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Rough sets based Ordinal Priority Approach to evaluate sustainable development goals (SDGs) for sustainable mining

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A R T I C L E I N F O

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A B S T R A C T

The Sustainable Development Goals (SDGs) have been adopted by countries and companies, including mining companies around the world. The aim of this study is to investigate the degree of importance of the seventeen sustainable development goals (SDGs) on sustainable mining using a rough sets based decision making approach. This novel approach consists of three consecutive stages, namely a questionnaire (survey), data analyses, and SDGs classification. Firstly, a survey is conducted to receive a response from internationally experts across different countries. Each participant is asked to evaluate the importance of each SDG. Secondly, the analyses are carried out to make a distinction among groups of participants who respond similarly and discover viewpoints from the industry, academia, and non-governmental organizations. Finally, the degree of importance of each SDG for sustainable mining is found using a novel decision making approach including Ordinal Priority Approach (OPA) based on rough sets. The survey of the results indicated that for all the participants of the survey, independently of their background, the most important SDG for sustainable mining was "SDG8: Decent work and economic growth", while the one perceived as the least important was "SDG14: Life below water". The main objective of SDG8 is to promote economic growth through job opportunities and decent work for all. This in turn leads to a more sustainable, long-term economic growth. While all SDGs play an important role, the proposed rough sets based decision making method provided a rational and objective evaluation performance of their perceived priority in the mining sector.

1. Introduction

The green economic recovery pathway is directly connected to reducing carbon emissions and succeeding in implementing a resource-efficient economy that generates quality employment, advances equity, and boosts infrastructure and community resilience. All these factors have been incorporated in the sustainable development goals (SDGs) developed by the UN (UN, 2015). The SDGs can thus act as green economy indicators. Improved mining policies by means of SDGs can stimulate environmental performance in the mining sector and create connections to the green and resource efficient economy (Adomako and Tran, 2022; Merino-Saum et al., 2018).

Notably, the accomplishment of Europe's goal of a green, digital economy and climate neutrality by 2050 requires to boost capacity in green mining, processing, production, reuse, and recycling and implement sustainable mining practices. A prerequisite for sustainability is the long-term maintenance of natural resources. Metals and minerals will continue to be necessary for the development of modern, sustainable communities, hence the mining sector needs to continue to evolve in order to fully take sustainability into account. The latter requires to consider the environment, society and economy. Health, social, and cultural factors are examples of relevant social considerations. Emissions, waste management, post-extraction cleanup, nature preservation, energy use, and climate all need to be taken into account when

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considering the environment. Social progress, wealth, competitiveness, resource management, and the circular economy are all facets of the economy. The mining industry should also collaborate with others to address sustainability issues, as the current carbon and climate footprints are in many ways not sustainable (Ciacci et al., 2020; Filipović et al., 2022; Janikowska and Kulczycka, 2021).

Focusing on social and environmental challenges within six categories—water, land, air, socioeconomic, health and safety, and quality of life—is a comprehensive approach to sustainability. These are complicated issues that call for systemic solutions to pinpoint the underlying causes and stop further deterioration. These problems are addressed by sustainable mining, which also benefits the local communities where it operates. There are overlaps between economic, social, and environmental objectives. For instance, focusing on renewable energy lowers operational costs, increases mine efficiency by ensuring a more reliable power supply, and lowers carbon emissions. (Adomako and Tran, 2022; Littleboy et al., 2019; Ruokonen, 2020).

Mining projects have a great opportunity to add value, build capacity, and strengthen the social consensus of the communities in which they operate, contributing to sustainable development has and thus taking on the challenge of identifying and mitigating environmental and social sustainability challenges (Laurence, 2011; Varouchakis et al., 2022). Another dimension of sustainable mining is the extraction and exploitation practices of the mineral resources. A decreased mine life frequently occurs as a result of the careless mining of an ore body. The resource must be managed and mined in an effective manner for sustainable mining to take place. Efficient mining practices are also related to both production and energy use, which are important sustainable development goals directly related to the mining sector (Aznar-Sánchez et al., 2019; Gastauer et al., 2018).

The mining sector has put a lot of effort into addressing sustainability issues like climate change, pollution, land degradation, worker and community health and safety, and human rights. However, if the goal of sustainability has not already been established, it can be exceedingly challenging to reach agreement on solutions in complex situations. The key issues that the mining industry should discuss towards sustainable mining include the viability of the minerals sector, control over land use and management, national and local social and economic development, environmental management, materials stewardship, and information access. The mining industry has to apply modern data collecting and processing tools, and implement monitoring actions to support the process of addressing these challenges, to drive efforts to accomplish the sustainable development goals (Gastauer et al., 2018; Mesquita et al., 2021). The United Nations Development Programme (UNDP), and the World Economic Forum have published the Sustainable Development Goals (SDGs) focusing on the role of the mining industry to positively contribute to all 17 stated UN-SDGs (Capello et al., 2021).

Environmental impact assessment is a very efficient tool for sustainable mining. The assessment of the impact of mining on humans, fauna and flora, soil, water, air, climate, landscape, resources, cultural heritage, and a comparative analysis of the interaction between these factors can inform mitigating measures and the effective implementation of sustainable mining practices (Mancini and Sala, 2018). Another tool to enhance sustainable mining is the Internet of Things (IoT), which accounts for the application of interconnected devices and systems to the common requirements of mining operations and a healthy environment. IoT architecture and technology supports the development of digital platforms to control and monitor mineral resources extraction operations, improved tailings management, monitoring and mitigation of pollutants, water quantity and quality, soil and human health (Salam, 2020).

Mining practices are considered sustainable when they support the environmental and socio-economic indicators, in a way that is aligned to the sustainable development goals (SGDs). The analysis of current and future demands in mining, responsible mining, novel decision-making approaches, implementation of practices by means of SGDs, improvements in metal recycling and mining rehabilitation methods are the critical factors that will lead to green and sustainable mining.

The aim of this study is to investigate the degree of importance of SDGs for sustainable mining using rough sets based Ordinal Priority Approach (OPA) method. The method includes three consecutive stages, namely a questionnaire (survey), data analyses, and SDGs classification. Firstly, a survey is conducted to receive a response from internationally experts across different countries. Secondly, the decision making and statistical analyses are carried out to make a distinction among groups of participants. Finally, the degree of importance of each SDG for sustainable mining is determined using a decision making model based on an OPA method. This study presents an improvement of the OPA method (Ataei et al., 2020) for determining the sustainable development goals' weight coefficients. The modification of the OPA method has been done through several aspects. The first aspect is integrating rough numbers into OPA methodology, thus enabling objective and adequate addressing of expert uncertainties and inaccuracies. Another aspect is the improvement of the traditional OPA methodology algorithm by implementing standardized elements of the integrated rough linguistic matrix into a rough linear model. This enables a more precise and objective definition of interval values of weight coefficients. The third aspect is the possibility of dual application of rough OPA methodology.

In addition to improving the OPA methodology, a novel methodology for determining the imprint of inaccuracies in rough numbers (RN) using flexible rough boundary intervals is proposed in this study. The proposed RN methodology also considers the mutual relations between the criteria and different levels of risk. By incorporating these advantages into the OPA methodology, a powerful tool has been created for processing uncertainties and inaccuracies in the information and objectively defining the weighting coefficients of the criteria.

The rest of this study is structured as follows: Section 2 provides an introduction to the sustainable development goals. The fundamental steps of the proposed methodology are defined in Section 3. Section 4 provides a questionnaire to determine the importance of the seventeen SDGs. The questionnaire results are then presented in Section 5, while Section 6 discusses the results on the sustainable development goals. Section 7 presents the conclusions and discusses the potential for future work.

2. Sustainable development goals

The United Nations approved the Sustainable Development Goals in 2015 as a global initiative to eradicate poverty, safeguard the environment, and promote peace and prosperity. The 17 SDGs (see Table 1) have been adjusted, depending on the scientific discipline, to focus on how they can positively contribute to meet specific challenges. The

Table 1
The sustainable development goals.

Goals	Actions
Goal 1	No poverty
Goal 2	Zero hunger
Goal 3	Good health and well-being
Goal 4	Quality education
Goal 5	Gender equality
Goal 6	Clean water and sanitation
Goal 7	Affordable and clean energy
Goal 8	Decent work and economic growth
Goal 9	Industry, innovation, and infrastructure
Goal 10	Reduced inequalities
Goal 11	Sustainable cities and communities
Goal 12	Responsible consumption and production
Goal 13	Climate action
Goal 14	Life below water
Goal 15	Life on land
Goal 16	Peace, justice and strong institutions
Goal 17	Partnerships for the Goals

contribution of the mining industry is explained in detail below in association with each SDG definition (Capello et al., 2021; Endl et al., 2021; Fraser, 2019; Hirons, 2020; Monteiro et al., 2019; Moomen et al., 2019; Parra et al., 2020; Sonesson et al., 2016; UN, 2015).

(1) SDG1 (C_1): No Poverty: Through the payment of taxes and royalties, the creation of jobs, the stimulation of the economy, and the provision of high-quality services, mining helps end poverty. In order to increase indirect employment, many nations mandate that mining corporations make investments in regional supplies and create a supply-chain strategy. In addition to creating jobs, businesses should collaborate extensively with local suppliers to build regional and national capacity for the delivery of goods and services. Mining firms should carefully consider land access plans and treat the local communities with respect and special consideration (Capello et al., 2021; Moomen et al., 2019).

(2) SDG2 (C_2): Zero Hunger: Ending hunger while enhancing the sustainability of the world's food and agricultural systems is the goal of SDG 2. By managing their effects on natural resources and working to end hunger, increase agricultural productivity, and promote sustainability, mining firms may support SDG2. It is possible for mining and farming or small-scale food production to co-exist, as long as mining companies take into consideration the needs of each livelihood, treating them with respect, building trust and avoiding negative impacts. Companies can work closely with communities or other stakeholders to find ways to monitor water management, consumption, use and quality. Mining companies should design and plan the infrastructure needed for the water storage (reservoirs) with respect to the availability of water resources. Companies can then identify design requirements, reduce adverse effects, respond to public concerns, and overall help to improve water management for the benefit of agriculture (Hirons, 2020; UN, 2015).

(3) SDG3 (C_3): Good Health and Well-being: Making sure people live healthy lives and encouraging wellbeing at all ages is one of the essential components of sustainable development. In order to prevent risks, mining corporations have commitments and policies for health and safety. The mining industry has made a significant commitment to develop high standards and management systems to ensure safe conditions for all their workers. The integration of the community into the organization's health and safety management systems is crucial. Mining companies should take into consideration the health and safety of their employees as well as the surrounding communities. Potential risks for the health and safety of the community may come from the infrastructure work that takes place. Working in rural and remote operations under the hard conditions of the mining sector presents a variety of difficulties, such as FIFO (fly-in, fly-out) lifestyles, challenging climate conditions, and being apart from family and friends. The relationships may suffer as a result of this. Companies should create programs that support a holistic approach to employee physical, mental, and emotional health in order to prevent this. The release of emissions and contaminants into the environment, such as chemicals and heavy metals, poses another threat to the health of populations. The sources of possible emissions and dangers to land, water, and people should be understood by businesses, and management strategies should be developed accordingly (Parra et al., 2020; Sonesson et al., 2016).

(4) SDG4 (C_4): Quality education: Education provides people with the building blocks they need to develop better lives for themselves. Through technical, vocational, and educational programs for their employees, mining supports high-quality education. Mining companies in collaboration with the local public services can invest in workforce education and training, as well as in creating new graduate programmes and scholarship opportunities for the youth. In addition, they can work together to understand the difficulties of providing comprehensive access to education and to identify opportunities for company involvement (Monteiro et al., 2019; UN, 2015).

(5) SDG5 (C_5): Gender Equality: All women and girls should have equal access to education, employment, and involvement in political and economic decision-making, which is a fundamental human right. Gender equality in the mining sector entails gender balance and equal remuneration for equivalent work at all organizational levels. Companies should ensure that provide equal opportunities and recognition for all (Fraser, 2019; Monteiro et al., 2019).

(6) SDG6 (C_6): Clean Water and Sanitation: Millions of deaths and the spread of disease can be attributed to poor sanitation. By reducing its own water footprint (e.g., through water recycling and efficiency measures), increasing the local supply through shared water infrastructure, and ensuring that the operations do not dispose of polluted water, mining operations can help ensure that everyone has adequate access to clean water and sanitary facilities. Businesses can find ways to support the watershed management strategy where they operate. Also, they can share the benefits of their expertise in material processing and infrastructure to bring water purification to underserved locations (Laurence, 2011; Mancini and Sala, 2018).

(7) SDG7 (C_7): Affordable and Clean Energy: The overarching objective is to lessen the detrimental effects on the environment and increase access to reliable energy for those who do not currently have it. By speeding the integration of energy efficiency measures and renewable energy sources into mine power supplies, the mining industry, which is predominantly energy-intensive, may contribute to energy sustainability. Programs for research and development that concentrate on fresh low energy solutions can be supported by mining companies. Instead of using diesel, forward-thinking businesses are turning to eco-friendly alternatives such as wind, solar, geothermal energy, etc (Monteiro et al., 2019; Sonesson et al., 2016).

(8) SDG8 (C_8): Decent Work and Economic Growth: SDG8's primary objective is to encourage economic growth that results in job opportunities and quality jobs for everyone. Mining corporations can contribute to the development of strategies that support domestic enterprises that are competitive in order to boost local content and supply capacity. As a result, the economy grows more sustainably and over the long run. The jobs opportunities generated by the direct employment are relatively limited comparing to the size of the capital investment. Understanding the impacts of the mining activity can lead to a better, long-term economic growth. There are three types of economic influence: direct (direct purchases of products and services by the mine), indirect (goods and services purchased by suppliers of the mine), induced (purchased at the household by the employees). Companies must build a comprehensive approach that promotes the support of local suppliers (Monteiro et al., 2019; UN, 2015).

(9) SDG9 (C_9): Industry Innovation and Infrastructure: Mining requires transport, water, energy, information and communication technology infrastructure. Shared use infrastructure, especially in countries that is not actively developed, represents a challenge for mining to expand critical services to those areas. While conventional infrastructure solutions are frequently primarily intended to support the mining operation, expanding infrastructure connectivity to neighboring regions can open up economic potentials. Distinct geological characteristics require specialized mining techniques; therefore, research and development programmes can be developed that contribute to in-country innovation. Furthermore, companies should provide technical/technological expertise through programmes to help the domestic companies to become suppliers (Mesquita et al., 2021; UN, 2015).

(10) SDG10 (C_{10}): Reduced Inequalities: Social inequality is a result of economic disparity, which can occasionally cause social unrest and damage the mining company's ability to function in society. By encouraging diversity in the workforce, harnessing direct, indirect, and induced economic advantages through local procurement, and

working with the government and local communities to facilitate open public consultations, mining may play a proactive role. Building local employment and training programmes can help; although, the job opportunities can be limited. Inflation is common in mining areas as there is a special increased demand for products and services, therefore, those without access to mining wages (that are increased comparing to others) can become poorer. Companies should be sensitive to local wage disparities and establish baseline welfare statistics before mining. They can train and recruit marginalized populations and include excluded groups in local procurement (Mancini and Sala, 2018; Sonesson et al., 2016).

(11) SDG11 (C_{11}): Sustainable Cities and Communities: Mining corporations can assist the growth of local infrastructure and involve all interested parties in land use and settlement planning and create the necessary mined land reclamation plan in order to help create sustainable cities and communities. Companies must plan the land use with the life-of-mine in mind. They can work with local government agencies to create green space, including abandoned mines (Hirons, 2020; Parra et al., 2020).

(12) SDG12 (C_{12}): Responsible Consumption and Production: Materials that are used often in life are produced via mining. On the other side, mining also produces waste, most of which is useless. Despite these difficulties, mining can assist more environmentally friendly production by working with governments and the entire supply chain to promote a circular economy that reduces waste inputs and boosts raw material reuse, recycling, and repurposing. Sustainable production demands cooperation between producers and consumers. Both are in charge of finding inefficiencies, enhancing sustainable consumption, and giving the necessary information to end customers about the source of the raw materials (Hirons, 2020; Moomen et al., 2019).

(13) SDG13 (C_{13}): Climate Action: Climate change plays a crucial role and affecting the national economies in the coming decades. By lowering their carbon footprint, mining corporations may help combat climate change. Additionally, businesses ought to work with interested parties to improve their adaptive capacities and include climate change measures into their policies and strategies. The primary goal of the companies should be to reduce emissions by using renewable energy, improve energy efficiency and measure and report product-related emissions. Companies can create climate-related environmental models, prepare for the effects of climate change on mines and communities and generally adopt corporate climate change, carbon management and disclosure policies (Endl et al., 2021; Laurence, 2011).

(14) SDG14 (C_{14}): Life below water: By detecting marine-related problems and mitigating measures, comprehending how dependent local communities are on marine resources, and helping to conserve the oceans and seas, mining corporations may contribute to the sustainability of the ocean. Proper disposal of tailings and waste, as well as, the assessment of the social and environmental impacts on fishing and marine base livelihoods should be included in each company's agenda. The aforementioned can be accomplished by companies working with local government to create coastal zone management plans, conservation areas and marine reserves (Endl et al., 2021; Mesquita et al., 2021).

(15)SDG15 (C_{15}): Life on Land: For food, water, housing, income, medicine, and other necessities, people rely on terrestrial ecosystems. The world needs to do a better job managing and protecting its valuable ecosystems. Ecosystems may suffer as a result of mining activities. Businesses should support the avoid, minimize, restore, enhance, and offset hierarchy of mitigation actions, which provides a framework for mining and other businesses to evaluate and decide what steps to take to conserve ecosystems and biodiversity. Businesses can work with governments, non-profit organizations, academic institutions, and local communities to restore habitats, plant new trees, and other activities that will protect and promote biodiversity (Monteiro et al., 2019; Sonesson et al., 2016).

(16)SDG16 (C_{16}): Peace, Justice and Strong Institutions: Conflict, tax evasion, human rights violations, and corruption are major examples that threaten inclusive and sustainable development. Mining companies should ensure transparency and refrain from undermining the reliability of government organizations. By preventing company-community friction, facilitating access to information, and upholding human rights, they can further ensure that they do not harm peaceful societies. The above can be achieved by promoting the rule of law, publicly report project-related payments and generally encourage a calm workplace and positive community relations (Capello et al., 2021; UN, 2015).

(17)SDG17 (C_{17}): Partnership for the Goals: Governments, the private sector and the civil society should collaborate to promote the sustainable development agenda. Mining companies can contribute to this by using environmentally friendly technologies in their operations, hiring people, collaborating with governments in shared infrastructure arrangements and paying a reasonable and fair part of the taxes they owe in the countries where they operate (Monteiro et al., 2019; UN, 2015).

3. A novel rough OPA framework

This section presents preliminary settings of the rough OPA methodology as shown in Fig. 1. Rough sets based decision making models have been successfully integrated into real-life problems (Durmić et al., 2020; Chattopadhyay et al., 2022; Sharma et al., 2022).

In the following part, some of the characteristics of the OPA method are presented: (1) Most subjective MCDM models for determining weighting coefficients of criteria/alternatives, such as FUCOM (Pamucar et al., 2018), DIBR (Pamucar et al., 2021) or BWM (Rezaei, 2015) are based on pairwise comparisons of decision attributes. However, most fundamental problems are based on complex decision-making models in which the final results are based on many decision attributes. This increases the required number of comparisons, which reduces the consistency of the results, and, thus, the quality of the obtained solution (Bakir and Atalik, 2021; Karamaşa et al., 2021a; Fazlollahtabar and Kazemitash, 2021). On the other hand, the OPA method uses an original algorithm based on defining the weighting coefficients of the criteria/alternatives based on the ranks of the criteria/alternatives. This facilitates the presentation of expert preferences and results in consistent solutions. Also, this eliminates the problem of a limited range of predefined scales for comparing criteria used in other models, such as the AHP method and BWM models (Alosta et al., 2021; Karamaşa et al., 2021b). (2) The OPA algorithm can be used both in group decision-making models and in models where information is based on the aggregated information. (3) When used in group models for decision-making, the OPA algorithm defines experts' weighting coefficients.

Suppose the research defines a set of n SDGs C_j ($j = 1,2, \ldots,n$). Also, suppose that m experts $\Im_e = \{\Im_1, \Im_2, \ldots, \Im_m\}$ participate in the research. Then, we can express an algorithm for applying the rough OPA model given through the next three steps:

Step 1: Creating an integrated rough linguistic matrix $\Omega = [\overline{\partial}_{\mathrm{j}}]_{\mathrm{n}\times 1}$. After conducting the survey, linguistic matrices are formed for each expert $\Omega^{\mathrm{k}} = [\partial_{\mathrm{j}}^{\mathrm{k}}]_{\mathrm{n}\times 1}$ $(1 \leq \mathrm{k} \leq \mathrm{m})$, where $\partial_{\mathrm{j}}^{\mathrm{k}}$ represents the assessment of the kth expert on the significance of the jth criterion. Thus we obtain k linguistic matrices $\Omega^1, \Omega^2, \ldots, \Omega^{\mathrm{k}}, \ldots, \Omega^{\mathrm{m}}$ which we can represent as follows:

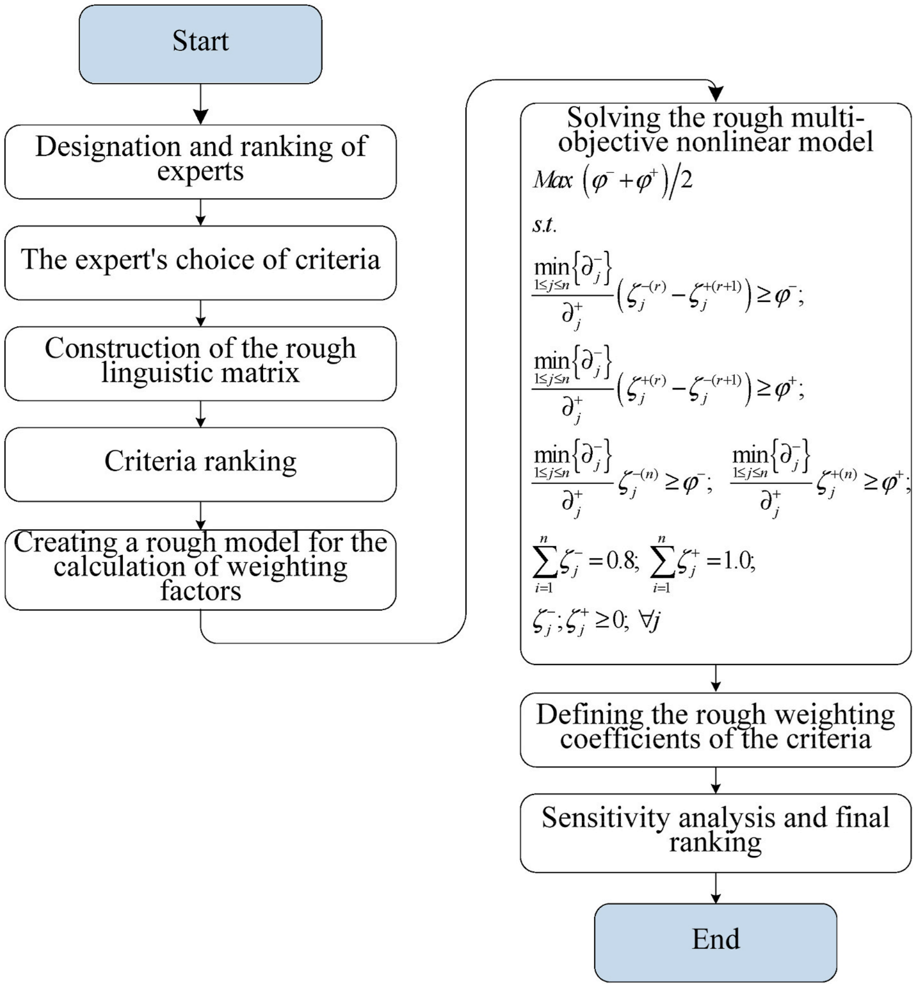

Fig. 1. The rough OPA methodology.

$$\Omega^* = \begin{array}{c} C_1 \\ C_2 \\ C_3 \\ \dots \\ C_n \end{array}\begin{bmatrix} \partial_1^1,\partial_1^2,\dots,\partial_1^k,\dots,\partial_1^m \\ \partial_2^1,\partial_2^2,\dots,\partial_2^k,\dots,\partial_2^m \\ \partial_3^1,\partial_3^2,\dots,\partial_3^k,\dots,\wp_3^m \\ \dots \\ \partial_n^1,\partial_n^2,\dots,\partial_n^k,\dots,\partial_n^m \end{bmatrix} \tag{1}$$

where $\partial_j^* = \{\partial_n^1,\partial_n^2,\dots,\partial_n^k,\dots,\partial_n^m\}$ represent sequences that describe the significance of criterion j. Suppose that the sequences $\partial_j^* = \{\partial_n^1,\partial_n^2,\dots,\partial_n^k,\dots,\partial_n^m\}$ are arranged in descending order as $\partial_j^1 \le \partial_j^2 \le,\dots \le \partial_j^k \le,\dots,\le \partial_j^m$. Then for each $\forall\partial_j^x,\partial_j^k \in \partial_j^*$, $1 \le k \le m$ we can define the upper and lower approximations of ∂_j^e as follows:

$$\begin{aligned} \underline{\partial}_j^k &= \bigcup_{1\le e\le m}\left\{\partial_j^e \in \partial_j^* \middle| \partial_j^k \le \partial_j^x\right\} \\ \overline{\partial}_j^k &= \bigcup_{1\le e\le m}\left\{\partial_j^e \in \partial_j^* \middle| \partial_j^k \ge \partial_j^x\right\} \end{aligned} \tag{2}$$

Based on Eq. (2), the lower and upper limits of ∂_j^e is defined as follows:

$$\begin{aligned} \partial_j^{k-} &= \left(\frac{1}{\lambda_L}\sum_{\substack{i,j=1\\ i\neq j}}^{\lambda_L}\partial_i^{kd_1}\left(\prod_{j=1}^{\lambda_L}\partial_j^{kd_2}\right)^{\frac{1}{\lambda_L-1}}\right)^{\frac{1}{d_1+d_2}} \left|\partial_i^{kb_1},\partial_j^{kb_2}\in\underline{\partial}_j^k\right. \\ \partial_j^{k+} &= \left(\frac{1}{\lambda_U}\sum_{\substack{i,j=1\\ i\neq j}}^{\lambda_U}\partial_i^{kd_1}\left(\prod_{j=1}^{\lambda_U}\partial_j^{kd_2}\right)^{\frac{1}{\lambda_U-1}}\right)^{\frac{1}{d_1+d_2}} \left|\partial_i^{kb_1},\partial_j^{kb_2}\in\overline{\partial}_j^k\right. \end{aligned} \tag{3}$$

where $1 \le k \le m$, λ_L and λ_U denote the number of elements within the lower and upper limits, and $d_1, d_2 \ge 0$.

The rough matrices of expert estimates are obtained with the help of Eqs. (2) and (3). By fusion of rough values we get an integrated rough linguistic matrix $\Omega = [\overline{\partial}_j]_{n\times 1}$, $\overline{\partial}_j = [\partial_i^-,\partial_i^+]$.

Step 2: Ranking the SDGs according to their importance. The rank SDGs are expressed based on the rough values from the integrated rough linguistic matrix $\Omega = [\overline{\partial}_j]_{n\times 1}$. A higher rough value $\overline{\partial}_j = [\partial_i^-,\partial_i^+]$ affects the better rank of the criterion, so if $\overline{\partial}_{p_1} > \overline{\partial}_{p_1}$ $(1 \le p_1, p_2 \le n)$, then the criteria C_{p_1} have a better rank than C_{p_2}. Also, if $\overline{\partial}_{p_1} = \overline{\partial}_{p_1}$, then the criteria C_{p_1} and C_{p_2} have the same rank. Based on these conditions, we can define the rank of the criteria:

$$\bar{\partial}_j^{(1)} \geq \bar{\partial}_j^{(2)} \geq \ldots \geq \bar{\partial}_j^{(r)} \geq \bar{\partial}_j^{(r+1)} \geq \ldots \geq \bar{\partial}_j^{(m)}; \forall j \tag{4}$$

where $\bar{\partial}_j^{(r)} = [\bar{\partial}_j^{(r)-}, \bar{\partial}_j^{(r)+}]$ represents the weighting coefficient of the jth criterion at the r-th rank.

Based on Eq. (4), we can derive the following relationships between successively ranked criteria:

$$\begin{aligned} &\bar{\partial}_j^{(1)} - \bar{\partial}_j^{(2)} \geq 0; \\ &\bar{\partial}_j^{(2)} - \bar{\partial}_j^{(3)} \geq 0; \\ &\ldots \\ &\bar{\partial}_j^{(r)} - \bar{\partial}_j^{(r+1)} \geq 0; \\ &\ldots \\ &\bar{\partial}_j^{(n-1)} - \bar{\partial}_j^{(n)} \geq 0. \end{aligned} \tag{5}$$

Also, Eq. (5) can be shown as follows:

$$\frac{\min\limits_{1\leq j\leq n}\left\{\partial_j^-\right\}}{\partial_j^+}\left(\bar{\zeta}_j^{(r)} - \bar{\zeta}_j^{(r+1)}\right) \geq 0; \forall j \tag{6}$$

where $\bar{\zeta}_j$ denotes the rough vector of the weighting coefficients of the criterion.

Step 3: A rough linear model is used to calculate the weights of the criteria. Based on conditions (4)–(6), a multi-objective nonlinear model (7) is applied.

$$\begin{aligned} &\text{Max Min}\left\{\frac{\min\limits_{1\leq j\leq n}\left\{\partial_j^-\right\}}{\partial_j^+}\left(\bar{\zeta}_j^{(r)} - \bar{\zeta}_j^{(r+1)}\right), \frac{\min\limits_{1\leq j\leq n}\left\{\partial_j^-\right\}}{\partial_j^+}\bar{\zeta}_j^{(m)}\right\}; \forall j \\ &\text{s.t.} \\ &\sum_{j=1}^{n}\bar{\zeta}_j = 1; \\ &\bar{\zeta}_j \geq 0; \forall j \end{aligned} \tag{7}$$

where $\bar{\zeta}_j$ denotes the rough vector of the weighting coefficients of the criterion.

We can transform a multi-objective nonlinear model (7) into a linear mathematical model, an Eq. (8).

$$\begin{aligned} &\text{Max } (\varphi^- + \varphi^+)/2 \\ &\text{s.t.} \\ &\frac{\min\limits_{1\leq j\leq n}\left\{\partial_j^-\right\}}{\partial_j^+}\left(\zeta_j^{-(r)} - \zeta_j^{+(r+1)}\right) \geq \varphi^-; \\ &\frac{\min\limits_{1\leq j\leq n}\left\{\partial_j^-\right\}}{\partial_j^+}\left(\zeta_j^{+(r)} - \zeta_j^{-(r+1)}\right) \geq \varphi^+; \\ &\frac{\min\limits_{1\leq j\leq n}\left\{\partial_j^-\right\}}{\partial_j^+}\zeta_j^{-(n)} \geq \varphi^-; \quad \frac{\min\limits_{1\leq j\leq n}\left\{\partial_j^-\right\}}{\partial_j^+}\zeta_j^{+(n)} \geq \varphi^+; \\ &\sum_{i=1}^{n}\zeta_j^- = 0.8; \ \sum_{i=1}^{n}\zeta_j^+ = 1.0; \\ &\zeta_j^-; \zeta_j^+ \geq 0; \forall j \end{aligned} \tag{8}$$

By solving model (8), we obtain rough weight coefficients of the jth criterion $\bar{\zeta}_j = [\zeta_j^-, \zeta_j^+]$.

Table 2
The main characteristics of the participants.

Country	Academia	Industry	Other	Total	N (%)
Brazil	9		1	10	12.82%
Ghana	4	1	1	6	7.69%
Australia	3	2	1	6	7.69%
Turkey	2	2	1	5	6.41%
Canada	5			5	6.41%
Germany	4	1		5	6.41%
Chile	3			3	3.85%
Colombia	3			3	3.85%
China	3			3	3.85%
Peru	1	1		2	2.56%
Pakistan	2			2	2.56%
Vietnam	2			2	2.56%
Poland	2			2	2.56%
Ukraine	2			2	2.56%
United Kingdom	2			2	2.56%
Iran	2			2	2.56%
Austria	1			1	1.28%
South Africa	1			1	1.28%
Russia	1			1	1.28%
Greece	1			1	1.28%
France	1			1	1.28%
India	1			1	1.28%
Portugal	1			1	1.28%
Mexico	1			1	1.28%
Singapore	1			1	1.28%
New Zealand	1			1	1.28%
South Africa	1			1	1.28%
Indonesia	1			1	1.28%
Sri Lanka	1			1	1.28%
Italy	1			1	1.28%
Japan	1			1	1.28%
Zambia	1			1	1.28%
Malaysia	1			1	1.28%
Mali			1	1	1.28%
Total	**66**	**7**	**5**	**78**	**100%**
%	**84.6%**	**9.0%**	**6.4%**	**100%**	

4. Problem description

In this section, the questionnaire and data collection and processing are presented. Information about the demographic, experiences, countries and departments of the experts are also given.

4.1. Data collection and processing

An online questionnaire was prepared to identify the degree of importance of sustainable development goals for sustainable mining. The online questionnaire [1] (see also Appendix A1) was conducted by e-mail invitations using Google Drive. 298 international experts were invited to participate in the online questionnaire, and it was filled out by 78 experts spread over 35 different countries. The participants were identified from publications related to mining such as industry experts, as well as experts from academia, local governments and non-government organizations (NGOs).

Seventy-eight out of the 298 experts responded to the questionnaire. The main characteristics of participants are presented in Table 2. It can be seen that 84.6% of the participants are from academia, 9.0% of the participants are from industry, and 6.4% of the participants are from other such as non-government organizations. As can be also seen from this table, the top countries with the highest level of participation to the questionnaire are Brazil, Ghana, Australia, Turkey, Canada, and Germany, respectively.

The frequency distribution of the experts in years of total professional experience in the mining industry is shown in Fig. 2. As can be seen this figure, the majority (58.97%) of the participants have between

[1] https://forms.gle/Mka67DhqRvgfJkKG9.

0 and 8 years, 28.21% of the participants have between 9 and 16 years, very few of the participants have more between 17 and 24, 25–32, 33–40, and 41–48 years of professional experience.

The participants were asked to self-rate their level of expertise in sustainable mining ('very low', 'low', 'medium low', 'medium', 'medium high', 'high', and 'very high'). The self-rated expertise of participants is shown in Fig. 3. According to this Figs. 3 and 34.62% of participants have a high level of expertise, 25.21% of participants have a medium high level of expertise, 16.67% of participants have a medium level of expertise, 12.82% of participants have a very high level of expertise, 1.28% of participants have low and very low level of expertise.

The distribution of the number of participants with respect to various departments is given in Table 3. Most of them were department of business, mining engineering, environmental, mineral processing, civil engineering, and chemical engineering.

A statistical analysis was performed in SPSS Software comparing the means between groups for each criterion. The Kruskal Wallis H-test (Kruskal and Wallis, 1952) is used for the analysis of the means among groups. The Kruskal Wallis test is the non-parametric alternative to the One Way ANOVA. It evaluates the differences among three or more independently sampled groups on a single, non-normally distributed continuous variable. The results of the Kruskal Wallis H-test for groups are presented in Table 4. When the significance levels of SDGs (sig. $\leq$ 0.05) were checked, there is no relationship among groups in terms of SDGs. The descriptive statistics of groups are also shown in Figs. 4–6.

The standard deviation of the SDGs is illustrated in Fig. 4. As seen in Fig. 4, the SDGs with the lowest std. deviation value have C_8 and C_6, respectively. The SDGs with the highest std. deviation value have C_{14} and C_2, respectively.

The mean of each criterion according to 78 expert evaluations is depicted in Fig. 4. It can be seen in Fig. 4 that C_6 and C_8 have the highest mean value, respectively. The SDGs with the lowest mean value are C_2 and C_5, respectively.

Fig. 5 shows the mean value of each criterion in terms of groups. For example, when we examine C_1 in term of each group, the mean value of industry experts has low value when compared to academia and other groups.

The Ward's method is applied to find the similarity among the participants. Ward's method is an approach for hierarchical cluster analysis, and the distance between two clusters is used for similarity. The hierarchical relationship among the participants is depicted using dendrogram as illustrated in Fig. 7. According to this dendrogram, the highest similarity was found for participants {6, 31, 3, 40, 37, 36 and 46}, {60, 78, 19, 63, 73, 4, 49, 2, 35, 44, 13 and 20}, ending with participant {58, 71, and 12}, respectively.

5. Analysis of results

In this section, the application of the rough OPA methodology for determining the weighting coefficients of the SDGs is presented.

Step 1: During the research, 78 experts were interviewed and were grouped into three groups: Academia, Industry, and Other. There were

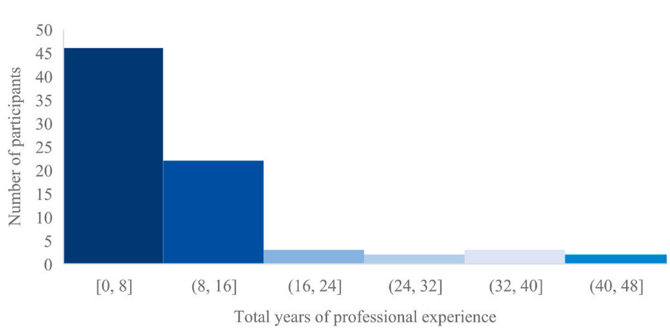

Fig. 2. Total years of participants' professional in the mining sector.

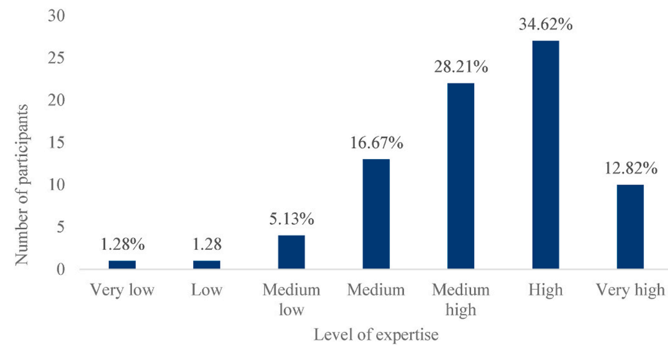

Fig. 3. Self-rated expertise of participants in the field of sustainable mining.

Table 3
The participants and their departments.

Department/division	Number of Participants
Department of Business	15
Department of Mining Engineering	11
Department of Environmental	9
Department of Minerals Processing	6
Department of Mining	4
Civil Engineering	3
Chemical Engineering	3
Development Studies	3
Department of Mining Reclamation	2
Civil and Environmental Engineering	1
No department	1
Faculty of Industrial Sciences and Technology	1
Department for Earth and Environmental Sciences	1
Production and Systems	1
School of Land Science and Technology	1
Department of Water	1
Department of Geodesy and Geoinformatics	1
Department of Planning and Sustainability	1
Institute of Mechanical Process Engineering and Mechanics	1
Department of Social and Applied Sciences	1
Political Science	1
Department of Anthropology	1
Safety and Sustainability	1
CEO	1
Social Sciences	1
Earth Sciences and Engineering	1
Department of Construction Management	1
Energy transition	1
Department of Metallurgical Engineering	1
Extractive Metallurgy	1
Earth Observatory of Singapore	1
Total	78

66 experts within the Academia group, seven experts in the Industry group, and five experts in the Other group. The experts presented their estimates of the significance of the SDGs using a seven-point scale: Very Low (VL) – 1; Low (L) – 2; Medium Low (ML) – 3; Medium (M) – 4 Medium High (MH) – 5; High (H) – 6; Very High (VH) – 7. By applying Eqs. (2) and (3), expert assessments from questionnaires were transformed into rough values. After aggregating expert assessments, an integrated rough linguistic matrix was formed. As three groups of experts participated in the research, the integrated rough linguistic matrix was formed for each group of experts: $\Omega^{Academia}$, $\Omega^{Industry}$ and Ω^{Other}. Also, the fourth rough linguistic matrix (Ω^{All}) was formed, in which the expert assessments of all three groups were aggregated. The following section presents an integrated rough linguistic matrix of expert groups as given in Table 5.

The previously presented ranks of SDGs within expert groups were used to define constraints (4)–(6) in the rough linear model. Thus, based on condition (6), a group of constraints was defined within the Academia group of experts as follows:

Table 4
Kruskal Wallis test statistics.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Chi-Square	1.981	1.114	1.900	.236	2.194	1.018	.032	.161	.665
df	2	2	2	2	2	2	2	2	2
Asymp. Sig.	.371	.573	.387	.889	.334	.601	.984	.922	.717
	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	
Chi-Square	1.118	4.847	2.941	.551	1.175	1.110	3.959	3.074	
df	2	2	2	2	2	2	2	2	
Asymp. Sig.	.572	.089	.230	.759	.556	.574	.138	.215	

$$\frac{3.12}{6.66}\left(\zeta_8^{-(1)}-\zeta_6^{+(2)}\right)\geq 0;\ \frac{3.12}{5.21}\left(\zeta_8^{+(1)}-\zeta_6^{-(2)}\right)\geq 0;$$
$$\frac{3.12}{6.44}\left(\zeta_6^{-(2)}-\zeta_{12}^{+(3)}\right)\geq 0;\ \frac{3.12}{5.02}\left(\zeta_6^{+(2)}-\zeta_{12}^{-(3)}\right)\geq 0;$$
$$\frac{3.12}{6.57}\left(\zeta_{12}^{-(3)}-\zeta_9^{+(4)}\right)\geq 0;\ \frac{3.12}{4.83}\left(\zeta_{12}^{+(3)}-\zeta_9^{-(4)}\right)\geq 0;$$
$$\frac{3.12}{6.42}\left(\zeta_9^{-(4)}-\zeta_7^{+(5)}\right)\geq 0;\ \frac{3.12}{4.93}\left(\zeta_9^{+(4)}-\zeta_7^{-(5)}\right)\geq 0;$$
$$\ldots$$
$$\frac{3.12}{5.93}\left(\zeta_{14}^{-(16)}-\zeta_2^{+(17)}\right)\geq 0;\ \frac{3.12}{3.24}\left(\zeta_{14}^{+(16)}-\zeta_2^{-(17)}\right)\geq 0.$$

where $\min_{1\leq j\leq 17}\{3.90, 3.12, 4.28, 3.90, \ldots, 4.09\} = 3.12$.

Restrictions for the remaining expert groups are defined in a similar way.

Step 3: Based on the constraints from *Step 2*, Eqs. (4)–(6), a rough linear model is defined for determining the final values of the weight coefficients of the SDGs by expert groups. In the following section, four rough linear models are presented:

Lingo 17.0 software is applied to solve rough linear models. Rough weight coefficients of SDGs, their crisp values, and rank SDGs are presented in Table 6.

A graphical representation of the rough weight coefficients of the SDGs within the expert groups is shown in Fig. 8. For example, Fig. 8(a) shows the distribution of the rough weight coefficients of the Academia expert group, while Fig. 8(b)-8(c) show the rough values of the Industry, Other, and All expert groups, respectively following calculations presented in Table 6. The SDGs ranking in each expert group presented in Fig. 8 depends on the highest calculated weight.

5.1. Sensitivity analysis

The initial values of the weighting coefficients and their ranks within the expert groups (see Table 6 and Fig. 8(a)–(c)) were defined for the values $d_1 = d_2 = 1$. Since the parameters d_1 and d_2 are used to present inaccuracies and risks in the information, it is necessary to analyze whether more significant uncertainties in the information affect the change of the initial ranks of the SDGs. In the following section, an analysis of the robustness of weight coefficients in the case of changing

$$\begin{array}{l}
\text{Rough}\\
\text{model 1: Academia}\\
\text{Max } (\varphi^- + \varphi^+)/2\\
\text{s.t.}\\
0.469\cdot(\zeta_8^- - \zeta_6^+)\geq\varphi^-\\
0.599\cdot(\zeta_8^+ - \zeta_6^-)\geq\varphi^+\\
0.484\cdot(\zeta_6^- - \zeta_{12}^+)\geq\varphi^-\\
0.621\cdot(\zeta_6^+ - \zeta_{12}^-)\geq\varphi^+\\
0.475\cdot(\zeta_{12}^- - \zeta_9^+)\geq\varphi^-\\
0.646\cdot(\zeta_{12}^+ - \zeta_9^-)\geq\varphi^+\\
0.486\cdot(\zeta_9^- - \zeta_7^+)\geq\varphi^-\\
0.633\cdot(\zeta_9^+ - \zeta_7^-)\geq\varphi^+\\
\ldots\\
0.526\cdot(\zeta_{14}^- - \zeta_2^+)\geq\varphi^-\\
0.963\cdot(\zeta_{14}^+ - \zeta_2^-)\geq\varphi^+\\
0.546\cdot(\zeta_2^+)\geq\varphi^-\\
1.00\cdot(\zeta_2^-)\geq\varphi^+\\
\sum_{j=1}^{17}\zeta_j^- = 0.8;\ \sum_{j=1}^{17}\zeta_j^+ = 1.0;\\
\zeta_j^-\leq\zeta_j^+;\ \zeta_j^-,\zeta_j^+\geq 0;\forall j
\end{array}
\quad
\begin{array}{l}
\text{Rough}\\
\text{model 2: Industry}\\
\text{Max } (\varphi^- + \varphi^+)/2\\
\text{s.t.}\\
0.369\cdot(\zeta_6^- - \zeta_{15}^+)\geq\varphi^-\\
0.383\cdot(\zeta_6^+ - \zeta_{15}^-)\geq\varphi^+\\
0.394\cdot(\zeta_{15}^- - \zeta_9^+)\geq\varphi^-\\
0.472\cdot(\zeta_{15}^+ - \zeta_9^-)\geq\varphi^+\\
0.389\cdot(\zeta_9^- - \zeta_8^+)\geq\varphi^-\\
0.522\cdot(\zeta_9^+ - \zeta_8^-)\geq\varphi^+\\
0.399\cdot(\zeta_8^- - \zeta_{13}^+)\geq\varphi^-\\
0.495\cdot(\zeta_8^+ - \zeta_{13}^-)\geq\varphi^+\\
\ldots\\
0.477\cdot(\zeta_5^- - \zeta_{14}^+)\geq\varphi^-\\
0.947\cdot(\zeta_5^+ - \zeta_{14}^-)\geq\varphi^+\\
0.534\cdot(\zeta_{14}^+)\geq\varphi^-\\
1.00\cdot(\zeta_{14}^-)\geq\varphi^+\\
\sum_{j=1}^{17}\zeta_j^- = 0.8;\ \sum_{j=1}^{17}\zeta_j^+ = 1.0;\\
\zeta_j^-\leq\zeta_j^+;\ \zeta_j^-,\zeta_j^+\geq 0;\forall j
\end{array}
\quad
\begin{array}{l}
\text{Rough}\\
\text{model 3: Other}\\
\text{Max } (\varphi^- + \varphi^+)/2\\
\text{s.t.}\\
0.372\cdot(\zeta_7^- - \zeta_{11}^+)\geq\varphi^-\\
0.428\cdot(\zeta_7^+ - \zeta_{11}^-)\geq\varphi^+\\
0.385\cdot(\zeta_{11}^- - \zeta_1^+)\geq\varphi^-\\
0.477\cdot(\zeta_{11}^+ - \zeta_1^-)\geq\varphi^+\\
0.389\cdot(\zeta_1^- - \zeta_{12}^+)\geq\varphi^-\\
0.465\cdot(\zeta_1^+ - \zeta_{12}^-)\geq\varphi^+\\
0.389\cdot(\zeta_{12}^- - \zeta_{13}^+)\geq\varphi^-\\
0.507\cdot(\zeta_{12}^+ - \zeta_{13}^-)\geq\varphi^+\\
\ldots\\
0.473\cdot(\zeta_{14}^- - \zeta_5^+)\geq\varphi^-\\
0.883\cdot(\zeta_{14}^+ - \zeta_5^-)\geq\varphi^+\\
0.513\cdot(\zeta_5^+)\geq\varphi^-\\
1.00\cdot(\zeta_5^-)\geq\varphi^+\\
\sum_{j=1}^{17}\zeta_j^- = 0.8;\ \sum_{j=1}^{17}\zeta_j^+ = 1.0;\\
\zeta_j^-\leq\zeta_j^+;\ \zeta_j^-,\zeta_j^+\geq 0;\forall j
\end{array}
\quad
\begin{array}{l}
\text{Rough}\\
\text{model 3: All}\\
\text{Max } (\varphi^- + \varphi^+)/2\\
\text{s.t.}\\
0.471\cdot(\zeta_8^- - \zeta_6^+)\geq\varphi^-\\
0.599\cdot(\zeta_8^+ - \zeta_6^-)\geq\varphi^+\\
0.478\cdot(\zeta_6^- - \zeta_9^+)\geq\varphi^-\\
0.613\cdot(\zeta_6^+ - \zeta_9^-)\geq\varphi^+\\
0.485\cdot(\zeta_9^- - \zeta_{12}^+)\geq\varphi^-\\
0.633\cdot(\zeta_9^+ - \zeta_{12}^-)\geq\varphi^+\\
0.474\cdot(\zeta_{12}^- - \zeta_7^+)\geq\varphi^-\\
0.657\cdot(\zeta_{12}^+ - \zeta_7^-)\geq\varphi^+\\
\ldots\\
0.533\cdot(\zeta_2^- - \zeta_{14}^+)\geq\varphi^-\\
0.969\cdot(\zeta_2^+ - \zeta_{14}^-)\geq\varphi^+\\
0.533\cdot(\zeta_{14}^+)\geq\varphi^-\\
1.00\cdot(\zeta_{14}^-)\geq\varphi^+\\
\sum_{j=1}^{17}\zeta_j^- = 0.8;\ \sum_{j=1}^{17}\zeta_j^+ = 1.0;\\
\zeta_j^-\leq\zeta_j^+;\ \zeta_j^-,\zeta_j^+\geq 0;\forall j
\end{array}$$

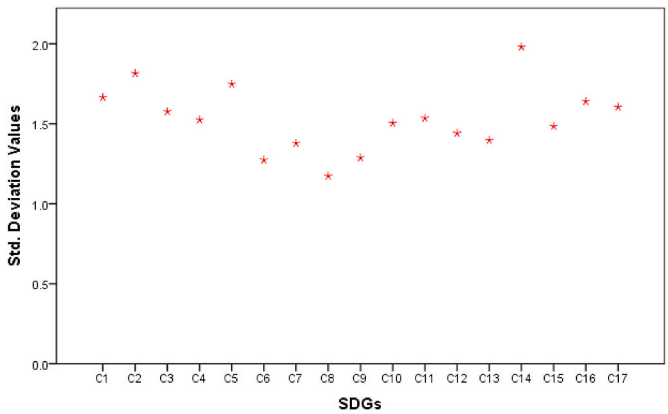

Fig. 4. Standard deviation of each SDG.

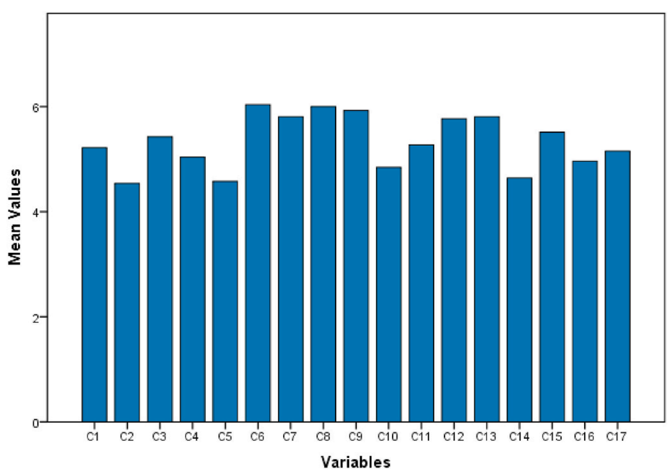

Fig. 5. Mean values of SDGs.

the parameters d_1 and d_2 was performed.

In this section, the change of the values of the mentioned parameters in the interval $1 = d_1, d_2 \leq 50$ is simulated. Fifty scenarios were implemented during which changes in the integrated rough linguistic matrix elements were monitored. After each scenario, the impact of the resulting changes on the results of the rough OPA model was analyzed. Fig. 9 shows the changes in the integrated rough linguistic matrix elements within the Industry expert group.

The results in Fig. 9 show that parameters d_1 and d_2 cause changes in the integrated rough linguistic matrix within the Industry Expert Group. Similar changes have occurred in the remaining expert groups. After analyzing new integrated rough linguistic matrix elements, the OPA rough linear model was launched. For each scenario, new values of the weighting coefficients of the SDGs were calculated and statistically compared with the initial values. Spearman's correlation coefficient (SSC) was used to compare the results. Fig. 10 shows the correlation of results over fifty scenarios within the Industry expert group.

The results from Fig. 10 indicate no significant changes in the rankings of the SDGs. To understand the statistical significance of the changes, SCC was used. The average value of SCC through scenarios is 0.911, which indicates a high correlation. Similar discrepancies occurred with the remaining groups of experts. Thus, the average value of SCC was obtained for the Academy group is SSC = 0.9425, for the Other group, SCC = 0.9378, while in the All group of experts the smallest deviations appeared, i.e., SSC = 0.9714. Based on the presented analysis, we can conclude that the initial weights of the SDGs presented in Table 6 and Fig. 8(a)–(c) are credible.

6. Discussions

According to the scores presented in Table 6 following the OPA analysis of participants ranking selections, a series of very useful outcomes can be identified. All SDGs are significant for enhancing sustainability in the mining sector. However, the survey participants prioritized SDGs to provide a scale of relative importance. Overall, the analysis showed that, when considering all the results from the participants of the survey, the most important SDG for sustainable mining was determined as SDG8: Decent work and economic growth, while the least important was SDG14: Life below water among 18 SDGs. The latter was determined as the least important SDG as well by the participants who belong to the industry group. SDG6: Clean water and sanitation was calculated as the most important for the same group. On the other hand, SDG8 was calculated as most significant for the academia group and SDG2: Zero hunger as the one with the lowest score. For the participants who belong to the group other, SDG7: Affordable clean energy was the most important SDG, while SDG5: Gender equality was the least important. It is relevant to note that these results follow from the background of each group and of their knowledge on the subject from different points of view. Also important is the fact that the results obtained and the resulting ranking explore the perceived priority, with all the SDGs being relevant and important.

The SDGs priorities for enhancing sustainability in the mining sector have been categorized in three groups (UN, 2015): 'indirect' (SDGs 1,2,

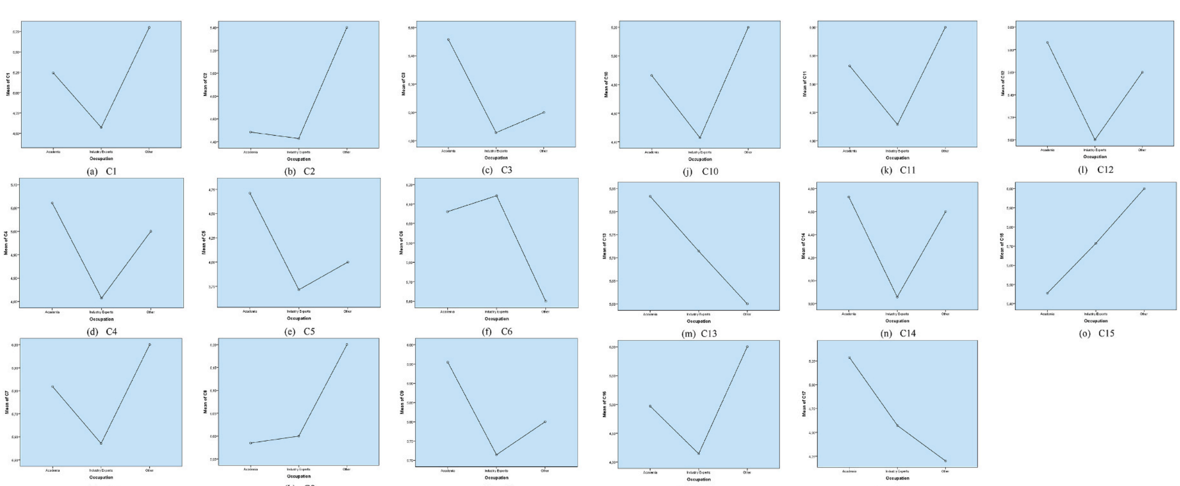

Fig. 6. The means of SDGs in terms of groups.

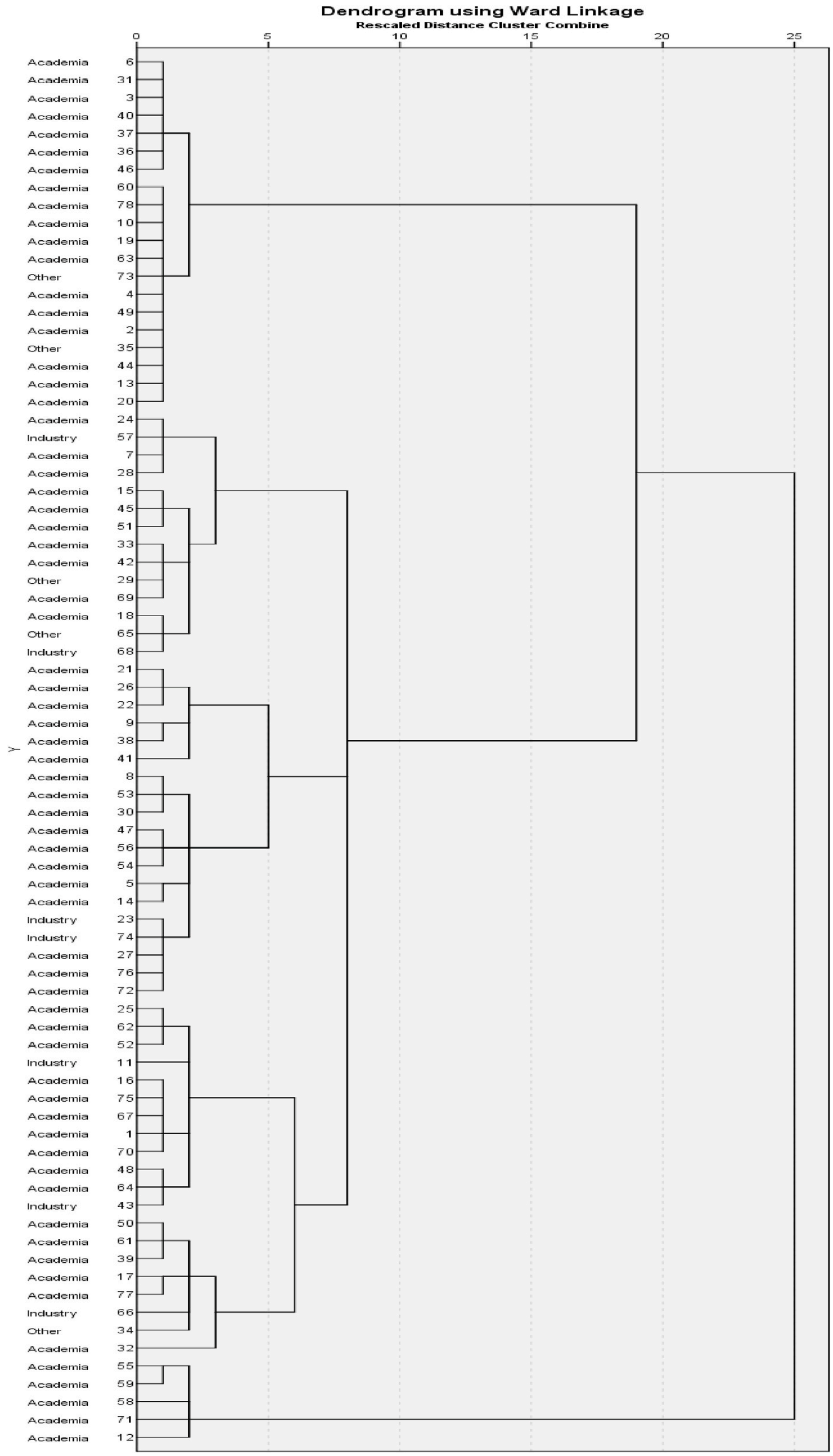

Fig. 7. The hierarchical relationship of the response of participants.

5,11,13,14), 'moderately direct' (SDGs 3,4,10,12,16), and 'very direct' (SDGs 6,7,8,9,15). The results assessment showed that the most important SDGs for sustainable mining are those that belong in the 'very direct' SDGs (6,7,8,9,15) category to sustainable mining as the most important ones, which agrees with the UN priorities. For the participants of the survey who belong to the industry group, SDG6 was calculated as the most important; SDG6 has a practical and very direct impact on sustainable mining to provide access to clean water resources. For those who belong to the academia group it was determined that sustainable development in the mining sector can succeed through economic growth

Table 5
Integrated rough linguistic matrix of expert groups.

Step 2: Based on the rough values from Table 5, the next rank within the expert groups was defined:

(1) Academia: $C_8>C_6>C_{12}>C_9>C_7>C_{13}>C_{15}>C_3>C_{11}>C_{17}>C_1>C_4>C_{10}>C_{16}>C_5>C_{14}>C_2$;
(2) Industry: $C_6>C_{15}>C_9>C_8>C_{13}>C_7>C_{12}>C_{17}>C_3>C_2>C_1>C_4>C_{11}>C_{10}>C_{16}>C_5>C_{14}$;
(3) Other: $C_7>C_{11}>C_1>C_{12}>C_{13}>C_{15}>C_2>C_4>C_8>C_6>C_{10}>C_{16}>C_9>C_3>C_{17}>C_{14}>C_5$;
(4) All: $C_8>C_6>C_9>C_{12}>C_7>C_{13}>C_{15}>C_3>C_{11}>C_{17}>C_1>C_4>C_{10}>C_{16}>C_5>C_2>C_{14}$.

Crit.	Academia	Industry	Other	All
C_1	[3.90,6.21]	[3.65,5.58]	[5.47,6.53]	[3.92,6.20]
C_2	[3.12,5.72]	[3.65,6.11]	[4.57,6.50]	[3.21,5.84]
C_3	[4.28,6.23]	[3.99,5.72]	[3.90,6.00]	[4.20,6.20]
C_4	[3.90,6.17]	[3.78,5.33]	[4.63,6.23]	[3.91,6.13]
C_5	[3.47,6.06]	[2.72,5.40]	[2.54,4.96]	[3.29,5.98]
C_6	[5.02,6.44]	[6.74,6.98]	[4.68,6.09]	[5.08,6.52]
C_7	[4.76,6.43]	[4.32,6.38]	[5.94,6.83]	[4.76,6.47]
C_8	[5.21,6.66]	[5.20,6.46]	[5.36,5.84]	[5.19,6.60]
C_9	[4.93,6.42]	[4.94,6.63]	[5.16,5.64]	[4.91,6.42]
C_{10}	[3.82,6.18]	[3.40,5.10]	[4.33,6.41]	[3.78,6.13]
C_{11}	[4.17,6.33]	[3.42,5.42]	[5.33,6.60]	[4.12,6.31]
C_{12}	[4.83,6.57]	[4.08,6.39]	[5.02,6.54]	[4.74,6.57]
C_{13}	[4.70,6.33]	[4.66,6.40]	[5.02,6.54]	[4.70,6.36]
C_{14}	[3.24,5.93]	[2.58,4.83]	[2.88,5.37]	[3.11,5.83]
C_{15}	[4.27,6.24]	[5.46,6.54]	[4.87,6.27]	[4.38,6.29]
C_{16}	[3.76,6.16]	[3.06,5.40]	[4.94,5.83]	[3.73,6.10]
C_{17}	[4.09,6.26]	[3.71,6.20]	[3.28,5.55]	[3.94,6.25]

and decent working environment (SDG8) based on the long-term raw materials demand. On the other hand, the participants who fall in the "others" group suggested as their priority the use of clean energy (SDG7) due to the widespread public concerns on energy use and its impact, and the targeting of zero carbon emissions. Overall, the analysis of the results for all the participants of the survey, independently of their background, suggested that the most important SDG is SDG8, which agrees with that calculated as most important for the academia group. The latter is logical considering that economic growth, which is a basic part of SDG8, allows for interventions regarding sustainability measures. In addition, it reinforces another key concept of SDG8, decent work, and overall supports the sustainability triangle of economy-society -environment.

On the other hand, the SDGs with the least perceived impact on sustainable mining (SDG14, SDG2, SDG5) belong to the indirect effects group according to the UN categorization (UN, 2015). This is understandable as these SDGs do not interfere directly with the mining activities. In more detail, the analysis of the results showed that the SDG with the least perceived impact on sustainable mining for the entirety of the participants as a whole group and for the industry group is SD14: life below water. In addition, it is worth mentioning that for the other two participants groups (academia and others) SDG14 was perceived as the second least important. SDG2: Zero hunger was perceived as the least important for the academia group, arguably seen as a goal that needs primarily support from other scientific disciplines to achieve, for example, sustainable and climate-resilient agriculture. Finally, for the

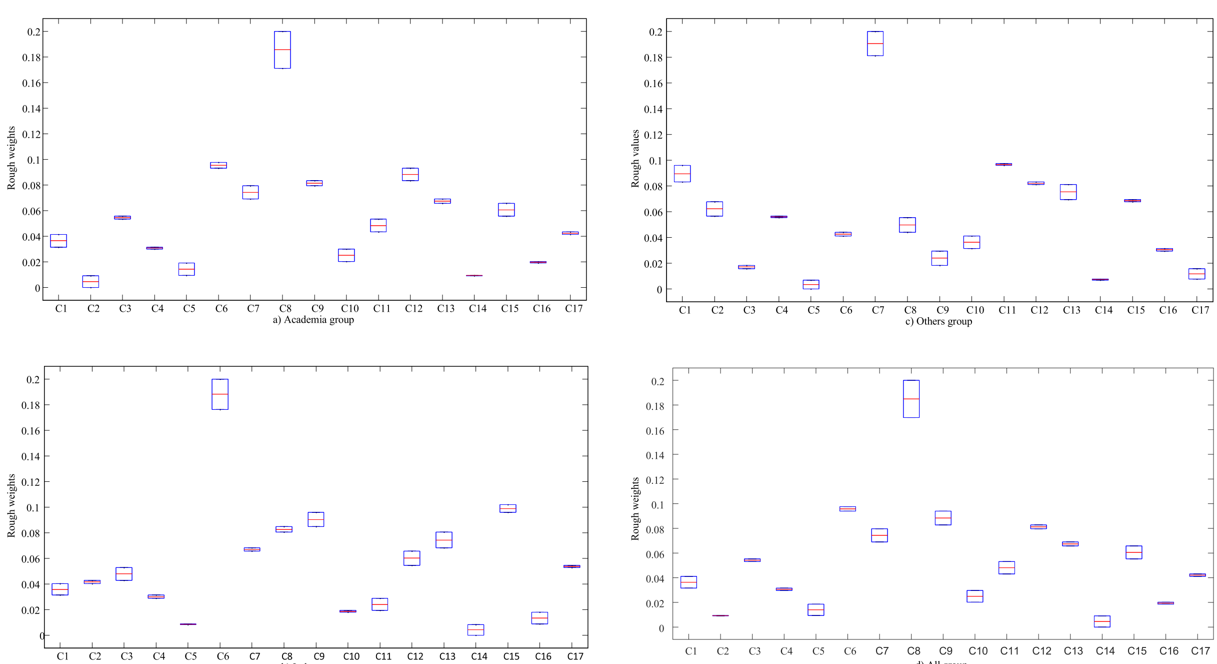

Fig. 8. Rough SDGs (C_1–C_{17}) weights distribution using OPA method for the different expert groups. SDG8 (C8) is the most important for all experts and academia groups, SDG6 (C6) for the industry group and SDG7 (C7) for the others group.

Table 6
wt coefficients of SDGs.

SDGs	Group 1: Academia			Group 2: Industry			Group 3: Other			Group 4: All		
	Rough weight	Crisp weight	Rank	Rough weight	Crisp weight	Rank	Rough weight	Crisp weight	Rank	Rough weight	Crisp weight	Rank
C_{1}	[0.031,0.041]	0.0333	11	[0.031,0.040]	0.0329	11	[0.083,0.096]	0.0887	3	[0.032,0.041]	0.0335	11
C_{2}	[0.000,0.009]	0.0004	17	[0.040,0.043]	0.0407	10	[0.056,0.068]	0.0600	7	[0.009,0.009]	0.0091	16
C_{3}	[0.053,0.056]	0.0538	8	[0.043,0.053]	0.0453	9	[0.016,0.018]	0.0158	14	[0.053,0.055]	0.0537	8
C_{4}	[0.030,0.031]	0.0302	12	[0.029,0.031]	0.0290	12	[0.055,0.056]	0.0557	8	[0.030,0.032]	0.0300	12
C_{5}	[0.009,0.019]	0.0102	15	[0.008,0.009]	0.0082	16	[0.000,0.007]	0.0002	17	[0.009,0.019]	0.0102	15
C_{6}	[0.093,0.098]	0.0953	2	[0.102,0.200]	0.1677	1	[0.041,0.044]	0.0417	10	[0.094,0.098]	0.0957	2
C_{7}	[0.069,0.079]	0.0729	5	[0.066,0.068]	0.0664	6	[0.181,0.200]	0.1983	1	[0.069,0.080]	0.0730	5
C_{8}	[0.098,0.200]	0.1654	1	[0.080,0.085]	0.0821	4	[0.044,0.055]	0.0470	9	[0.170,0.200]	0.1960	1
C_{9}	[0.079,0.083]	0.0809	4	[0.085,0.096]	0.0897	3	[0.018,0.029]	0.0198	13	[0.083,0.094]	0.0878	3
C_{10}	[0.020,0.030]	0.0216	13	[0.018,0.019]	0.0179	14	[0.031,0.041]	0.0333	11	[0.020,0.030]	0.0215	13
C_{11}	[0.043,0.053]	0.0457	9	[0.019,0.029]	0.0206	13	[0.096,0.097]	0.0965	2	[0.043,0.053]	0.0456	9
C_{12}	[0.083,0.093]	0.0877	3	[0.054,0.066]	0.0579	7	[0.081,0.083]	0.0818	4	[0.080,0.083]	0.0810	4
C_{13}	[0.066,0.069]	0.0667	6	[0.068,0.080]	0.0727	5	[0.069,0.081]	0.0739	5	[0.066,0.069]	0.0669	6
C_{14}	[0.009,0.009]	0.0090	16	[0.000,0.008]	0.0003	17	[0.007,0.008]	0.0069	16	[0.000,0.009]	0.0004	17
C_{15}	[0.056,0.066]	0.0586	7	[0.096,0.102]	0.0988	2	[0.068,0.069]	0.0683	6	[0.055,0.066]	0.0586	7
C_{16}	[0.019,0.020]	0.0191	14	[0.009,0.018]	0.0094	15	[0.029,0.031]	0.0298	12	[0.019,0.020]	0.0188	14
C_{17}	[0.041,0.043]	0.0416	10	[0.053,0.054]	0.0532	8	[0.008,0.016]	0.0083	15	[0.041,0.043]	0.0415	10

group of "others", SDG5: Gender equality is seen as the least important. Thus, more commitment and effort is required by the mining companies to support the action.

The rough criteria weights of each SDG in terms of groups are shown in Fig. 11 and overall, they show a good overlap. There is only significant variability among groups for criteria such as SDG8 and SDG6. As we previously discussed both criteria belong in the direct priorities of SDGs for sustainable mining, but this variability appears because of the different prior significances of the group that is directly connected to mining activities (Industry) and the groups that they follow the subject from an indirect perspective. The findings and aforementioned analysis in this section agree with discussions and analysis of relevant work in the literature (Endl et al., 2021; Fraser, 2019; Monteiro et al., 2019; Segura-Salazar and Tavares, 2018).

The level of SDG importance for sustainable development in mining maps the linkages between mining operations and the SDGs, validates their current efforts and sparks new ideas. Mining processes may cause land-use changes, deforestation, erosion, soil deterioration, contamination of nearby water systems, impairing of ecosystems health, noise and airborne pollution. EU priorities on Sustainable and Responsible Mining and the Green Deal targets require implementation of strategies to increase local communities' acceptance, perform balanced production, comply with environmental regulations, succeed carbon-neutral operations and reduce environmental footprint of mining. This work provides a prioritization of SDGs by means of mining experts experience to help meet these targets reducing the environmental impact of mining and enforcing sustainability. The determined SDGs prioritization if adopted by companies and government bodies can mitigate and gradually

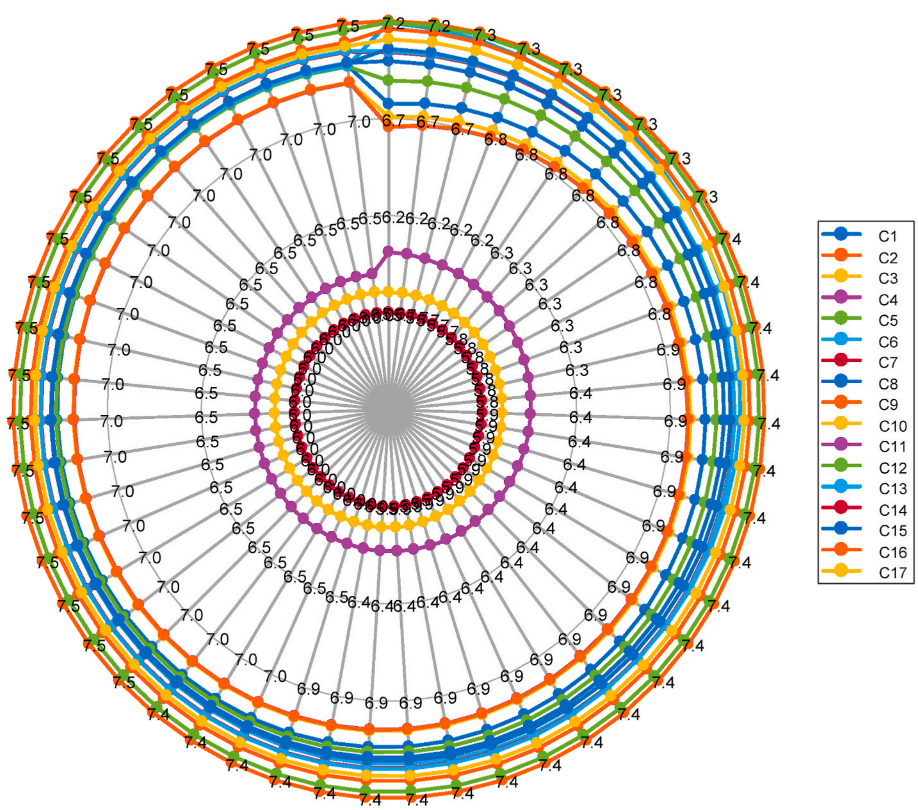

Fig. 9. Dependence of the elements of the integrated rough linguistic matrix within the Industry expert group on the change of parameters d_1 and d_2.

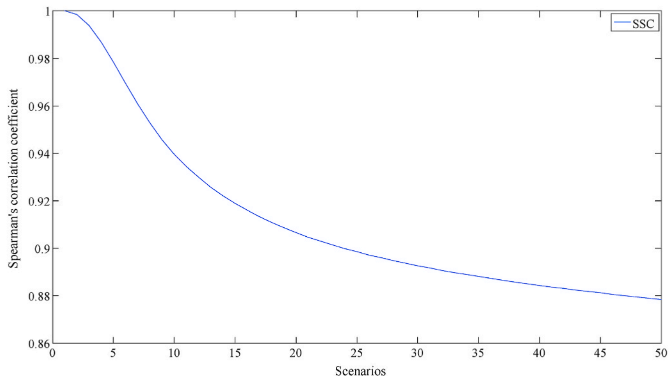

Fig. 10. Spearman's correlation coefficient (SCC) - Industry expert group.

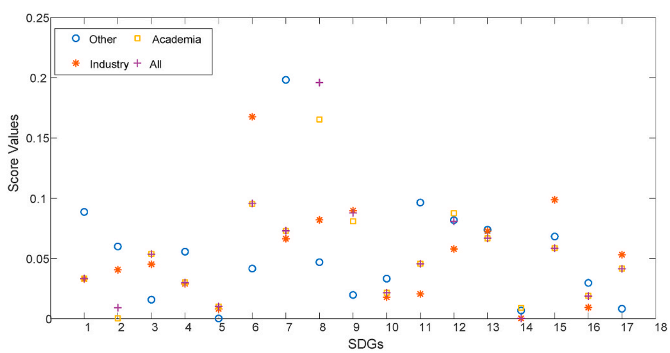

Fig. 11. The overlapping chart of three groups.

minimize the impact of mining activities. This would provide a pathway for successfully achieving the sustainability goals and have a multidimensional and direct effect in mining operations.

Operators of mines should record the mining activity implications in terms of achieving sustainability and then link them with the resulting ranking of SDGs to address them by means of their importance. They will thus address implications and promote sustainability in terms of priority goals that have a multidimensional impact.

7. Conclusions and policy recommendations

Sustainable development in the mining sector is an important topic and must be analyzed in terms of many goals. The degree of importance of SDGs affecting sustainable mining using a decision making model is determined. In particular, this work presents a new model including rough sets based OPA for determining the weights assigned to the SDGs. The framework of this study has three stages as follows: questionnaire (survey), data analyses, and SDGs classification. Firstly, a questionnaire was conducted receiving a response from internationally experts. Secondly, the analyses were carried out to make a distinction among groups. Finally, the degree of importance of each SDG for sustainable mining was determined using a rough sets OPA methodology. The model used in this study can be used as a decision support system for decision makers.

While the proposed rough sets based OPA model provides a rational and objective evaluation performance, one of the limitations of the model is its mathematical complexity. This feature may also be a limiting factor in its application to other MCDM problems. Thus, future studies will focus on improving software based on this decision support system. In future studies, other fuzzy sets can be applied for the OPA method, such as hesitant, type 2 neutrosophic sets, intuitionistic, Aczel-Alsina norms, to capture uncertainty of experts' subjective judgments. An additional avenue for further research is linked to the fact that there exist many types of minerals of economic relevance, with the various alternatives (such as industrial minerals, precious elements, base metals, energy raw materials) posing different challenges in terms of SDGs, and thus being interesting to investigate the differences between those alternatives exploiting the techniques presented in this study. The proposed model can be generalized to various decision-making problems to determine weights of the criteria. For example, evaluation of site selection indicators of sustainable transport, offshore wind farm site selection, risk assessment, selecting smart technology, portfolio selection process, site selection of car sharing station, and evaluation of groundwater potential index for sustainable groundwater management.

Overall, the implementation of SDGs can relate sustainable mining to the green recovery, encouraging better environmental performance, enhancing circular economy, informing decision making, and fostering innovation and capacity growth. This entails practical policy recommendations such as supporting a whole-of-government strategy and involving numerous stakeholders; implementing regulatory strategies by means of SDGs used during the mining process, mine closure, site rehabilitation, and ecosystems monitoring; supporting applied research to help the mining sector to innovate and enhance its performance from an environmental perspective; enhancing capacity building through education, training, and employment; rehabilitating abandoned mines and the possibility of reprocessing legacy mines; supporting uptake of new technology; prioritizing environmental sustainability and safety; creating guidelines and benchmarks to enhance the mining industry's environmental performance. Policies prioritization require continuous monitoring and diagnosis of the factors that improve sustainability performance.

CRediT authorship contribution statement

Muhammet Deveci: Conceptualization, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Pablo R. Brito-Parada:** Conceptualization, Validation, Investigation, Writing – original draft, Writing – review & editing. **Dragan Pamucar:** Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Emmanouil A. Varouchakis:** Validation, Investigation, Writing – original draft, Writing – review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resourpol.2022.103049.

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