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Operative instruments to support public authorities and industries for the supply of raw materials: A decision support tool to evaluate the sustainable exploitation of extractive waste facilities

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ABSTRACT

The need to guarantee access to raw materials (RM) has stimulated EU policies to find alternative and integrative sources to exploit. RM can be recovered from anthropogenic deposits and from productive cycles, applying respectively landfill mining and circular economy approaches. In order to assess, quickly, whether extractive waste facilities prove to be sufficiently rich to become potentially exploitable, the use of a Decision Support Tool (DST) is presented here. This tool investigates waste facilities both with quantitative (technical and economic) and qualitative (social and environmental) data. The outputs of the DST are represented by several possible scenarios, useful to decide if and how to approach extractive waste exploitation. After working on the structure of the DST, the produced support instrument has been tested and validated using data and processing flow chart of 3 real case studies: the one of Gorno (Zn–Pb) mining site is presented here.

1. Introduction

The supply of Raw Materials (RM) and Critical Raw Materials (CRM) represents a global challenge to guarantee the high development standards of the EU: the updated list identifies 30 CRM (European Commission, 2020). The huge need of RM and CRM has therefore pushed Europe to adopt policies to promote the exploitation of waste from landfills (landfill mining and enhanced landfill mining- LFM and ELFM – approaches; Jones et al., 2013) and from productive cycles (Circular Economy approach; European Commission, 2015; 2019); stimulating, on the one side, the recovery of RM/CRM/SRM (secondary raw materials) together with a simultaneous reclamation of polluted areas, and, on the other, an economic system aimed at minimizing waste production, contemporarily reducing natural resource exploitation. In a circular system, the value of products and materials is maintained for as long as possible; energy emissions and waste production are minimized, and resources are kept within the economy when a product has reached the end of its life. In that context, "circular use" of CRM and RM usually refers to recovery or recycling. Extractive wastes (EW; Extractive Waste Directive, 2006) may contain valuable RM and CRM that have never been exploited and injected into the economy so far. As a consequence of the present EU policy, landfills and existing waste streams (including EW facilities and EW) can be indicated as integrative sources to exploit CRM/RM/SRM (Afum et al., 2019; Blengini et al., 2019; Burlakovs et al., 2018, 2018, 2018; Careddu et al., 2018; Keith-Roach et al., 2016). Indeed, thinking about EW to further extraction helps to minimize waste production and to save natural resource: the amount of existing EW can be reduced by exploiting the remaining valuable fractions, which in turn minimizes new waste generation thanks to a reduced need for extracting virgin (natural) resources.

The potential for the recovery of RM and CRM from EW depends on several factors such as their amount, concentration and mineralogy, the re-processing technology (commercially available and economically viable) and the market demand (Mammadli et al., 2022; Mathieux et al., 2017).

Mining is a major strategic and political decision for a government, indeed, it can generate economic and social returns. It represents the primary source to exploit all minerals and metals. Secondary sources can and should integrate RM supply, also reducing the bottlenecks linked to "natural" minerals and metals demand, but they cannot substitute the

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total dependence on mining industry. Thus, economic and social impacts of mining are evident at local and national levels, generating both negative and positive consequences. Mining should be a booster for the local economy, increasing the income of local people and also creating new business opportunities for other indirect businesses (Mancini and Sala, 2018). The individual income generated by mining is represented by workers' salaries and wages, which contributes to improving household welfare. A study conducted, shows that miners' income is significantly higher than agricultural income, so many workers have no intention of leaving that job (Barreto et al., 2018). The sale of mineral resources is an important source of revenue for local government, thus, many governments, rich in mineral resources, continue to make significant investments in land use (Widana, 2019). The Mining Industry could also increase employment, indeed the Mining Industry requires unskilled, semi-skilled and professional labours; often the first two come from the local population, so it is a benefit to the local community. It also creates employment through investment in infrastructure such as in water, health and roads sectors. Mining also contributes to the development of down-stream sectors such as transport, packaging, communication, insurance, security, etc. (Widana, 2019).

Mining activities are also linked to environmental issues which have to be faced on the basis of different regulations and tools. At the European level it is mandatory to apply the indications present in the Extractive Waste Directive, which provides measures, procedures and guidance to prevent and reduce, as far as possible, any adverse effects on the environment and human health resulting from the management of EW. "Prevention or minimization" of waste can be also seen in the view of EW "recovery" (Art. 5 sets specific requirements related to both the minimization and the recovery of EW) (Extractive Waste Directive, 2006). In the last decades, strong effort has been put to prevent, reduce and minimize the negative environmental impacts from the management of the EW, through the adoption of new management strategies and technologies. In this context, the methodology based on the identification of the best available techniques (BAT) for EW management are developed to prevent or reduce any related adverse effects on the environment and human health (Garbarino et al., 2020).

The Life Cycle Assessment (LCA) of extractive materials is another tool for the evaluation of environmental impacts of the operations connected to exploitation and processing (Frändegård et al., 2013). The identification and analysis of the best technical assumptions allow for the strengthening of the LCA modelling of waste (Bisinella et al., 2017; Gentil et al., 2010).

The application of risk-specific approaches to EWs, BAT and LCA aims at minimizing negative impacts on the environment and human health.

1.1. Short literature review of RM/CRM/SRM exploitation from EW

As already stated, extractive wastes (and EW facilities) can be indicated, after a proper field survey, material characterization, evaluation of potential exploitable resources (Dino et al., 2018), and environmental impacts assessment (EIA. González-Corrochano et al., 2014; Mehta et al., 2018; Schaider et al., 2007; Tiruta-Barna et al., 2007), as a potential "ore deposit" to exploit, following the LFM and ELFM approaches. Recent literature has shown that EW facilities can be exploited to recover RM/CRM/SRM.

Several studies investigated the potential to recover RM/CRM/SRM from past EW facilities present in the mining area (Afum et al., 2019; Blengini et al., 2019; Burlakovs et al., 2018). Even if EW facilities cannot be considered as landfills (Extractive Waste Directive, 2006), the approach applied for RM/CRM/SRM recovery from EW facilities can be intended as "landfill mining" and "enhanced landfill mining" (LFM and ELFM).

Studies on landfill mining have historically focused on the recovery the recovery of areas where there is a landfill and on landfill remediation, instead of focusing on the recovery of RM/CRM/SRM from landfill. Recent literature has shown that EW facilities can be exploited to recover RM/CRM/SRM.

A study by Van Zyl et al. (2016) estimated that approximately 75 major tailing re-mining projects are taking place globally for the reclamation of copper, diamond, and gold. Ghosh and Das (2017) showed recovery of Mn by bioleaching of iron-manganese EW from Odisha, India. Henne et al. (2018) demonstrated the recovery of copper from Cu-sulfide inclusions minerals of waste rock (WR) by bioleaching in the Salobo mine, Brazil. The physicochemical, mineralogical, and elemental characterization of EW from the exploitation of both iron ores and polymetallic minerals (Pb–Zn–Ag) was done to evaluate the possibility of recovering strategic elements, like Ga, In, Ge, and rare earth elements (REE) in mining areas of México (Ceniceros-Gómez et al., 2018). Recently, a French geological survey identified interesting old EW to assess potential metal recovery, with emphasis on critical metals. There are further studies that have been undertaken to depict the economic benefits by reusing waste generated from mines, i.e., Pactwa et al. (2018) presented economic and social benefits that can be obtained from lignite mine waste in Poland. Other examples of the reuse of EW are the synthesis of fired bricks from red clays by-products (Loutou et al., 2019), the use of coal mine waste to make eco-friendly bricks (Taha et al., 2017) or the reuse of mine waste rock as aggregates for production of concrete (El Machi et al., 2020).

Despite the good results of the studies concerning EW facilities exploitation, the research on the implementation of circular economy principles in Italian abandoned mine sites is at the beginning stages and has still not been fully realized. Nevertheless, the potential and growing interest in making the Italian economy more and more circular is increasing (MISE, 2017).

1.2. Decision support tools as predictive tools to assess commodities supply

The concept of applying a Decision Support Tool (DST) in technical projects is not new (Jordan and Abdaal, 2013). Since the early 1960s, the idea of Decision Support has evolved from theoretical studies to practical applications (Arnott et al., 2004; Power, 2007). From those early days, it was recognized that DST could be designed to support decision-makers at any level, not only in business and management application domain (Keen, 1980). This evolution also expanded the field of DST beyond the initial business and management application domain: DST could support operations and strategic decision making, and financial management (Lattanzio, 2018; Serrano-Cinca and Gutierrez-Nieto, 2013). Several Decision Support Tools (DST) based on life cycle assessment (LCA) are currently available to assess the sustainability of waste management systems and to accelerate the transition to a circular economy (Salemdeeb et al., 2022; Vea et al., 2018).

A Decision Support Tool is based on sustainability criteria (Bardos et al., 2018), providing decision support that takes into account the environmental, economic and social impacts of mining activities. Recently, sustainability has been globally indicated as a key goal at local and multinational levels. At EU level several actions have been lunched to boost the transition to a more sustainable society:

- governance actions (i.e., Portugal is investing a lot, at government level, to guarantee the transition to energy supply from renewable sources);
- sustainable finance (ready for industries and in progress as for mining industry).

Also, other Countries have launched several actions in order to live in a more sustainable society. For example, the Mining Association of Canada (MAC) launched, in 2004, the Towards Sustainable Mining (TSM) initiative. It is a world-recognized sustainability standard which helps mining companies in Canada to operate in the most socially, economically and environmentally responsible way. Many other mining associations around the world settled in Countries such as Norway, Finland, Spain, Botswana, Brazil, Argentina, the Philippines, Australia and Colombia are implementing the TSM.

A good example of the government which is investing in the transition towards a more sustainable society is represented by Chile, which is investing a lot to guarantee the transition to clean industries to contrast global climate change (which is very detrimental to that area). The example of Chile could (and seems to) help in the transition to sustainability in South America.

Sustainability is also high on the agenda not only from a political governmental point of view but also for the global players in the mining industry. Many companies are taking into account in their strategies, aspects such as climate change, reduction of environmental impact, health of the workforce, renewable energies. For example, Kamoa Copper S.A. (copper producer, Democratic Republic of Congo) is powered by clean, renewable hydro-generated electricity or Komatsu (a Japanese equipment provider), is actively developing solutions in order to improve a long-term emissions reduction.

DSTs, designed to help in transition to a more sustainable RW/CRM supply, can use multi-criteria analysis to implement sustainable management (Tasoulas et al., 2011; Alamanos et al., 2021).

Starting from these statements, a DST for extractive waste (DST-EW) has been designed to help public authorities, mining companies and stakeholders in investigating if (and how) a precise EW facility shows the right conditions (resource quality and quantity, environmental, social and economic impacts, technical factors, etc.) to be exploited for CRM/RM/SRM production. The integration of different types of knowledge (i.e., local and expert knowledge), disciplines and perspectives in the development of effective and sustainable policies can find extremely useful support by the participatory development and implementation of DST.

1.3. A decision support tool for extractive waste

The DST-EW moves from the already developed DST concerning municipal solid waste (MSW) and commercial and industrial waste (CIW), developed by Pastre et al. (2018). MSW/CIW-DST gives the possibility to enter the composition of the waste (either as literature data or as real data) and to analyse nine scenarios that differ according to the type of treatment (i.e. soil washing, excavation, screening, shredding, air separation, ballistic separation, magnetic separation, eddy-current separation and Advanced Thermal Treatment (ATT)). For each scenario, on-site/off-site treatment activities were considered and 3 options were proposed as in the following: (i) all the treatments are carried out on-site (no transport), (ii) the sorting, screening and processing is carried out on-site but the refuse-derived fuel (RDF) is transported to an off-site Waste to Energy facility, (iii) the excavated waste is only screened on-site, then transported to a waste treatment facility for sorting and processing, consequently the RDF is recovered in a WtE facility. The tool determines environmental, social and economic indicators for each scenario, using multi-criteria analysis and the best scenario, from a sustainability standpoint for landfill mining, is identified.

As for the DST-EW, it is not possible to identify a common methodology for CRM/SRM recovery, since it is closely related to the specific characteristics of the ore deposits, extraction and processing techniques and efficiency of exploitation. In general, EW facilities are represented by homogeneous materials (often heterogeneous in size distribution, but similar in rock and mineral content): this homogeneity is connected to the condition of each specific ore deposit and to the specific treatment activities applied during the processing. As in the landfill mining approach, the procedure to exploit EW facilities is not unique at European and national level. However, it is possible to identify operational methodologies to estimate the quantity, quality and value of CRM/RM/SRM present in the EW facilities (Dino et al., 2018).

The tool uses quantitative data (linked to the reserves still present in the EW facility and to the economic impacts related to the exploitation of the deposit) and qualitative data (environmental and social impacts) in order to define the most promising scenario(s) for the management/recovery of EW facilities. The aim of the DST-EW is to provide a preliminary assessment of the feasibility of the exploitation of EW in a simple and integrated way, by incorporating the social, environmental and economic factors involved in the exploitation processes: the tool identifies, using site-specific information together with bibliographic data, which parameters contribute in making the resource exploitable and evaluates the costs and benefits in a simple and fast way.

The present EW DST has been tested and validated on three different case histories concerning:

- an operating mining site which exploited feldspar from granite quarry dumps,
- a non-operating mining site for Zn–Pb exploitation
- a non-operating mining site for Ni exploitation

The present paper shows the results concerning the Gorno (Zn–Pb) mining site (Northern Lombardy Region, Italy. Gorno mining site is described in Section 2.2).

1.4. Newalty and innovations of the DST-EW

As stated, sustainable mining is a major strategic and economic decision for a government which can contribute to reduce dependence on the “international mining industry”. Furthermore, this kind of decision can generate several positive or negative consequences such as new salaries, employment, investments in infrastructure, new local businesses, adverse effects on human health and environment.

In the past, sustainability was only considered from the economic point of view; today, according to European policies related to” Green Deal”, the meaning of sustainability is wider and aspects such as environmental and social issues have to be considered. Sustainable development is a core principle of the European Union and several actions have been launched in order to push transition towards a more sustainable society. In order to cope with all these aspects, the proposed DST-EW, which involved economic social and environmental variables, could be an important support for the strategic decision-making process, especially for Local and Central Government with the aim to drive political and economic strategies.

Due also to “European Green Deal” there is a growing awareness of sustainability and ethics in the mining sector, as a consequence, Companies are also increasingly considering social and environmental aspects in their evaluations and for this reason the proposed DST-EW could be useful for private companies too.

A further innovative aspect, as illustrated in the simulation reported in Section 4, is related to the fact that different scenarios can be created depending on the importance given to different economic, social, and environmental variables. It is therefore possible to select the scenario that best suits the exigencies, goals of the economic actors (government, companies), together with sensitivities towards environmental and social sustainability.

In a nutshell, the possibility to select “the best scenario” according to the user’s criteria for selection (economic, environmental and social variables) is therefore a distinguishing feature for the proposed DST.

2. Material and methods

2.1. DST input and output

The DST-EW, here presented, is a tool that allows an initial understanding of the feasibility of exploiting EW facilities by estimating the net income of the project, as well as the social and environmental impacts. The user enters the characteristics of the EW facility in the “User Input” tab.

The DST’s elaboration starts from the definition of the EW facilities’

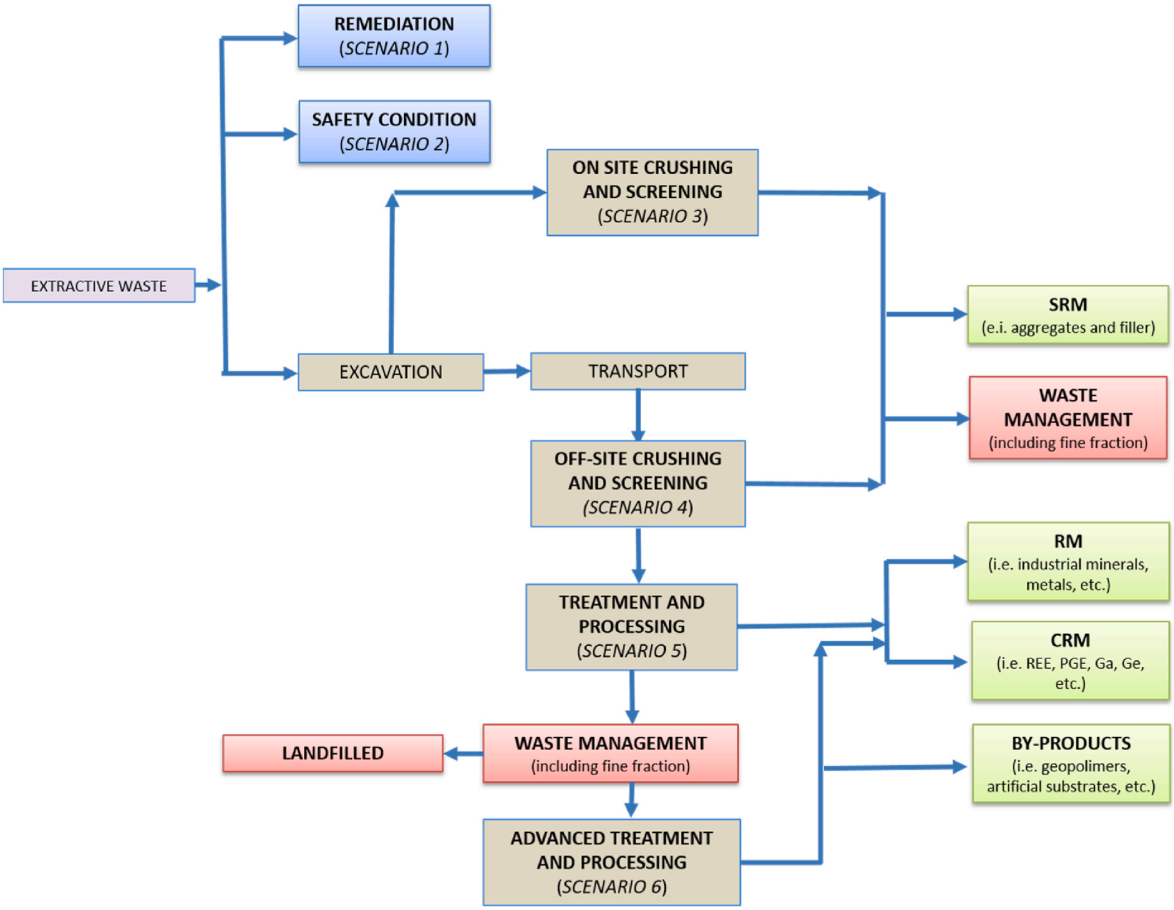


Fig. 1. General flow chart used to build the different scenarios to be used for the DST-EW.

characteristics (such as total amount of EW present in EW facilities, total landfill area, waste annual production, etc.) and EW's composition. Other input data concerns the design characteristics (such as the presence of geomembranes, i.e., present in tailings' basins), the number and type of residents around the site, the distance from the EW facilities to the processing plant and the economic values of reclaimed land.

To guarantee the flexibility of the DST-EW, different scenarios can be considered. Each scenario is characterized by a number of actions or technologies (i.e. remediation, excavation, transport, crushing, sieving, flotation, magnetic separation, waste management, etc.), that characterize each step connected to EW management and recovery, summarized in a general flow chart (Fig. 1). The possible general alternatives, as for operational activities concerning EW facility management/exploitation, can be summarized as:

- remediation and/or safe operation of EW facility (*Scenario 1* and *2*);
- production of filler (i.e., for roads and infrastructures) and aggregates to be used in situ or ex situ (i.e., aggregates for concrete, aggregates for road construction, railway ballast, etc.) (*Scenario 3* and *4*);
- treatment and processing to obtain RM, CRM (i.e., feldspar from granite dumps, Zn/Pb associated with Ga, Ge, In, Cd from Zn/Pb mining dumps, PGE associated to Ni in Ni mining dumps, etc.), with production of waste to be managed (*Scenario 5*)
- advanced treatment and processing to obtain RM, CRM and by-products (i.e., recovery of fine fractions for the production of cultivable substrates, geopolymers, etc …) (*Scenario 6*).

For each alternative, a flowchart is built, indicating operative steps and general machineries needed to exploit the EW facility.

A DST-EW provides a structured process in which all assumptions, model parameters, and predicted outcomes can be reviewed and documented. Therefore, the steps in the decision process can be made transparent to those not directly involved in the process. Uncertainties can be addressed through multiple use of the DST-EW to examine the impact of model parameters and different scenarios on the decision variable.

Pursuing this goal, the data to be used for evaluating the best possible solution (for the specific site) are:

- **General data**: tonnes of landfilled material; tonnes of waste yearly produced– in the case of active landfill sites; presence of background barrier of the landfill; number of residents within a radius of 1 km; value of the area once cultivated (€/m^2) – Residential, industrial, agricultural, landfill; Distance in km from the EW facility to the treatment plant, existing;
- **Economic data:** capital cost for the needed technologies; operating costs; transport costs; costs for waste management; production rate for each production process, selling price of the products and by-products obtained from the recovery of the landfilled material. Capital costs are fixed costs, incurred in order to purchase assets such as buildings, machinery, equipment. Operating costs are the ongoing expenses incurred from the normal day-to-day running of a business. Operating costs include both costs of goods, costs for utilities, payroll. All the economic data are estimated values based on the study of Italian mining companies.
- **Environmental data**: i.e. parametrized data related to: GHG (Green House Gases), PM (Particulate Matter), odours, VOCs (Volatile Organic Compounds), NOx and SOx, water contamination, soil contamination, biota interference, noises, water production, metal

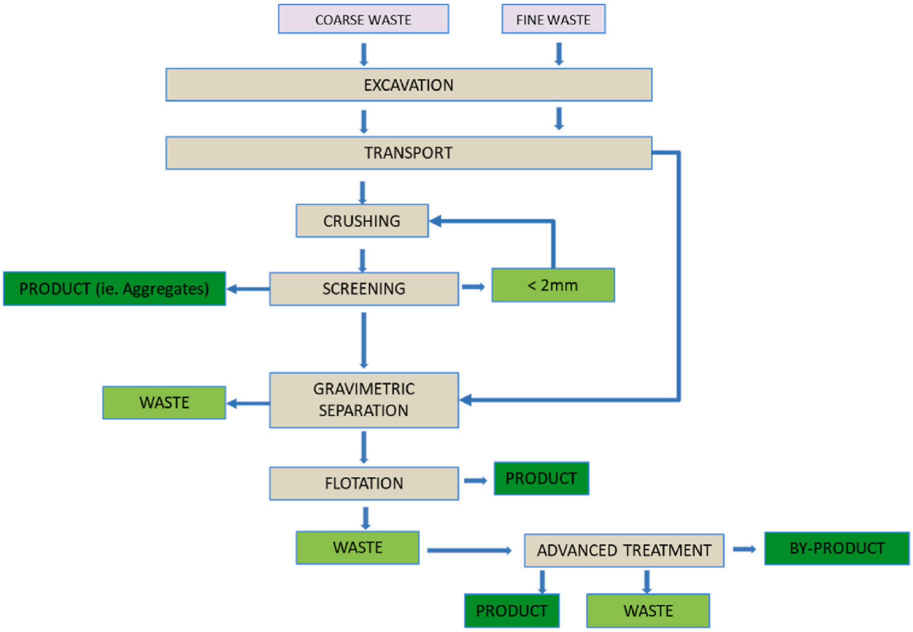


Fig. 2. Flow chart used to build the different scenarios for Gorno EW facilities (reported in Fig. 3).

recovery): score from −3 to +3 (−3, −2: Highest positive impact compared to the do nothing scenario; −1 +1: Mild impact compared to the do nothing scenario; +2, +3: Highest negative impact compared to the do nothing scenario). The choice of the indicators values depends on the user experience;

- **Social data:** i.e., parametrized data relating to (Pastre et al., 2018):
  - community involvement: measures the community involvement and acceptance of the project. This involvement depends on the consequences created that directly affect their life;
  - human health: measures the impacts on the health of the site-workers and community members caused by the incidence of VOCs, noise, odour, dust and bioaerosols;
  - ethical considerations: measures the possibility of creating ethical disputes. For example, groundwater gets contaminated and a population is served from this source;
  - nuisance on neighbourhoods: measures the occurrence of nuisance factors (e.g., noise, light pollution, smells, litter, and debris off site);
  - evidence of Sustainability and Level of Uncertainty: measures the degree of environmental sustainability, as well as the levels of uncertainty related to the outcomes.

The score for these parameters ranges from −3 to +3 (−3, −2: Highest positive impact compared to the do nothing scenario; −1 +1: Mild impact compared to the do nothing scenario; +2, +3: Highest negative impact compared to the do nothing scenario). The choice of the indicator values depends on the user experience.

It is possible to decide the criterion for the selection of the best scenario (for each specific site) by choosing between different options which can be economic, social, or environmental.

On the basis of the entered data, it will be possible to evaluate the best scenario(s) resulting from the feasibility analysis (rough) related to the EW facility exploitation project that is to be carried out. According to the proposed scenarios, the parameter “best scenario selection criteria” gives you the option to choose the criteria under which the best scenario is chosen. The available options are:

- The best case for net income
- The best case for revenue
- The best case for lower costs
- The worst case related to net income
- The worst case related to revenues
- The worst case for lower costs
- The best environmental score
- The best social score

In order to consider all the different possible scenarios, it has been decided to also include zero revenues in “the worst case related to revenues”. Clearly, a private company would not consider this type of scenario enthusiastically, unlike a Governmental Entity that might instead place more emphasis on non-economic aspects such as environmental protection, human health, etc.

The impacts are assessed using the radar chart which individually classifies the economic, social, and environmental impacts of the scenario with the other eight scenarios studied (Scores from 0 to 100). If the score is 0, the scenario has the worst impact on appearance compared to the other scenarios, if it has 100 it has the best impact.

The proposed DST provides calculations of the social and environmental impact of all scenarios considered by multiplying the impacts from the database (worst case scenario) by the calibration factors (Input_factors) resulting from the chosen technologies.

The first result is an assessment of the economic, environmental, and social impacts of the most profitable project. The best-case scenario is calculated considering the highest revenues from the use of the land, and assuming that the client already has all the equipment to carry out the treatment and recovery on site. The worst-case scenario assumes that the client has to invest in all the technologies and has to transport the waste to an off-site treatment/processing plant.

The proposed DST tool allows all impacts of the scenarios to be seen and compared through radar charts. Using radar charts, economic, social, and environmental impacts of the proposed scenario are assessed individually and compared with the “do nothing” scenario and the other eight baseline scenarios. A score of 0 indicates that the proposed scenario has the worst impact (economic, social or environmental) compared to the other scenarios, while a score of 100 corresponds to the best result.

Different technologies provided by Sustainable Remediation Forum for the UK (SuRF-UK, Claire 2011), Capital Expenditure (CAPEX) and Operating Expenditure (OPEX) are associated with the sustainability indicators characterising the baseline scenarios (i.e., general scenarios

Table 1
Different TABS present in the DST-EW.

TABS	FUNCTION
Introduction	Entry tab for the simulation
Scenario overview	Presentation of the considered scenarios and Technologies
Scenario input	Data entry
Best scenario results	It shows the results of the feasibility analysis of the landfill mining project
Scenario comparison	Overview of the potential scenarios and comparison of their impacts (social, economic, and environmental)
Technologies comparison	The database gathering the economic data and social and environmental scorings for the individual technologies
Costs	Summarizes all the costs from technologies comparison. It includes CAPEX and OPEX costs resume, Transportation costs and Waste Management costs
Soc_Env impacts	Sheet including the calculation of the social and environmental impacts. Provides details such as the calibration factors and the transportation for all scenarios
Waste_characterization	The content of the 2 proposed waste compositions (i.e., for metal DST waste composition is Coarse waste >2 mm and Fine waste <2 mm)
Calibration_factors	Gathering the functions and calculates the calibration factors for the social and environmental impacts
Outputs calc	Calculates and gathers all the output information regarding all different scenarios. Also contains the indication about how best scenario is evaluated
Production	Calculate the amount of production and waste material according with the production rates and the grade for all the scenarios
Revenues	Calculates the revenues (i.e., from extractive waste facilities exploitation)
Radar chart	Calculates scores to compare the economic, environmental and social performance of the indicated scenarios

reported in Fig. 1). The scores range from −3 to +3: 3 means the best improvement on the indicator compared to the "do nothing" scenario, and +3 means the worst impact on the indicator.

The output of the DST investigation is represented by different scenarios which consider, together with social and environmental impacts, the economic profitability associated to the technical solutions planned to be used (i.e., remediation, in-situ or ex-situ treatment, transport, advanced treatment, etc.).

2.2. *Case study: Gorno mining area*

The Gorno mining site, which industrially operated from 1837 to 1982, is located within the Seriana, Riso and Brembana valleys (Lombardy, NW Italy). It belongs to the Alpine type of zinc-lead-silver stratabound ore deposits, associated with the middle Triassic carbonatic series. The mineralization (Zn–Pb ± Ag ± baryte ± fluorite) mostly occurs within the "Metallifero" (i.e., "ore-bearing") Formation of Upper Ladinic – lower Carnian age (Omenetto and Vailati, 1977; Rodeghiero and Vailati, 1978).

The primary mineralization is composed of sphalerite (ZnS) and galena (PbS), with minor pyrite (FeS_2), marcasite (FeS_2), chalcopyrite ($CuFeS_2$) and argentite (Ag_2S). The dominant gangue minerals are calcite, dolomite, and quartz (±ankerite). A secondary mineralization, composed of oxidation products of sphalerite (namely *Calamine*), was historically preferred for ore exploitation (underground mining pits). Consequently, often the rocks enriched in sphalerite and galena were separated from the *Calamine* and placed outside the adits, forming several EW facilities present all around the mining area. Those EW facilities, which show high content in Zn from sphalerite, can potentially be intended as exploitable, due to the Zn content and to the estimated volume both of indicated and inferred resources (Dino et al., 2018). The present study focuses on the Monte Arera mining site: data concerning EW characteristics and volumes, and information to draw the flow chart described in Fig. 2 refer to already published research (Dino et al., 2018; Mehta et al., 2020).

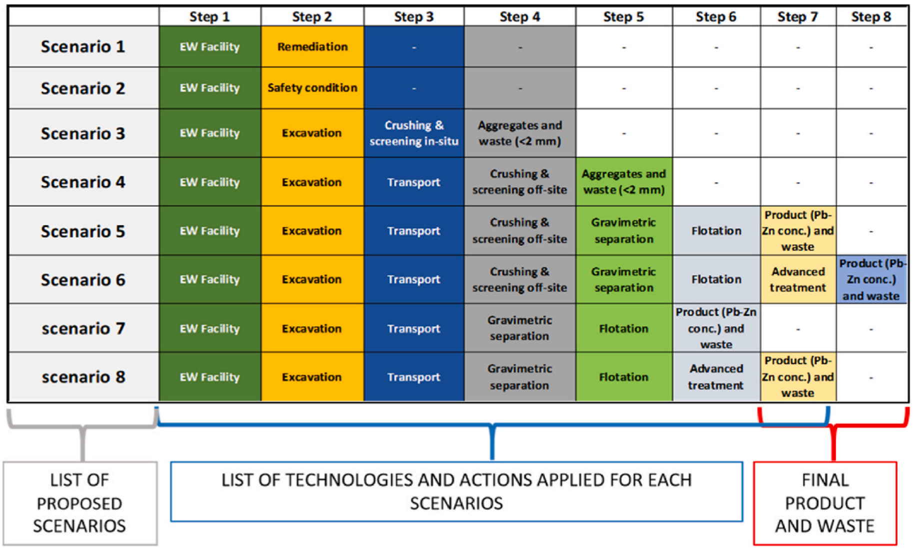
3. How DST-EW works and used algorithms

This tool is thought to assess a first evaluation of the feasibility of EW facilities exploitation. It is developed on the broadly-used Microsoft Office Excel that provides an easy way to program powerful calculation models using many variables. Further development of the tool, in progress, using other programming languages, such as Matlab or Python, will allow more detailed and sophisticated analysis.

Table 1 shows the 14 TABS present in the DST-EW and indicates their functions.

As stated, the definition of the EW facilities' characteristics is needed and represent the first step to approach when using the DST-EW. EW facilities' characteristics represent the filling data required in the "Scenario input" tab. The next step requires the defining of different scenarios and associate to each of them the technologies and actions necessary for obtaining specific products, designing a flow chart as shown in Fig. 3 and then filling the scenarios table in the "Scenario overview" tab (Example in Fig. 4a).

Should the user want to analyse different sites and situations, it is



	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8
Scenario 1	EW Facility	Remediation	-	-	-	-	-	-
Scenario 2	EW Facility	Safety condition	-	-	-	-	-	-
Scenario 3	EW Facility	Excavation	Crushing & screening in-situ	Aggregates and waste (<2 mm)	-	-	-	-
Scenario 4	EW Facility	Excavation	Transport	Crushing & screening off-site	Aggregates and waste (<2 mm)	-	-	-
Scenario 5	EW Facility	Excavation	Transport	Crushing & screening off-site	Gravimetric separation	Flotation	Product (Pb-Zn conc.) and waste	-
Scenario 6	EW Facility	Excavation	Transport	Crushing & screening off-site	Gravimetric separation	Flotation	Advanced treatment	Product (Pb-Zn conc.) and waste
scenario 7	EW Facility	Excavation	Transport	Gravimetric separation	Flotation	Product (Pb-Zn conc.) and waste	-	-
scenario 8	EW Facility	Excavation	Transport	Gravimetric separation	Flotation	Advanced treatment	Product (Pb-Zn conc.) and waste	-

Fig. 3. Table reporting the single operative steps to exploit RM/SRM/CRM from a Zn–Pb closed mine in Northern Italy.

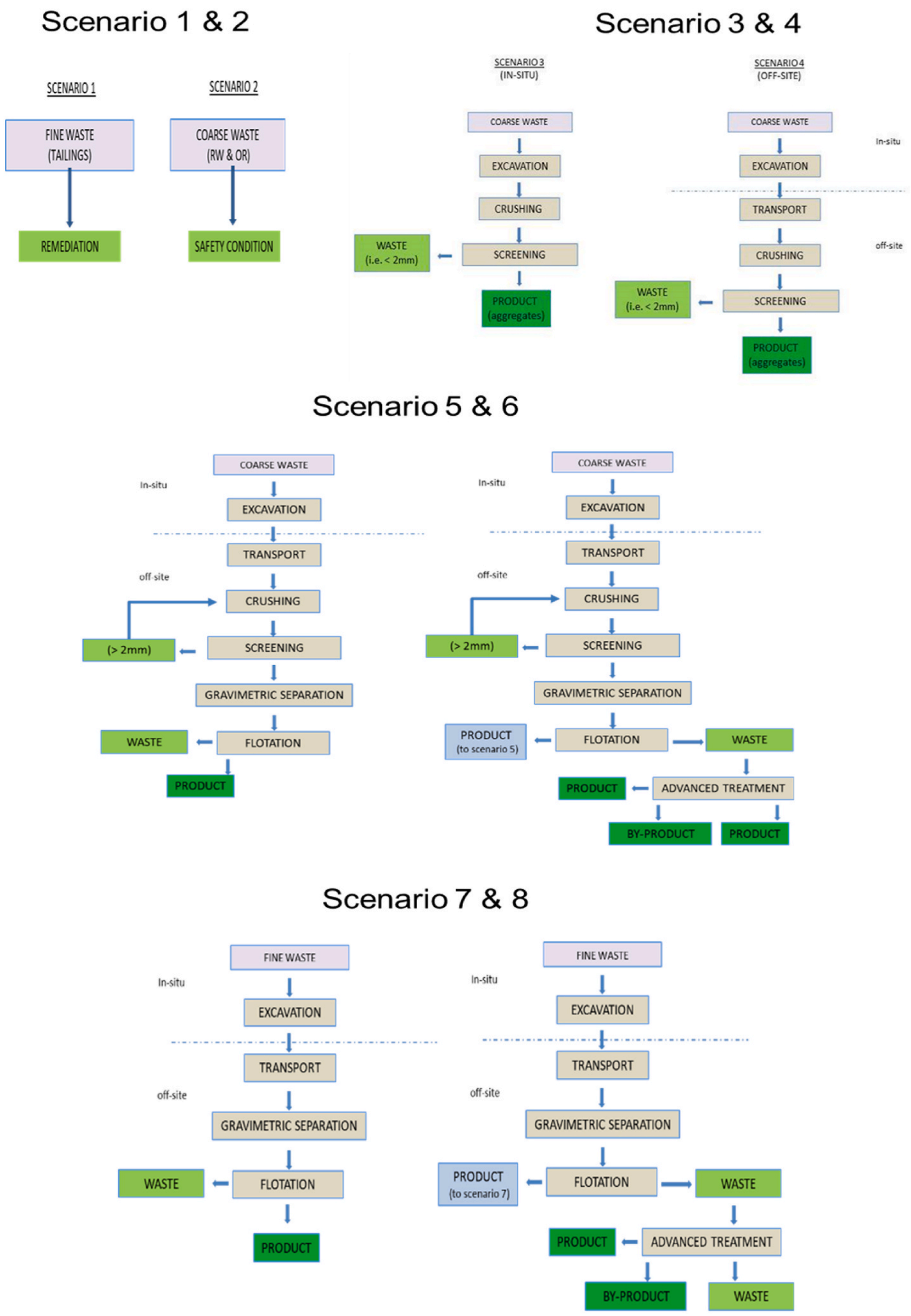


Fig. 4. Flow chart designation. This step is necessary to understand the scenarios, the technologies/actions used and the final products.

necessary to define different flow charts and adapt the scenario table on the tool: this action generally takes 1–2 h of work.

The tool is designed to analyse up to eight scenarios at the same time. On the one hand, by updating the scenario table the other tabs are automatically updated, thus, it is not necessary to make any other changes to the tool. On the other hand, changing the evaluation criteria requires a deeper restructuring of the tool, with greater time consumption.

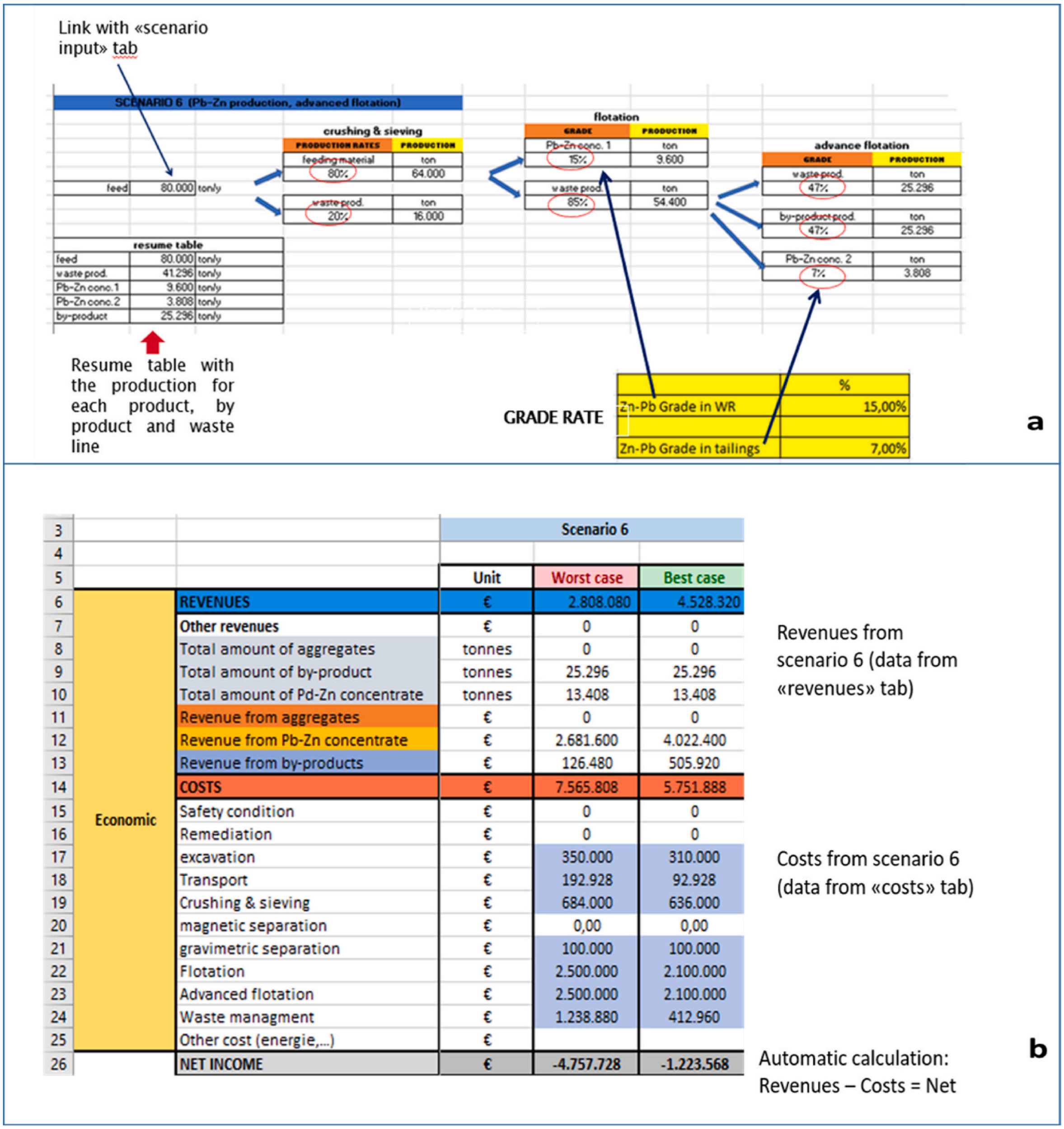
Due to the difficulties in finding quantitative information on the environmental impacts of the selected technologies, these are scored by comparing them with each other rather than by giving them absolute values (values ranging from −3 and +3). In addition, the remaining technologies are assessed by comparing them with the support of scientific articles and personal judgment.

The given score captures the impact of the technology in the worst possible case.

The performance of all the scenarios and their options are calculated by adding the scores of the technologies they involve: i.e., if the longest scenario involves ten technologies, the scale of the performance for each indicator ranges from −30 to +30. A score of −30 represents the highest beneficial impact on the indicator in comparison with the “do-nothing” scenario, while a score of +30 represents the highest negative impact.

However, this environmental performance describes the risk of impact in the worst possible case, but some conditions may reduce the negative impact on the environment, so the score should be reduced. Therefore, the tool possesses calibration factors to take environment data into account that can mitigate the negative impacts of landfill mining.

The same scale and approach used to determine the scores for the environmental indicators is used to quantify the social indicators. The sum of all the involved technologies is calculated, then adjusted with the calibration factors. For example, the Human Health and Nuisance on



resume table		
feed	80.000	ton/y
waste prod.	41.296	ton/y
Pb-Zn conc. 1	9.600	ton/y
Pb-Zn conc. 2	3.808	ton/y
by-product	25.296	ton/y

	%
Zn-Pb Grade in WR	15,00%
Zn-Pb Grade in tailings	7,00%

3			Scenario 6		
4					
5			Unit	Worst case	Best case
6	Economic	REVENUES	€	2.808.080	4.528.320
7		Other revenues	€	0	0
8		Total amount of aggregates	tonnes	0	0
9		Total amount of by-product	tonnes	25.296	25.296
10		Total amount of Pd-Zn concentrate	tonnes	13.408	13.408
11		Revenue from aggregates	€	0	0
12		Revenue from Pb-Zn concentrate	€	2.681.600	4.022.400
13		Revenue from by-products	€	126.480	505.920
14		COSTS	€	7.565.808	5.751.888
15		Safety condition	€	0	0
16		Remediation	€	0	0
17		excavation	€	350.000	310.000
18		Transport	€	192.928	92.928
19		Crushing & sieving	€	684.000	636.000
20		magnetic separation	€	0,00	0,00
21		gravimetric separation	€	100.000	100.000
22		Flotation	€	2.500.000	2.100.000
23		Advanced flotation	€	2.500.000	2.100.000
24		Waste managment	€	1.238.880	412.960
25		Other cost (energie,...)	€		
26		NET INCOME	€	-4.757.728	-1.223.568

Fig. 5. a. "Production" tab here reported for the scenario 6 (Pb and Zn concentrate product, advanced flotation). **b.** The "outputs calc" table, including the revenues values associated to Scenario 6 (i.e.). In Scenario 6 no costs for remediation and safety conditions occur.

neighbourhood indicators have a calibration factor to take the influence of the number of close residents in account, living at less than 1 km from the analyzed site. In this case a calibration factor ranges from 0,1 to 1,0, which may vary linearly to consider different situations from less than 200 to over 1000 residents, can adjust the indicators for Human Health and Nuisance on neighbourhood from 10 to 100% of their original value.

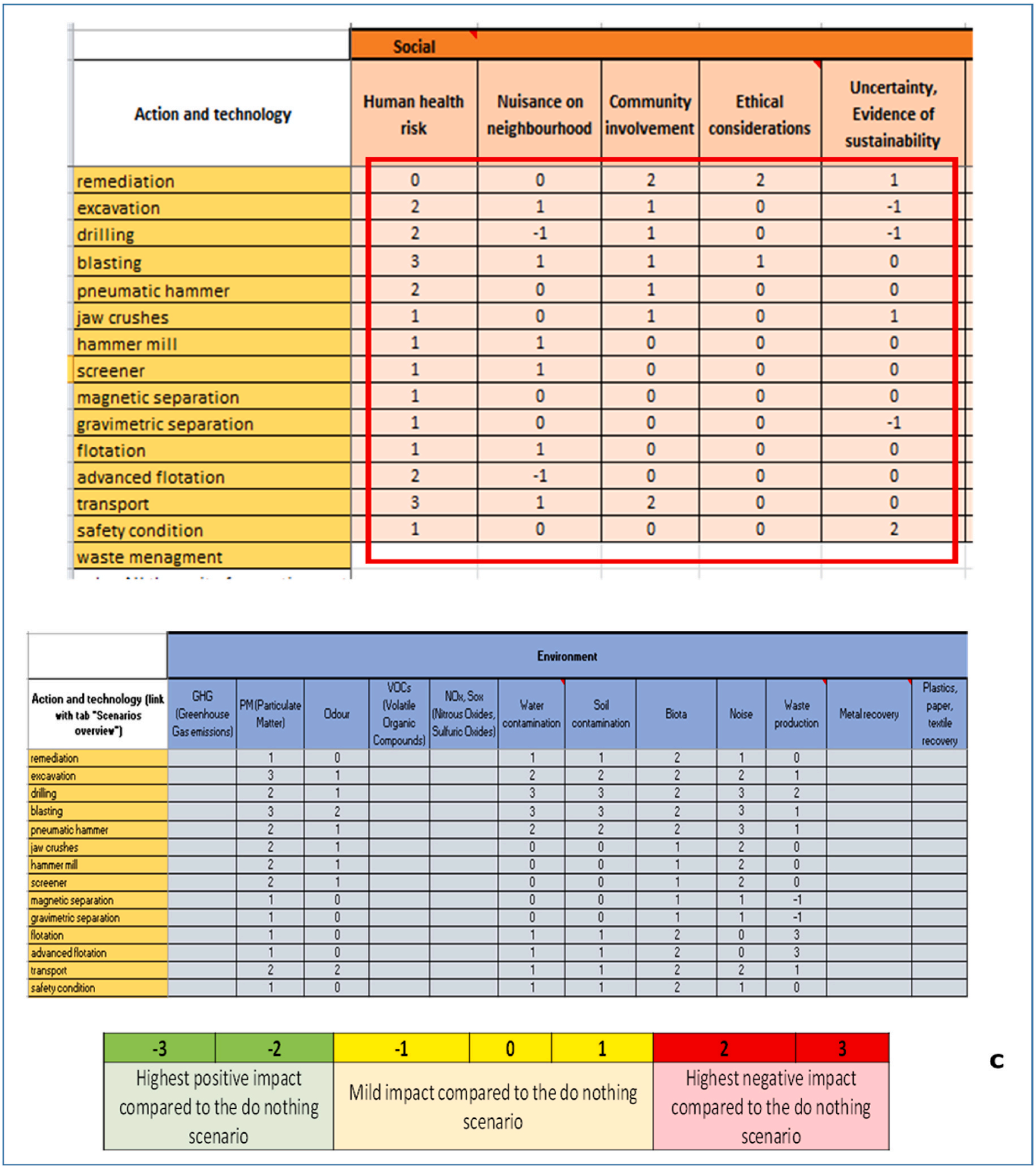
The economic analysis is carried out on the basis of some indicators:

- **Net income** – It is the difference between the revenues and the costs connected to EW facilities exploitation. This is the most important indicator because it enables the user to understand the economic feasibility of the project;
- **Revenue** – The tool is set to calculate the revenues for sale of the recovered metals, the aggregates, the by-products and for the use of reclaimed land, i.e., residential, industrial, agricultural, nature or more landfill space.
- **Costs** – the tool considers both operational and capital costs from the mining processes. Specifically, operational cost includes the cost of the on-going landfill mining processes and transportation costs to the recovery facilities; the capital costs considered are the costs of building facilities or acquiring machinery.

The prices used in the Case Study analysis relate to bibliographic data prior the last price jump due to the COVID-19 outbreak and the war in Ukraine. The costs of excavation, separation techniques, transportation and energy were derived from the market and from indications of mining companies.

The procedure followed to estimate the revenue from the recovery materials is done by calculating total amount of recovery metals, aggregates and by-products and then multiplying it by their market prices.

Revenue from recovery materials = Amount of materials (tonnes) x markets price (€/tonne)



	Social				
Action and technology	Human health risk	Nuisance on neighbourhood	Community involvement	Ethical considerations	Uncertainty, Evidence of sustainability
remediation	0	0	2	2	1
excavation	2	1	1	0	-1
drilling	2	-1	1	0	-1
blasting	3	1	1	1	0
pneumatic hammer	2	0	1	0	0
jaw crushes	1	0	1	0	1
hammer mill	1	1	0	0	0
screener	1	1	0	0	0
magnetic separation	1	0	0	0	0
gravimetric separation	1	0	0	0	-1
flotation	1	1	0	0	0
advanced flotation	2	-1	0	0	0
transport	3	1	2	0	0
safety condition	1	0	0	0	2
waste menagment					

	Environment											
Action and technology (link with tab "Scenarios overview")	GHG (Greenhouse Gas emissions)	PM (Particulate Matter)	Odour	VOCs (Volatile Organic Compounds)	NOx, Sox (Nitrous Oxides, Sulfuric Oxides)	Water contamination	Soil contamination	Biota	Noise	Waste production	Metal recovery	Plastics, paper, textile recovery
remediation		1	0			1	1	2	1	0		
excavation		3	1			2	2	2	2	1		
drilling		2	1			3	3	2	3	2		
blasting		3	2			3	3	2	3	1		
pneumatic hammer		2	1			2	2	2	3	1		
jaw crushes		2	1			0	0	1	2	0		
hammer mill		2	1			0	0	1	2	0		
screener		2	1			0	0	1	2	0		
magnetic separation		1	0			0	0	1	1	-1		
gravimetric separation		1	0			0	0	1	1	-1		
flotation		1	0			1	1	2	0	3		
advanced flotation		1	0			1	1	2	0	3		
transport		2	2			1	1	2	2	1		
safety condition		1	0			1	1	2	1	0		

-3	-2	-1	0	1	2	3
Highest positive impact compared to the do nothing scenario		Mild impact compared to the do nothing scenario			Highest negative impact compared to the do nothing scenario	

Fig. 6. Social and environmental data (i.e.), for each technology and action, inserted according to personal experience and literature data. same here.

These calculations are done for a worst and a best case which depend on the price of electricity. While revenues from land reclamation depend on the final use of the recovered land.

The economic, environmental, and social impacts for all landfill mining scenarios and their different transport option are evaluated and can be compared among each other in the “Scenario_comparison” tab. A worst case and a best-case scenario are determined for the three calculated economic parameters (net income, revenues, and costs).

To simplify the user experience, it was decided to display a radar chart. This chart shows the results of comparing the economic, environmental, and social impacts of all the evaluated scenarios (Example in Fig. 7) with each other. The scale varies from 0 to 100: zero means that the selected process has the worst impact among all the evaluated scenarios, and 100 means the selected process has the best impact among all the evaluated scenarios. The tool compares all scenarios on the criteria chosen by user. The best one regarding the selected criteria is displayed in the “Best Scenario Results” tab.

4. Results and discussion

The EW DST, developed in an interactive Microsoft Office Excel folder, is a user-friendly tool, and is to be used by non-computer experts. It allows for, using specific criteria and indicators, a preliminary assessment of the feasibility of the exploitation of EW in different alternative ways (scenarios). The purpose of scenario analysis is to consider and better understand how an EW might perform under different points of view. Scenario analysis, therefore, evaluates a range of hypothetical outcomes by considering a variety of alternative plausible outcomes under a given set of assumption and constraints. A critical aspect of *scenario analysis* is the selection of a set of scenarios that

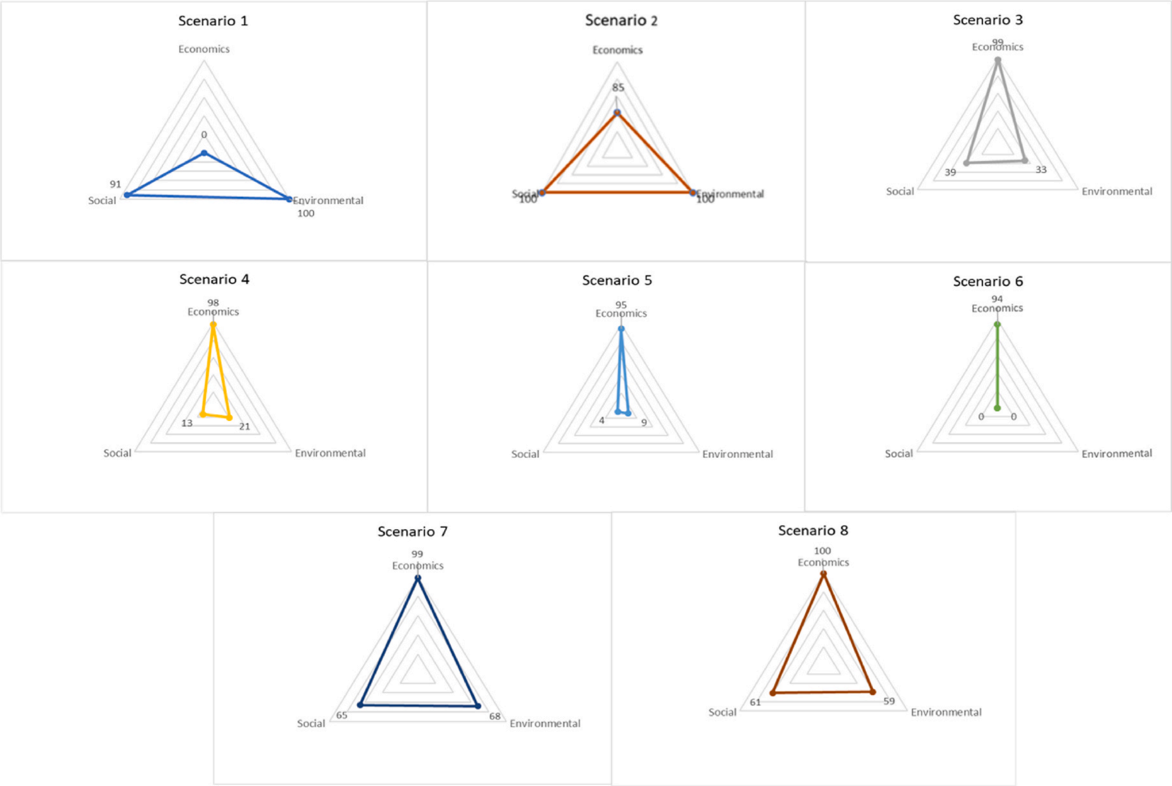


Fig. 7. Radar charts for scenario comparison.

cover a reasonable variety of possible outcomes, considering economic, environmental, and social aspects.

A scenario describes a path leading to a particular outcome: it highlights key factors for the DST analysis.

The present paper reports the results connected to the use of DST for the evaluation of potentialities connected to EW facilities in Gorno mining area: after designing the flow charts for each scenario (i.e., in Fig. 2), the Scenario table (Fig. 3) have been filled. The table reports the single steps (technology/action) to obtain a specific product associated to each scenario.

All the technologies or actions used in all the scenarios proposed (remediation, excavation, drilling, blasting, pneumatic hammer, jaw crusher, hammer mill, screener, gravimetric separation, flotation, enhanced flotation, transport, safety condition, waste management) have been indicated in a summary table, which is linked to different calculation folders in the Excel DST.

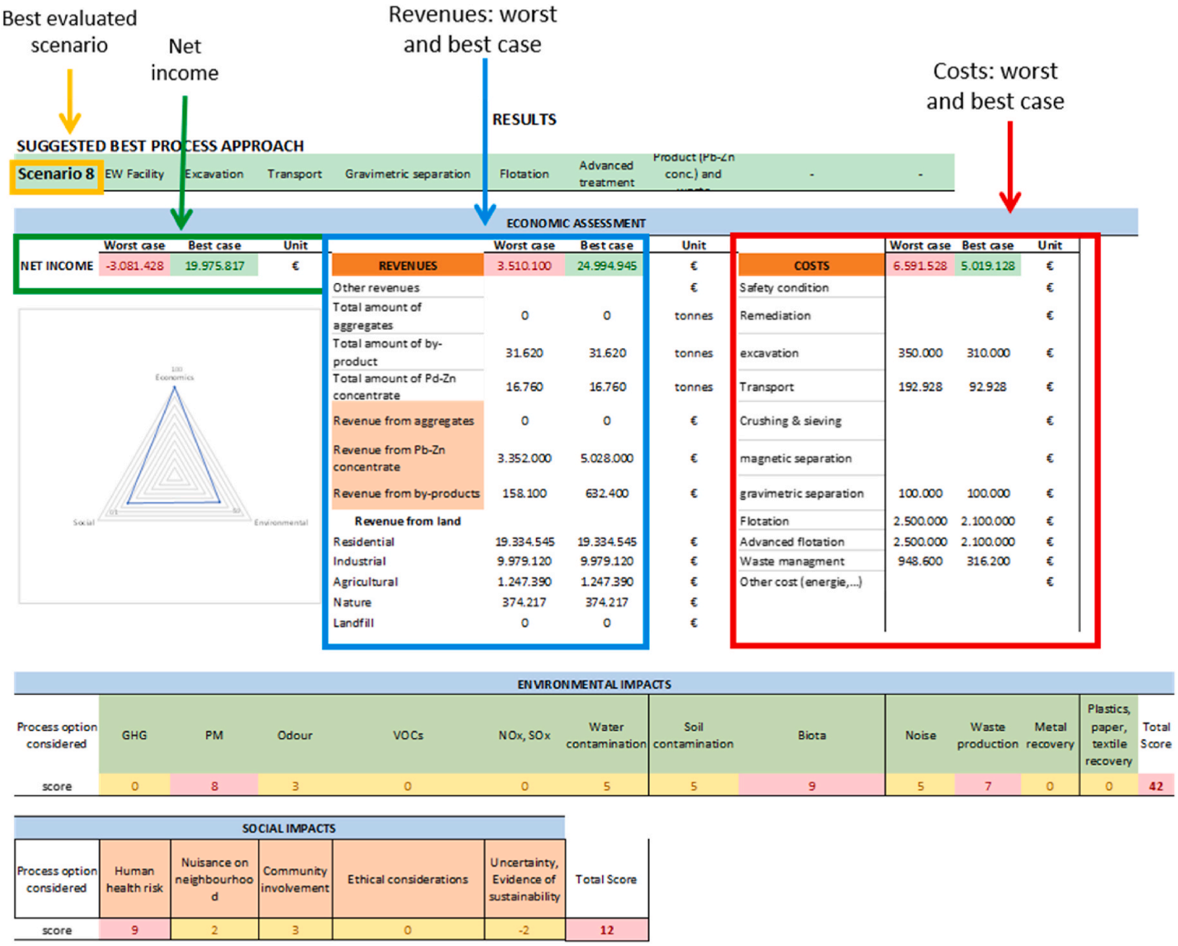
For each scenario (Nagaraj, 2005) the user creates a simply flow chart (Fig. 4) and assigns production rates (%) and a grade rate (for the mineral concentration only): i.e. in the scenario 6 (Pb and Zn concentrate product, advanced flotation), according to literature data (Güven et al., 2010; Day et al., 2002) and work experience, the production rate has been chosen (Fig. 5a).

The economic results for Scenario 6 are shown on Fig. 5. b, where estimated costs and earnings have been evaluated on the basis of published literature data (using different tables linked one to each other) to obtain a "summation" table, reporting worst and best cases revenues. At the same time qualitative data about social and economic impacts (Goedkoop et al., 2013) have been collected in two separate folders (Fig. 6), linked to the main ones. Social impacts such as human health risk and nuisance on neighbourhood are proportional to the number of people living in the areas surrounding the landfill. The use of transportation (i.e.) has negatives impact on gas emissions.

All simulated scenarios are compared with radar charts (Fig. 7). Each graph is related to a scenario and represents the three components to be assessed: social, environmental, and economic impacts. The length of a spoke is proportional to the magnitude of the component and a line is drawn connecting the data values for each spoke. The "best scenario results tab" displays the economic, environmental, and social assessment results for the best scenario, according to the user's criteria for selection. The user, selecting the various criteria for the best scenario, can encourage an economic approach or evaluate the repercussion in the social sphere or even minimize the impacts on the environment. Each scenario represents therefore different stakeholder goals. The definition of the reference scenario can emphasize an environmental protection approach, putting in the background the economic convenience of the process, or an economic approach, in which more importance is given to revenues or to the minimization of initial investment costs.

Fig. 8 shows, i.e., the results for "**the highest best-case revenues**". In this option the best possible solution is **Scenario 8**. The tab displays for an economic assessment, the optimization of revenues, according to a range (worst case - best case) both in terms of costs and in terms of revenues. This approach reflects the point of view of an entrepreneur who can assess the maximum expected return on investment. The EW DST estimates the revenues produced by the sales of the aggregates, the recovered metals and by-product. Focusing on social impacts, with "**the best social score**" criteria, for the case study, **Scenario 2** is the best one. The "results tab" shows (Fig. 9a) costs clearly higher than before, lower revenues and consequently even negative profits, but with a much better score for the social aspects. Similarly, if the user has the goal to minimize environmental impacts, through the option "the best environmental score" (Fig. 9b), the best scenarios are the numbers 1 and 2, again with inadequate economic results. In these scenarios the given score captures the impact of the technology in the worst possible case. From an economic point of view, scenario 1 shows higher costs than scenario 2, due to remediation activities, but both are still the least cost-effective of all 8 scenarios analyzed, as shown by the economic score in the radar charts (Fig. 7).

The EW DST applies a calibration factor, to take into account, action



SUGGESTED BEST PROCESS APPROACH

Scenario 8	EW Facility	Excavation	Transport	Gravimetric separation	Flotation	Advanced treatment	Product (Pb-Zn conc.) and waste	-	-

ECONOMIC ASSESSMENT

	Worst case	Best case	Unit
NET INCOME	-3.081.428	19.975.817	€

	Worst case	Best case	Unit
REVENUES	3.510.100	24.994.945	€
Other revenues			€
Total amount of aggregates	0	0	tonnes
Total amount of by-product	31.620	31.620	tonnes
Total amount of Pd-Zn concentrate	16.760	16.760	tonnes
Revenue from aggregates	0	0	€
Revenue from Pb-Zn concentrate	3.352.000	5.028.000	€
Revenue from by-products	158.100	632.400	€
Revenue from land			
Residential	19.334.545	19.334.545	€
Industrial	9.979.120	9.979.120	€
Agricultural	1.247.390	1.247.390	€
Nature	374.217	374.217	€
Landfill	0	0	€

	Worst case	Best case	Unit
COSTS	6.591.528	5.019.128	€
Safety condition			€
Remediation			€
excavation	350.000	310.000	€
Transport	192.928	92.928	€
Crushing & sieving			€
magnetic separation			€
gravimetric separation	100.000	100.000	€
Flotation	2.500.000	2.100.000	€
Advanced flotation	2.500.000	2.100.000	€
Waste managment	948.600	316.200	€
Other cost (energie,...)			€

ENVIRONMENTAL IMPACTS

Process option considered	GHG	PM	Odour	VOCs	NOx, SOx	Water contamination	Soil contamination	Biota	Noise	Waste production	Metal recovery	Plastics, paper, textile recovery	Total Score
score	0	8	3	0	0	5	5	9	5	7	0	0	42

SOCIAL IMPACTS

Process option considered	Human health risk	Nuisance on neighbourhood	Community involvement	Ethical considerations	Uncertainty, Evidence of sustainability	Total Score
score	9	2	3	0	-2	12

Fig. 8. Best scenario results for the option “the highest best-case revenues”.

or technology that can mitigate the negative impacts of the EW activity, as well as the small number of residents in the area.

5. Conclusion

The supply of Raw Materials and Critical Raw Materials is a need and a challenge to guarantee the high development standards of the EU. Such fundamental commodities can be exploited both from natural (orebodies) and anthropogenic deposits (landfills and extractive waste facilities); in particular, anthropogenic deposits can be indicated as integrative deposit to the natural ones.

The evaluation of potential resources and impacts (social, economic, and environmental) associated to those “new ore-deposits” is mandatory to program their sustainable exploitation. The DS-EW is thought to be a first approximation towards calculating the feasibility of EW exploitation, as well as a first step to further and more detailed analysis.

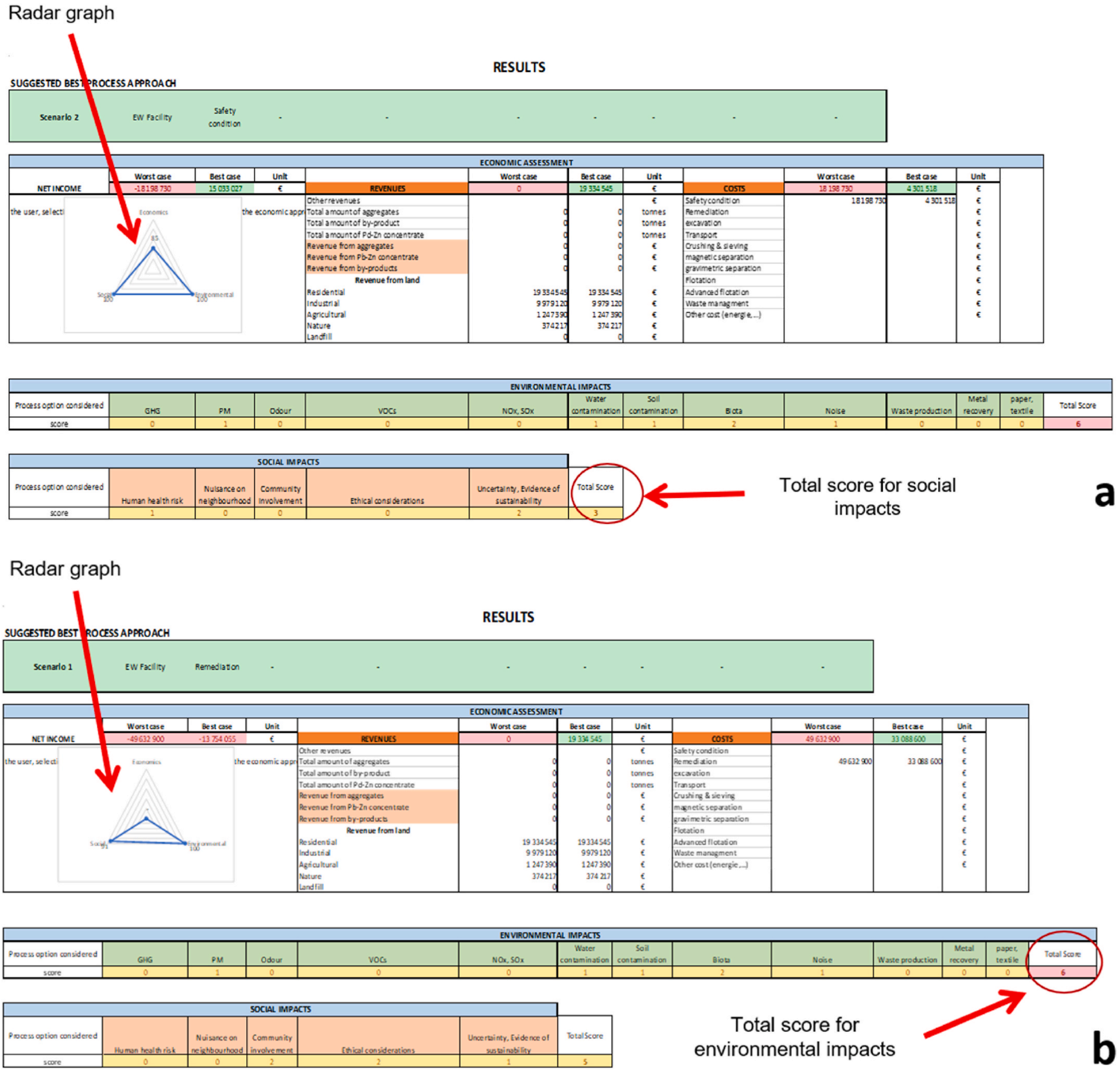
The tool can be considered as a starting point for mining operators, stakeholders, students, users interested in EW exploitation, by estimating its benefits and possible impacts. In addition, the DST-EW helps the research on EW facilities exploitation and brings new dimensions and novelty in approaching the systematic analysis of potential resources present in “anthropogenic ore deposits”. Indeed, this tool:

- Evaluates the impacts of EW facilities on three aspects of sustainability: economic, environmental, and social;
- can be applied to different EW facilities, adapting to site-specific characteristics;
- provides improved transparency of the decision-making processes
- permits the effects of uncertainty on the decision to be quantitatively addressed.

As DST considers social, economic, and environmental dimensions, this tool allows for more comprehensive assessments in line with “sustainable mining”, and it tries also to balance all the new requirements that have emerged as a result of European policies related to the “Green Deal”. As a consequence, the user, during the decision-making process, will be able to assess and to provide for variables such as ethics, impact of pollution, environmental protection, social welfare, human health, etc. Further to this, the DST-EW could be also useful in order to drive political and economic decision made by Local and Central Government.

The evolution of the DST could be the implementation of a DST 2.0 which enhance the following actions:

- **Social aspects**: in addition to the number of people living in the areas, the level of investigation could be increased by considering the stratification of inhabitants in terms of age, gender, fragile inhabitants such as old people or children as these data could impact, for example, on human health risk.
- **Economic aspects**: the level of investigation could be increased with regard to the costs included in the DST; the aim is to improve the level of accuracy and precision of evaluations. It will be also useful to increase the number of operating costs included in the DST; operating costs such as rent, insurance, assets depreciation, maintenance expenses and other overhead costs.
- **Environmental aspects**: including site-specific impacts assessed for the different scenarios, linking the DST-EW to risk analysis and LCA.



RESULTS

SUGGESTED BEST PROCESS APPROACH

Scenario 2	EW Facility	Safety condition	-	-	-	-	-	-	-

ECONOMIC ASSESSMENT

	Worst case	Best case	Unit
NET INCOME	-18198 730	15 033 027	€

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the economic appr

REVENUES	Worst case	Best case	Unit
	0	19 334 545	€
Other revenues			€
Total amount of aggregates	0	0	tonnes
Total amount of by-product	0	0	tonnes
Total amount of Pd-Zn concentrate	0	0	tonnes
Revenue from aggregates	0	0	€
Revenue from Pb-Zn concentrate	0	0	€
Revenue from by-products	0	0	€
Revenue from land			
Residential	19 334 545	19 334 545	€
Industrial	9 979 120	9 979 120	€
Agricultural	1 247 390	1 247 390	€
Nature	374 217	374 217	€
Landfill	0	0	€

COSTS	Worst case	Best case	Unit
	18 198 730	4 301 518	€
Safety condition	18198 730	4 301 518	€
Remediation			€
excavation			€
Transport			€
Crushing & sieving			€
magnetic separation			€
gravimetric separation			€
Flotation			€
Advanced flotation			€
Waste managment			€
Other cost (energie,...)			€

ENVIRONMENTAL IMPACTS

Process option considered	GHG	PM	Odour	VOCs	NOx, SOx	Water contamination	Soil contamination	Biota	Noise	Waste production	Metal recovery	paper, textile	Total Score
score	0	1	0	0	0	1	1	2	1	0	0	0	6

SOCIAL IMPACTS

Process option considered	Human health risk	Nuisance on neighbourhood	Community involvement	Ethical considerations	Uncertainty, Evidence of sustainability	Total Score
score	1	0	0	0	2	3

RESULTS

SUGGESTED BEST PROCESS APPROACH

Scenario 1	EW Facility	Remediation	-	-	-	-	-	-	-

ECONOMIC ASSESSMENT

	Worst case	Best case	Unit
NET INCOME	-49 632 900	-13 754 055	€

the user, selecti

the economic appr

REVENUES	Worst case	Best case	Unit
	0	19 334 545	€
Other revenues			€
Total amount of aggregates	0	0	tonnes
Total amount of by-product	0	0	tonnes
Total amount of Pd-Zn concentrate	0	0	tonnes
Revenue from aggregates	0	0	€
Revenue from Pb-Zn concentrate	0	0	€
Revenue from by-products	0	0	€
Revenue from land			
Residential	19 334 545	19334 545	€
Industrial	9 979 120	9979 120	€
Agricultural	1 247 390	1247 390	€
Nature	374 217	374 217	€
Landfill	0	0	€

COSTS	Worst case	Best case	Unit
	49 632 900	33 088 600	€
Safety condition			€
Remediation	49 632 900	33 088 600	€
excavation			€
Transport			€
Crushing & sieving			€
magnetic separation			€
gravimetric separation			€
Flotation			€
Advanced flotation			€
Waste managment			€
Other cost (energie,...)			€

ENVIRONMENTAL IMPACTS

Process option considered	GHG	PM	Odour	VOCs	NOx, SOx	Water contamination	Soil contamination	Biota	Noise	Waste production	Metal recovery	paper, textile	Total Score
score	0	1	0	0	0	1	1	2	1	0	0	0	6

SOCIAL IMPACTS

Process option considered	Human health risk	Nuisance on neighbourhood	Community involvement	Ethical considerations	Uncertainty, Evidence of sustainability	Total Score
score	0	0	2	2	1	5

Fig. 9. a. Best scenario results for the option "the best social score". **b.** Best scenario results for the criteria "the best environmental score".

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Author contributions

Conceptualization, G.A.D., M.C., and S.M.; methodology, G.A.D., M. C., and S.M.; software, G.A.D., M.C., and S.M.; validation, G.A.D., S.M. and P.R.; formal analysis, G.A.D., M.C., S.M., P.R. and A.F; investigation, G.A.D., M.C., and S.M.; resources, G.A.D.; data curation, G.A.D., M.C., S. M., P.R. and A.F.; writing—original draft preparation, G.A.D., M.C., S.M. and A.F.; writing—review and editing, G.A.D., M.C., S.M., P.R. and A.F.; visualization, G.A.D., M.C., and S.M.; supervision, G.A.D. and S.M.; project administration, G.A.D.; funding acquisition, G.A.D. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Giovanna Antonella Dino reports financial support was provided by University of Turin.

Data availability

Data will be made available on request.

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