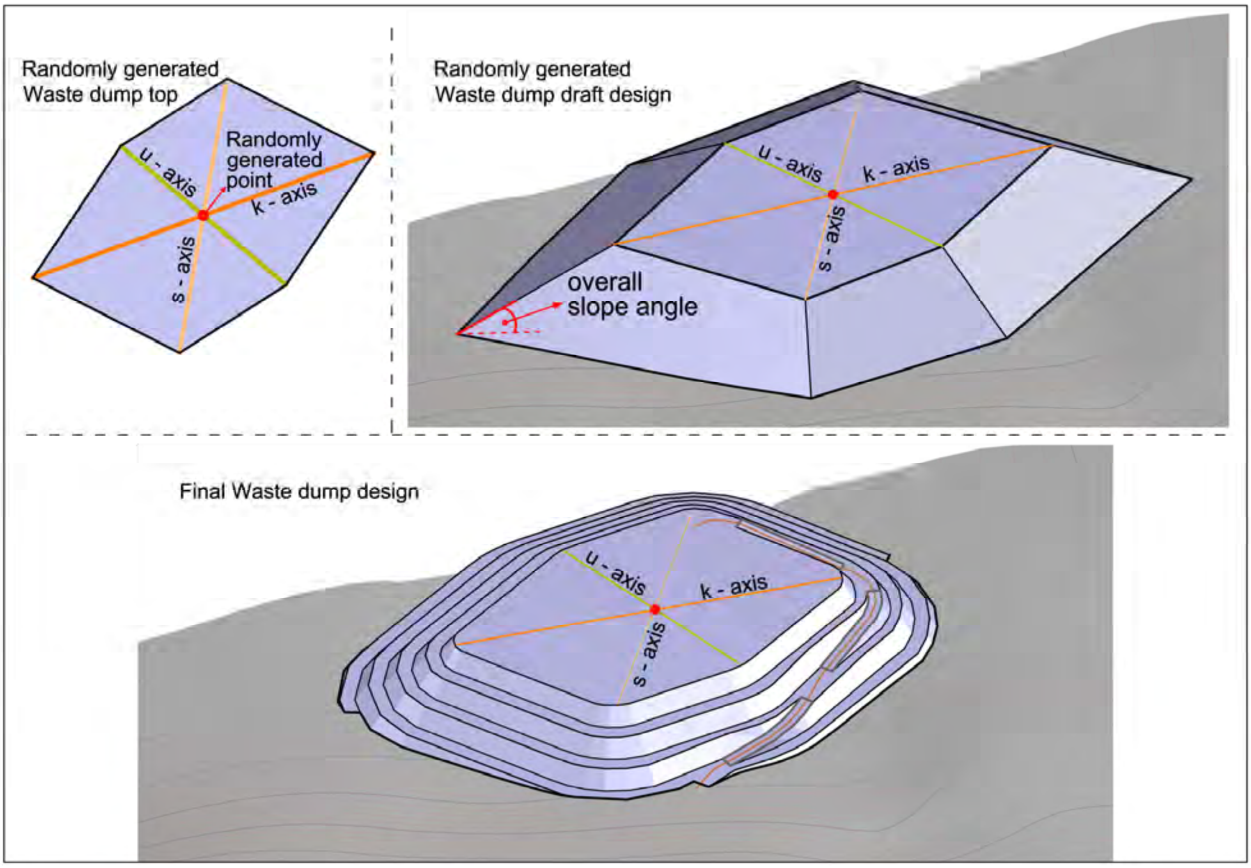

Figure 5. Model basic geometry steps.

Via the other steps, after the GA optimisation process and heuristic analysis of the generated solutions, the final waste dump design is created (Figure 5).

As emphasised in the introduction, the value of the land on which the waste dump is formed also represents a significant part of the total cost, in addition to the cost of hauling. For this reason, special attention in the model is given to the valuation of the land zones that are candidates for the creation of waste dumps. It is important to note that the value of a piece of land does not only mean the value that could be obtained by simply buying the land and that other factors should also be taken into account. These factors include various risks, such as the existence of administrative obstacles or problems related to the acquisition of ownership, the risk of mine expansion along a zone around the current final pit limit, the waste dump environmental impact, etc. In order to take into account all these different factors and to ultimately valorise them (using a single price per square meter of land), the AHP method is used in the model.

To accurately assess the value of land, the area of interest is divided into a number of zones according to the type of land (civil and industrial zone, agricultural zone, forest, etc.). Each zone is further subdivided into sub-zones, which, in practice, may represent private plots (Figure 6). Zones and sub-zones of different land types are marked with different colours (Figure 6). A nominal value (EUR/m^2) based on the corresponding zone (type of land) is assigned to each sub-zone. This value is increased by coefficients obtained by applying the AHP method. These coefficients represent all the additional factors (various risks, administrative obstacles, environmental impact) that are characteristic of each sub-zone. The additional factors are specific to each mining project and can be modified according to the needs and realistic conditions of each location. It is important to note that if the estimated environmental impact (for example), in the case of a sub-zone, is significant enough to completely prevent the formation of a waste dump, the coefficient obtained using the AHP method will increase the value of that sub-zone and disqualify all solutions that include waste dump design along that sub-zone.

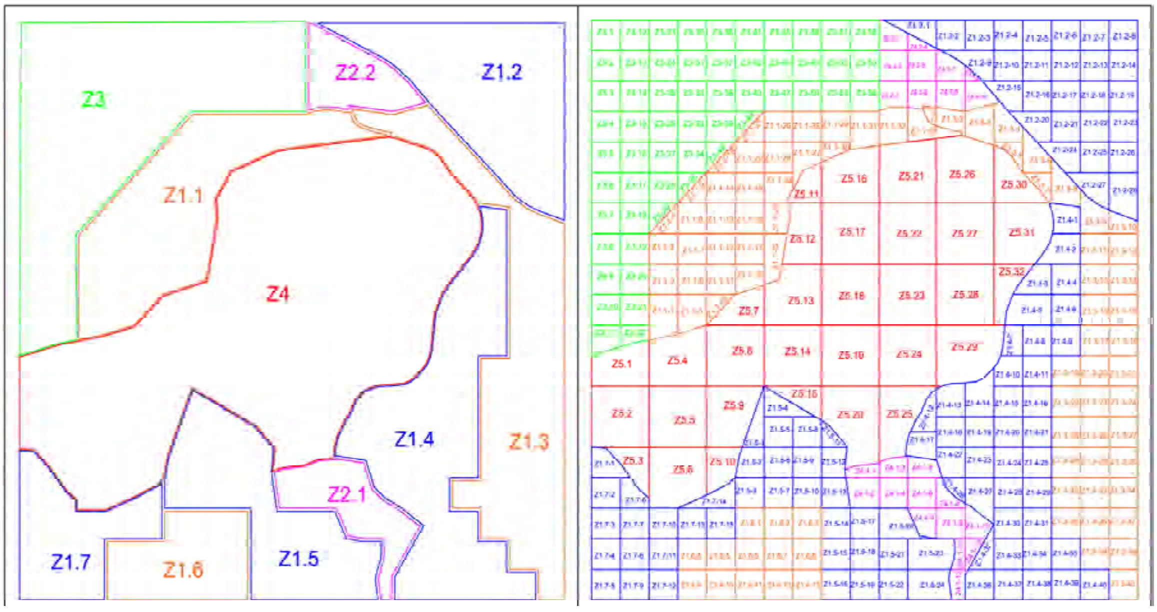

Figure 6. An example of an area of interest division into zones and sub-zones.

Finally, if there are civil, infrastructural or industrial facilities in a sub-zone, additional costs have been added to that sub-zone.

The value of an individual subzone (i) in the model is calculated based on the equation:

$$V_{sz_i} = V_{z_i} \times A_{sz\_i} \times \sum \left(\frac{1}{k_1} + \ldots\ldots + \frac{1}{k_n} \right) + V_{a\_i}, \quad (1)$$

where:

V_{sz_i}—Value of sub-zone i (EUR),

V_{z_i}—Value of sub-zone i, based on a type of land (EUR /m^2),

A_{sz_i}—Area of sub-zone (m^2)

$k_1 \ldots\ldots k_n$—Coefficients obtained from the AHP method for all additional factors,

V_{a_i}—Value added if civil, infrastructural, industrial facilities, etc., are located in subzone i (EUR).

The introduction of the AHP method into the algorithm of the presented model was carried out to more accurately determine the input parameters (value of the land for the potential waste dump) and thus create better conditions for further optimisation. It is understood that the use of the AHP method in the presented model is not mandatory and can be avoided if there is not enough data for analysis or a detailed assessment is not required.

2.2.2. Step 2—Waste Dump Optimisation—Objective Function, Constraints and Variables

Once the initial population has been generated and the zones of interest have been evaluated, the optimisation process is carried out. From a strictly theoretical point of view, the number of possible solutions for the location and design of the waste dump is practically infinite. Anyone can imagine a waste dump that is a few metres higher or lower, a few meters wider or narrower, or in a location that is shifted in a certain direction. Given the nature of the problem and the infinite number of possible solutions, the GA was chosen for optimisation.

The initial step in GA optimisation is defined by the objective function [51]. It is also necessary to define the elements to be optimised (variables), as well as their limits (constraint functions) [63]. Additionally, at the very beginning of the optimisation process, it is necessary to define the number of individuals in the initial population, as well as the number of generations.

The technological operation of waste handling generates unavoidable costs. By reducing these costs, the performance of a mining project can be significantly improved. Bearing this in mind, the objective function of the proposed model is to minimise the cost of waste dump formation. This means that the solution with the lowest cost is considered to be the best. It is important to note that, by using the AHP method, additional factors that do not have monetary values (administrative and legal obstacles, possible environmental impact, etc.) can be included in the proposed model.

In the specific case, the cost of creating a waste dump can be influenced by various factors, but in general, two basic categories (present in the creation of any waste dump) are:

1. Costs related to the value of the land on which the waste dump is built and
2. Haulage costs.

For this reason, special attention in the model is given to these two categories.

The costs associated with the land value are defined in Equation (1). The haulage costs can be divided into two components: horizontal and vertical transport. This division into types of transport is essential for the functioning of the algorithm. The relationship between the cost values of the horizontal and vertical transport components optimises the design of the waste dump (Trade-off between having a waste dump with a larger area and a smaller height or vice versa. The location of the waste dump is also largely determined by the cost of haulage (a waste dump closer to the mine and at a lower elevation will generate lower costs). Taking all this into account, the objective function can be written in the form:

$$Minimize\ C_{min} = C_1 + C_2 + C_3, \tag{2}$$

where:

C_1—is the cost related to the value of the land along which the waste dump is formed, and it is defined by Equation (1),

C_2—represents the horizontal component of haulage costs,

C_3—represents the vertical component of the haulage costs.

The horizontal component of the haulage costs represents the costs that would be incurred to haul the waste material along the horizontal part of the route (sections without inclines) from the centre of mass of the waste material in the pit to the pit exit point and from the pit exit point to the centre of mass of the waste dump. This component is divided into two parts (to and from the pit exit point). If the waste exit point from the pit is already defined, the route should include the increase in length due to curves along the route. The horizontal component of the cost is defined by an equation:

$$C_2 = V \times L_t \times C_t, \tag{3}$$

where:

V—is the volume of loose waste material to be placed on the waste dump (m^3),

L_t—is the horizontal distance between the centre of mass of the waste material in the pit and the waste dump (km),

C_t—is the cost of hauling 1 m^3 of waste material over a horizontal distance of 1 km (EUR/m^3/km).

The value of C_t can be obtained from existing open pit statistics or from mining equipment manufacturers' manuals.

The vertical component of the haulage cost represents the additional cost of lifting the material from the elevation of the waste material centre of the mass in the pit to the elevation of the waste dump centre of mass. It essentially represents haulage costs on sections of road with gradients and is defined by an equation:

$$C_3 = V \times \frac{\Delta H}{i} \times C_t \times k, \quad (4)$$

where:

V—is the volume of loose waste material to be deposited on the waste dump (m^3),

ΔH—is the elevation difference between the waste material centres of mass in the pit and the waste dump (m),

i—Average ramps grade (%),

$\frac{\Delta H}{i}$—Total length of inclined sections (m),

C_t—Cost of hauling 1 m^3 of waste along a horizontal distance of 1 km (EUR/m^3/km),

k—Cost adjustment coefficient between horizontal and vertical components.

Hauling material along inclined sections of road has a negative effect on energy consumption, truck speed, and increases the overall stress on the machinery (more about this can be found in [12] and numerous manuals from various mining equipment manufacturers). For this reason, the cost of hauling on inclined sections of road is significantly higher than the cost of hauling on horizontal sections of road. This difference is represented by the cost adjustment coefficient (k) between the horizontal and vertical components. A similar method for converting vertical to horizontal distance is presented by Li et al. [64]. In general, the coefficient k will vary in different locations (different open pits) and will depend on many factors (quality of road construction, type of truck, organisational conditions at the pit, slope of ramps, etc.).

Considering the above, the objective function can be defined by the following equation:

$$Minimize\ C_{min} = V_{z_i} \times A_{sz\_i} \times \sum \left(\frac{1}{k_1} + \ldots + \frac{1}{k_n} \right) + V_{a\_i} + V \times L_t * C_t + V \times \frac{\Delta H}{i} \times C_t \times k, \quad (5)$$

Despite the fact that the objective function defined in Equation (5) has a unique form adapted to the functionality of the model, it is based on earlier research [11,18,37,64] on the influencing factors and the importance of cost minimisation in the formation of waste dumps.

It is understood that each mining project has its own unique mining conditions, i.e., different sets of factors can affect the cost structure of waste dump formation to a greater or lesser extent. Bearing this in mind, it is clearer that Equations (2) and (5) provide only the general structure of the most common costs of waste dump formation and that for a specific mining project, this equation can be expanded with additional cost categories (cost of reclamation, groundwater conditions of waste dump base, necessary preparatory works that precede the waste dumping process, the costs of removing humus and topsoil from a certain area, etc.). Additionally, it is important to note that the objective function of the applied optimisation algorithm is based on cost minimisation, which is a universal goal in mining projects. Therefore, the developed model can be successfully applied to open pits with different types of mineral deposits.

It should also be noted that these equations provide only the initial costs of waste dump formation. Final costs may vary significantly and will be known more precisely after the engineering and construction phase of the project.

Introducing constraints into the optimisation algorithm reduces the number of possible solutions. In this way, model functioning is significantly accelerated. Constraints should be defined in such a way that technically infeasible solutions are rejected (infeasible variants of the generated waste dumps). At the same time, constraints should be carefully defined in order not to reject solutions with potential.

The following constraints are incorporated into the model:

- waste dump capacity (volume),
- waste dump elevation,
- waste dump position in XY plane.

The capacity of the waste dump is determined by the volume of waste to be excavated from the pit, increased by the swell factor. Considering the stochastic nature of the optimisation algorithm, the exact value of the required capacity cannot be formulated as a constraint, as this would significantly reduce the number of possible solutions. Specifically, in this way, generated waste dumps that have a slight deviation from the required volume would be rejected from the optimisation algorithm, which would considerably reduce the set of solutions and thus the possibility of finding the solution (waste dump) with the best value of the objective function. For this reason, the capacity constraint should be set as a range of values around the exact required volume. A wider volume range, from the minimum volume (V_{min}) to the maximum volume (V_{max}), will increase the set of potential solutions but also the optimisation time. The experience gained during the development and extensive testing of the model suggests that all solutions up to 5% smaller and 10% larger than the required volume should be considered for further optimisation (next generation in GA). The range is not symmetrical because we deliberately favour solutions (waste dumps) that have a slightly higher capacity (reserve up to +10%) than waste dumps that have a slightly lower capacity than required (down to 5%). The constraint related to the waste dump capacity is formulated by the equation:

$$V_{min} \leq V \leq V_{max}, \tag{6}$$

The elevation of the top of the waste dump should not exceed a reasonable value (Z_{max}). The maximum elevation of the waste dump is usually limited by some administrative norm. The minimum elevation of the potential waste dump top must be higher than or equal to the lowest elevation of the terrain (Zt_{min}). The constraint range related to the waste dump elevation is formulated by the equation:

$$Zt_{min} \leq Z \leq Z_{max}, \tag{7}$$

Generated waste dumps (potential solutions) must be located within the boundaries of an area which is suitable for waste dumping. This constraint is formulated as:

$$(WD_{i \ldots n}) \in \mathit{Suitable\ area}, \tag{8}$$

where WD_i is the potential waste dump solution i (where i is from 1 to n-number of potential solutions).

All geometric parameters defining the waste dump design can be considered variables (genes) in GA optimisation. The choice of parameters, whose value will be varied to obtain new solutions (chromosomes) in the GA process, depends on the conditions under which the optimisation is carried out and is subject to engineering decisions.

Changing the shape of the top or base area, as well as the overall slope angle and the top elevation of the waste dump, will affect the design of the waste dump. Since the waste dump base area in the proposed model is determined (controlled) by the initial random generation of the waste dump top area, and as the overall slope angle is based on the waste material property (the largest angle that guarantees stability is used), the waste dump top elevation and shape are treated as variables.

2.2.3. Step 3—Heuristic Analysis of Optimization Results and Final Waste Dump Design

During the algorithm execution, many optimised solutions (waste dump designs) are generated. Infeasible solutions, i.e., those that do not meet the given constraints, are rejected during the optimisation process. The performance of feasible solutions is different, i.e., they have a higher or lower value of the objective function (cost minimisation). The solution with the lowest cost of waste dump formation (EUR /m^3 of waste material) is used for further processing (detailed engineering). Optimisation results are exported from the model in analytical and graphical form. Analytical form (csv file format) provides basic input parameters and results. Graphical form (dxf file format) is suitable for import into some 3D mining software, where contour lines of the best solution can be generated. Based on the generated contour lines (whose equidistance corresponds to the elevation of the dump benches), the final design is produced. This last step (from contour line to final design) is done manually by an experienced engineer.

The functionality of the developed model can be used in two modes.

In the first mode, the volume constraint is set in a narrow range around the required volume. All generated waste dump designs will have the required capacity (volume of waste material from the pit increased by the swell factor).

In the second mode, the volume constraint is set in a wide range. The maximal value of the volume range (V_{max}—from Equation (6)) is set to the required volume, and the minimal value of the volume range (V_{min}—from Equation (6)) is set to a value several times smaller. This mode examines the case in which it is potentially more cost-effective to create two (or more) waste dumps whose sum of volumes corresponds to the required volume. This case is particularly interesting when there are several physically separated zones (where the formation of waste dumps is possible) around the pit.

3. Case Study

In order to illustrate how the model works, a case study has been conducted for the Buvac open pit mine. The Buvac is located in the Prijedor Municipality, in the north-western part of Bosnia and Herzegovina, entity of the Republic of Srpska (Figure 7).

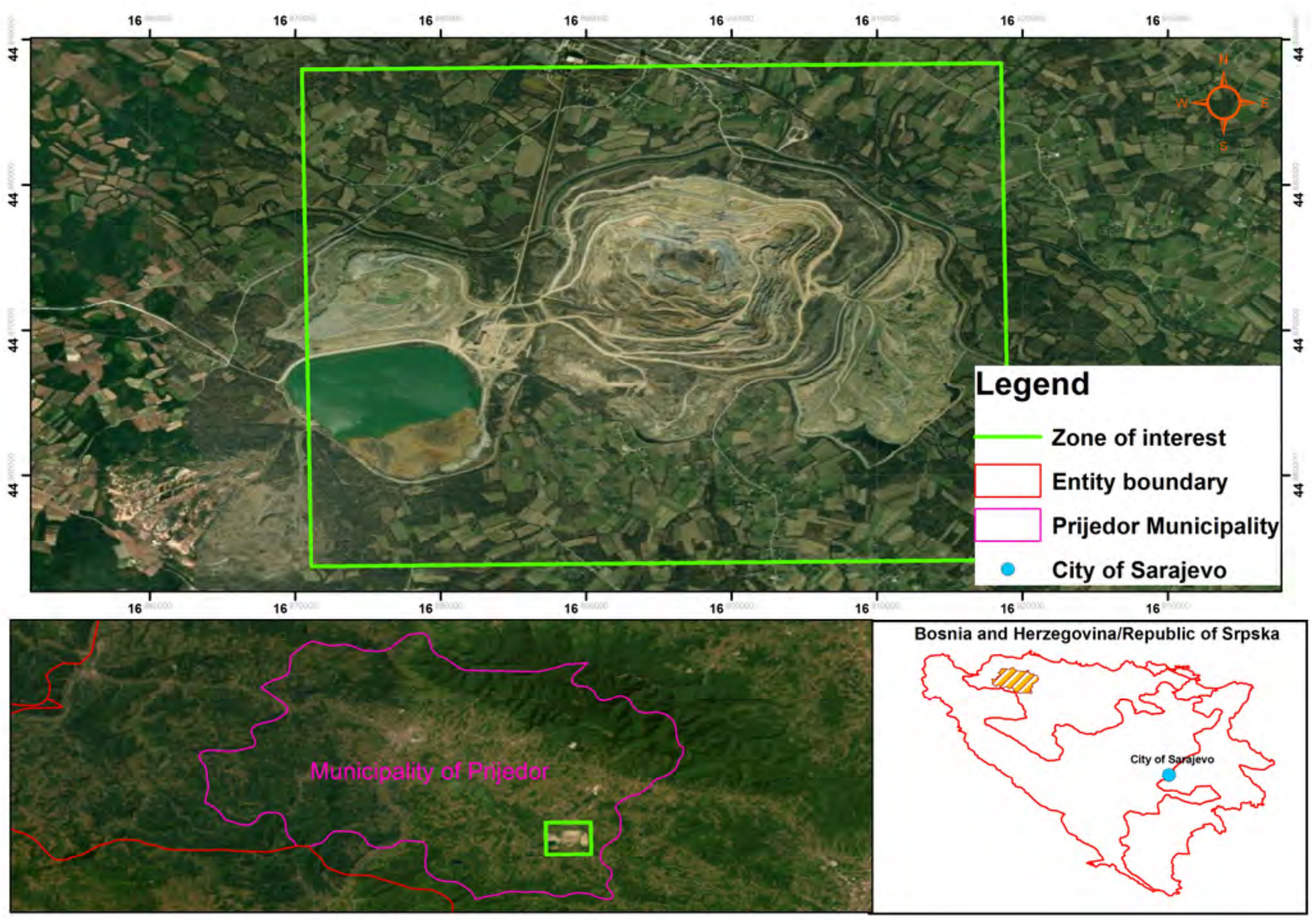

Figure 7. The location of open pit Buvac (Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, Aero Grid, IGN, and the GIS User Community).

Mining operations at the Buvac open pit started in 2008, and the capacity is set at 1.5 million tons of iron ore. In the past, waste material was dumped in the area of the former open pit "Jezero" (southwest of Buvac) and in the waste dump located south of the Buvac open pit. Since these two sites have reached full capacity, it is necessary to find additional space and define a new waste dump for future operations. By the end of the mine's life, an additional 16.5 million m^3 of waste will be excavated. Taking into account the swelling factor, it is necessary to design a waste dump with a capacity of 20 million m^3.

Buvac Waste Dump Optimization

The presented model was developed using the educational version of Matlab software [64], with integrated modules for Monte Carlo and Genetic algorithms. The AHP method conducted for the valorisation of the terrain around the Buvac open pit was developed in Microsoft Excel [65], while Surpac software [66] was used for heuristic data analysis and detailed engineering. The whole process was carried out on a computer with relatively modest characteristics (12 Gb of RAM memory, 7th generation I7 processor, integrated graphics card).

In order to accurately assess the value of the land surrounding the pit, the area of interest is divided into four zones according to the type of land (Z1-Agricultural Area, Z2-Mine Property Area, Z3-Residential Area, Z4-Mining Area). Each zone (except Z4-Mining Area) is further divided into sub-zones (private plots of land, Figure 8). The value of each sub-zone is determined based on the corresponding zone (type of land) and coefficients obtained by applying the AHP method (factors and other details of the AHP method are shown in Table 1). The final design of the open pit mine did not include the entire deposit but only those parts where mining was economically justified. This means that there is potential for future expansion of the pit boundaries along certain sub-zones. For this reason, the potential expansion of the open pit limits is included in the list of AHP analysis factors. The possibility of obtaining all administrative permits and property rights is not the same for all sub-zones, so this factor is also included in the AHP analysis. The creation of waste dumps along the various sub-zones will have a greater or lesser impact on the environment (inevitable noise and dust emissions, impact on waterways, etc.). Therefore, using the AHP method, the environmental impact of each sub-zone was assessed individually, depending on the location of the sub-zone in relation to existing settlements. Finally, the value of each sub-zone (obtained from the type of land and the AHP analyses) is additionally increased if there are civil, infrastructural or industrial facilities in some sub-zones (according to Equation (1)).

Table 1. Factors and coefficients from AHP analysis.

Factor	Coefficient	Rang	Index
Potential open pit expansion	0.657	1	K1
Potential administrative obstacles	0.105	3	K2
Increased environmental impact	0.238	2	K3

The mining area (Z4) represents the zone where open pits and existing mining facilities are located, and as such, is not suitable for the waste dump formation. For this reason, the value of this zone has been artificially inflated to avoid the generation of results along this zone.

In order to implement the GA optimisation process, it was necessary to define the constraints. As mentioned above, the required capacity of the waste dump is 20 million m^3. By surveying the area around the open pit ("overall zone of interest"), it was found that the areas to the north and south of the pit contain settlements (the value of the land here is significant, so we should not expect solutions in these areas). There are also existing mining facilities (old waste dumps and tailing ponds) along the south side of the pit. Since this is recognised as Zone 4—Mining Area (where it is not possible to form a waste dump), the southern side is practically disqualified from consideration, i.e., the algorithm will not be able to generate solutions here.

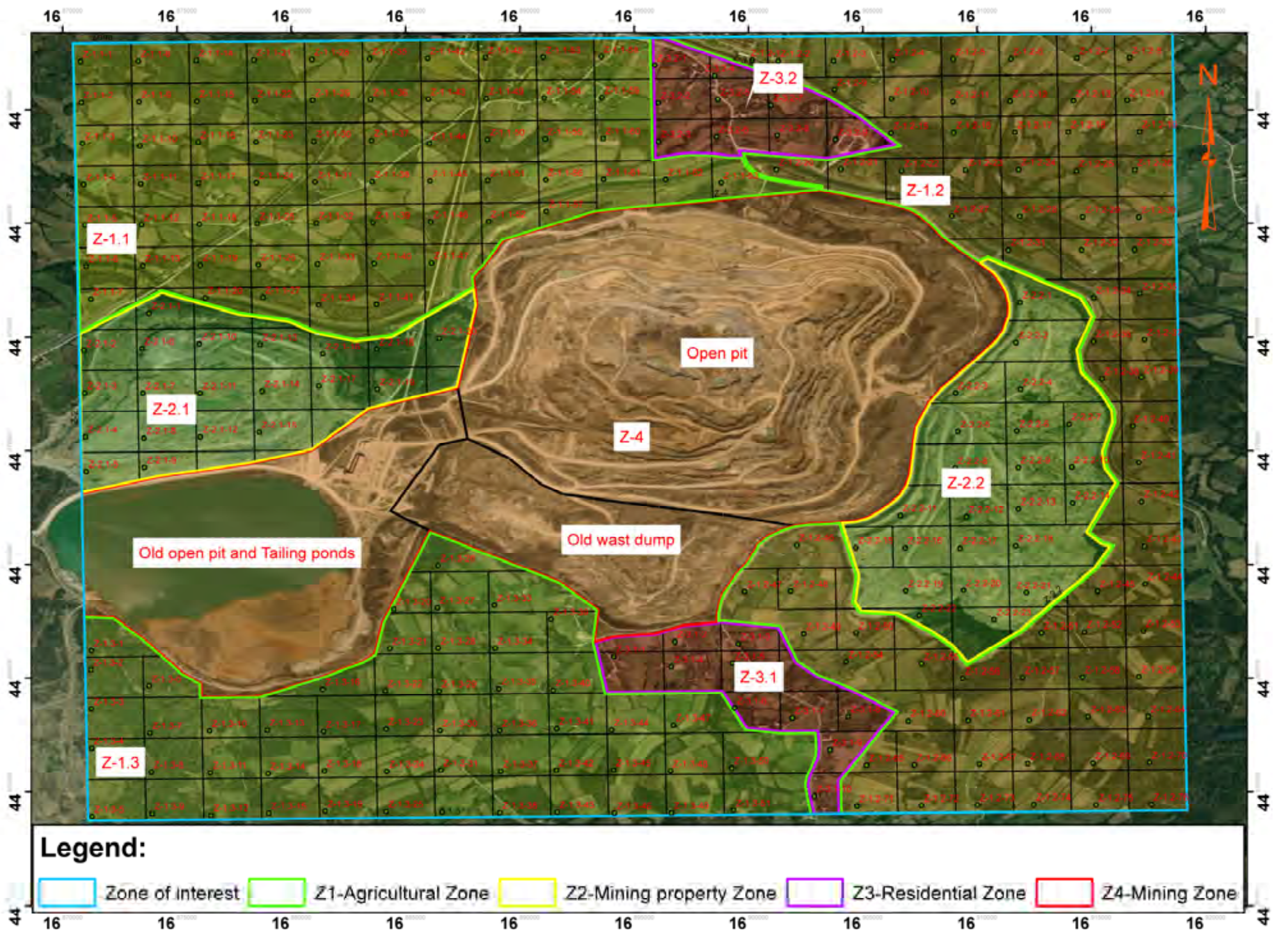

Figure 8. Division into zones and sub-zones (Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, Aero Grid, IGN, and the GIS User Community).

Based on statistical data from the open pit, the cost of hauling 1 m^3 over 1 km is estimated to be EUR 0.8 for the horizontal component and EUR 1.2 for the vertical component of the haul.

After further consideration, it was determined that it is possible to form one or more waste dumps along the eastern and western sides of the mine. Since there are two physically separated areas (east and west sides of the pit) where the formation of waste dumps is possible, the second mode of operation of the optimisation is used. This means that the volume constraint (Equation (6)) is given in a wide range; specifically, the minimal volume V_{min} is set to 6 million cubic metres, and the maximal volume V_{max} is set to 22 million cubic metres (note that a slightly larger value than the required volume is deliberately given):

$$6 \times 10^6 \text{ m}^3 \leq V \leq 22 \times 10^6 \text{ m}^3, \tag{9}$$

The constraint range, related to the waste dump elevation, is set between 150 m for Zt_{min} (the lowest terrain elevation in the zone of interest) and 240 m for Z_{max} (the highest waste dump elevation):

$$150 \text{ m} \leq Z \leq 240 \text{ m}, \tag{10}$$

The elevation and shape of the waste dump top area were used as variables in the optimisation process.

During the testing of the model's functionality, it was found that in order to reduce the processing time, it is more practical to perform more optimisations with a smaller initial population than vice versa. For this reason, 15 optimisations were performed with the aim of generating a sufficient set of solutions. Note that in each optimisation, all parameters and constraints were the same. The basic GA optimisation parameters are given in Table 2.

Table 2. Basic GA optimisation parameters.

Model Operational Mod	Volume Range (m^3)	Number of Initial Population Members	Number of Optimisations	Generations Number
Mod 2	6×10^6–22×10^6	2250	15	5

In further analysis, the 15 best solutions were considered, and the results analysis are shown in Table 3. The solutions are listed in the table from best (the smallest objective function) to worst. The graphical results for the 15 considered solutions are presented in Figure 9. In order to more clearly show the spatial position of the generated solutions, the border of the mining area (the area where waste dumps cannot be generated) is marked with a red line (Figure 9).

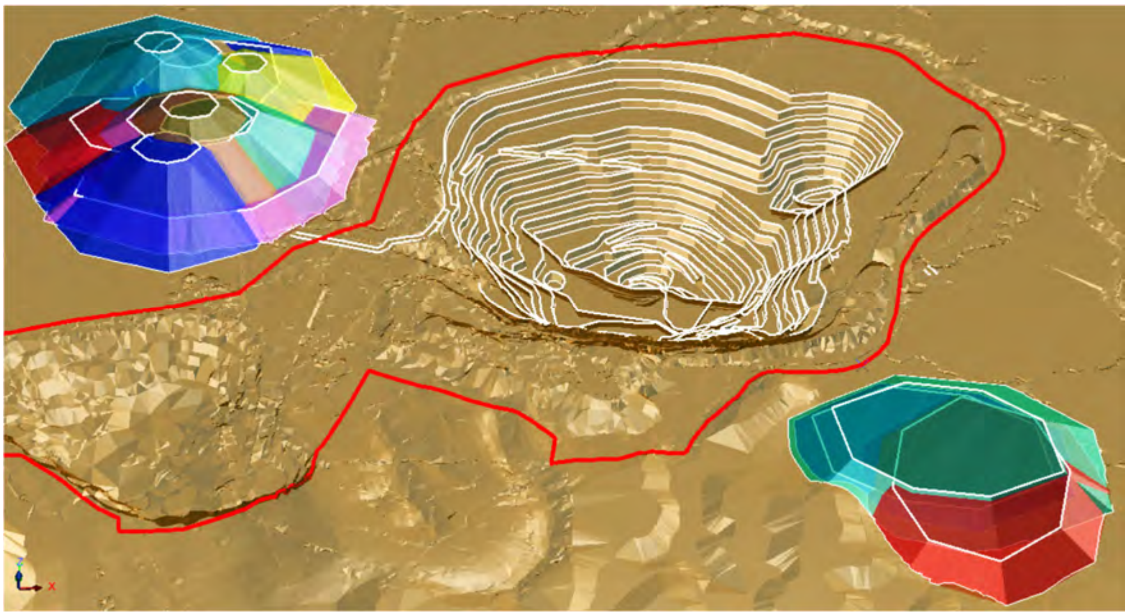

Figure 9. Graphical results for the top 15 solutions.

Table 3. Analytical results of top 15 solutions.

Solution Rang Number	Point Coordinates			Haul Distance Component (m)		Costs (mil EUR)			Waste Dump Volume (10^6 m^3)	Objective Function (EUR/m^3)
	X	Y	Z	Horiz.	Verti.	C_1	C_2	C_3		
1.	6,411,903	4,970,738	177	1288	1740	13.82	28.02	0.19	13.05	3.13
2.	6,414,142	4,969,217	179	1459	1786	10.21	18.75	0.14	8.12	3.33
3.	6,411,895	4,971,018	193	1430	2053	13.68	29.46	0.14	11.96	3.62
4.	6,412,230	4,971,409	192	1465	2048	21.05	44.15	0.20	17.97	3.64
5.	6,411,660	4,970,804	198	1537	2158	12.23	25.76	0.14	9.95	3.83
6.	6,414,185	4,969,180	200	1516	2207	24.22	52.90	0.18	20.48	3.87
7.	6,414,286	4,968,992	197	1719	2150	24.70	46.32	0.20	17.96	3.97
8.	6,411,898	4,970,760	217	1301	2537	16.43	48.06	0.15	15.79	4.09
9.	6,411,834	4,971,128	209	1543	2374	10.63	24.53	0.11	8.61	4.10
10.	6,412,016	4,971,044	216	1348	2520	9.36	26.26	0.12	8.68	4.12
11.	6,411,836	4,970,765	216	1359	2524	20.39	56.78	0.16	18.75	4.12
12.	6,411,942	4,970,816	220	1286	2598	19.81	60.04	0.16	19.26	4.15
13.	6,411,761	4,970,614	220	1378	2606	14.70	41.73	0.12	13.34	4.24
14.	6,411,836	4,970,765	236	1359	2912	21.73	69.84	0.17	19.98	4.59
15.	6,411,745	4,971,070	238	1584	2963	25.19	70.69	0.18	19.88	4.83

4. Analysis and Results

As can be seen from Table 3. the best-ranked solution with the required capacity (20 million m^3) is solution number 6. This solution has an objective function value of 3.87 EUR/$m^{3,}$ and if we wanted to dispose of all the waste in one place, we would adopt this solution as a draft design for further development of the final design. Consequently, the solution ranked 6 was taken into further consideration (as Option 1).

Within the overall zone of interest, there are two physically separate locations (the eastern and western sides of the mine) where it is possible to form a waste dump (all top 15 generated solutions are in these two locations). The possibility of creating several smaller waste dumps with a total volume corresponding to the required volume (20 million m^3) should also be investigated. When considering this possibility, we should keep in mind that the design of many generated solutions will overlap (Figure 9). Waste dumps that overlap cannot be taken into account when analysing this option. The solutions ranked 1 and 2 (Table 3) have a total volume (21.2 million m^3) slightly higher than the required value of 20 million m^3. A slightly higher value than required is useful because it provides the necessary reserve of waste dump capacity. Additionally, these two solutions have the smallest objective function values, and their designs do not overlap, which makes them the best candidates for analysing the possibility of waste dumping along multiple locations. Combinations of other solutions (solution numbers 2 and 3, or 3 and 5, etc.) have a volume whose sum is close to the required value, but their objective function value is higher, or their designs overlap. For this reason, the combination of solutions 1 and 2 is also considered (as Option 2).

In the final stage, the performance of two possible options was compared (Table 4). Option 1—selection of a waste dump in one location (a unique waste dump with the required volume—solution number 6). Option 2—choosing waste dumps in two locations (combination of solutions 1 and 2).

Table 4. Performance comparison of the analysed options.

Compared Options	**Option 1 (Solution—Rang Number 6)**	**Option 2 (Combination of Solutions with Rang Number 1 and 2)**	
		Solution with Rang Number 1	**Solution with Rang Number 2**
Top elevation	200 m	177 m	179 m
Volume	21.48×10^6 m^3	13.05	8.12
		Volume sum = 13.41 + 8.74 = 21.2×10^6 m^3	
Objective function	3.87	3.13	3.33
		3.21 (mean value weighted by volume)	

As can be seen from the Table 4, Option 2 has a significantly better (smaller) objective function value and is therefore adopted as the basis (draft design) for the detailed waste dump design. The generated draft design, as well as the border of the mining area (red line) is presented in Figure 10.

Based on the adopted draft solution, the final detailed design of the waste dumps was created. It is important to note that in the case of open pit Buvac, the main part of waste material is overburden (approximately two-thirds of the total mass), i.e., only a smaller part is waste rock.

For this step, it was necessary to introduce additional geometric parameters:

- Bench height is 10 m, Bench angle is 33°, Safety bench width is 40 m,
- Ramp gradient is 8%, Ramp width is 25 m.

The final design consists of two waste dumps, with a total volume of 20.8 million. m^3, and is shown in Figure 11.

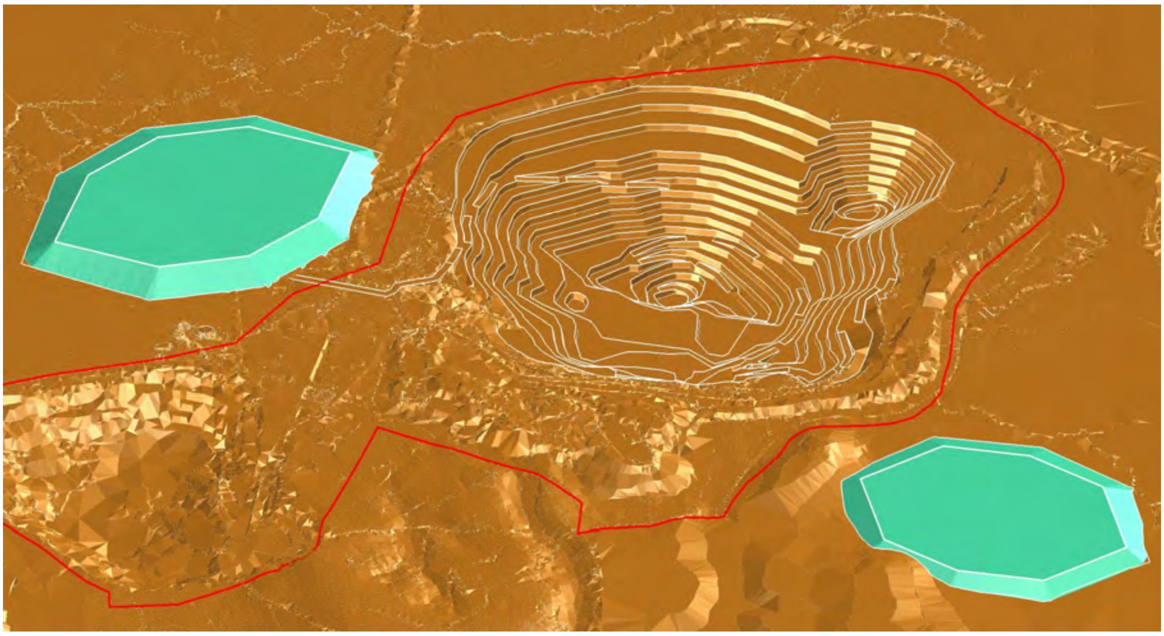

Figure 10. Selected draft design.

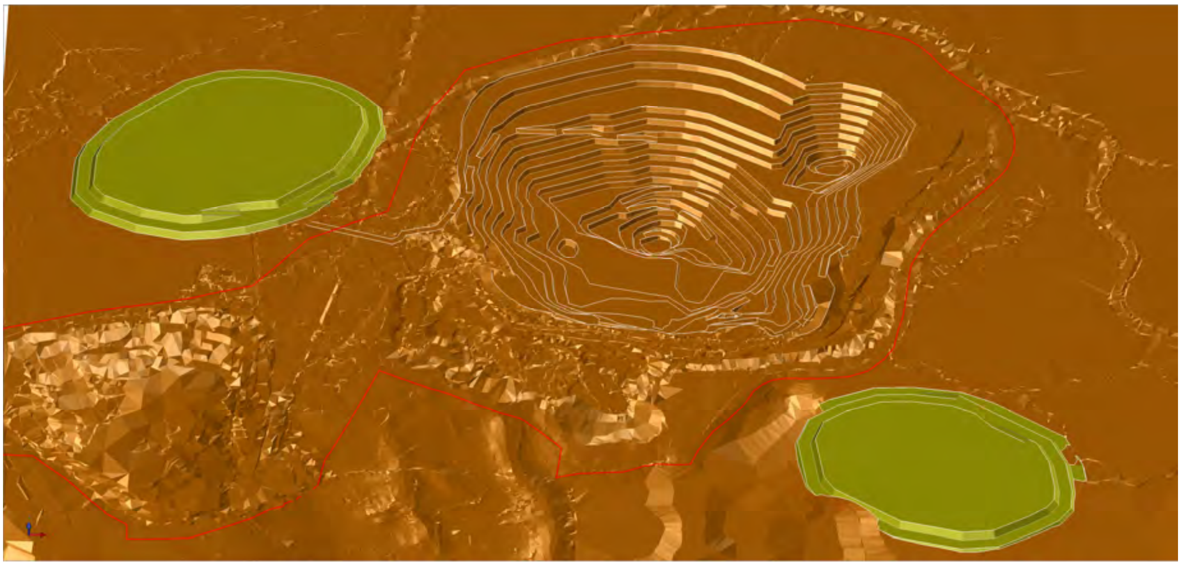

Figure 11. Final Waste dump design.

5. Conclusions

As can be seen from the above, the proposed hybrid model has the ability to include various factors (economic, environmental and technological) of the waste dumping process and produce optimised solutions with the potential to improve the overall performance of mining projects. In particular, the presented hybrid model can offer and rank a large number of solutions regarding waste dump design and location.

For the functioning of the model, it is necessary to analyse and define the input parameters and constraints, which is usually very time-consuming. Despite the tedious process of defining a set of input parameters required for the model's optimisation algorithm to function, the realised benefits are significant. The process of defining the parameters is precisely what drives us to take a detailed look at all the influencing factors and evaluate their impact on the waste dumping process (something that is unfortunately often ignored in reality). This is particularly important in the process of defining the objective function, which can and should be adapted to each individual mining project. In addition, the proposed process of evaluating sub-zones using the AHP method allows for the ranking of additional factors that are different for each location.

During the application and testing, a lengthy data processing time was identified as a basic drawback in the model's operation. For the presented case study, the processing time was 8 h per optimisation, which can be considered long. However, it should be kept in mind that the development and testing of the model was done with relatively modest resources (primarily from the hardware aspect, but also considering the number of people involved in the research and their available time). It is a realistic assumption that with more resources, the functioning of the model could be optimised and the processing time reduced. Taking into account that the model is used to make important decisions (position and design of the waste dumps, which will have a long-term impact on the overall performance of the project), a longer processing time can be considered justified.

As a next step, further improvements should focus on increasing overall performance, which could reduce processing time and ensure model stability. One of the possible tools for this could be a different programming language.

Once the technical component has been improved, the model would be able to support larger populations and provide potential solutions more quickly. In parallel, some other mathematical models could be considered as add-ons to the ones presented once in this paper.

As previously mentioned, the optimisation of waste dumps is often a neglected issue in mining practice. Solutions are usually formed without detailed analysis and a mathematically defined optimisation process. In such conditions, engineers often rely on experience and their subjective judgment when making decisions. One of the main goals and benefits of the model is to reduce subjectivity in the decision-making process.

The results of the proposed model depend entirely on the quality of the input parameters and are governed by defined constraints. Additionally, despite the graphical and analytical form, the generated waste dumps are only a draft of the final solution and additional analysis is required to transform the draft into a detailed (final) engineering solution. With this in mind, it is important to note that the presented hybrid model is not intended to replace an experienced waste dump design engineer. It is a useful and valuable tool that should contribute to and assist engineers in the process of solving important planning issues.

The functioning of the model is verified via an example (active open pit). In the case study, 2250 members of the initial population (different waste dump variants) were generated, and a total of 110 optimised solutions were obtained through 15 optimisations. In the last step, the 15 best solutions were used in the analysis; the solution with the best value of the objective function was adopted, and the final waste dump design was created.

The presented model is able to provide an optimised solution (in analytical and graphical form) for the draft waste dump design, on the basis of which the final waste dump design can be defined. For this reason, the functionality of the presented model is unique and represents a novelty and, therefore, a contribution to mining practice and science.

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