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Review

Decision-support models for sustainable mining networks: fundamentals and challenges

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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

Natural resource endowments have the potential of transforming the prospects of many developing economies. However, a nation's mineral resources can only generate prosperity if specific technology assets are employed in a way as to effectively develop its resource sector, capture value from it, and transform that value into long-term benefits. The roadmap to such an ambitious goal lies in effective management, supported by consistent, formal decision-making methods. Yet, integrating environmental and social goals into strategic, tactical and operational decisions is a complex challenge, often addressed without adequate analytical rigour. We provide a systematic analysis of the literature devoted to the development and application of quantitative decision-support methods with sustainability considerations in the mining industry. By establishing a framework based on the fundamental elements inherent to decision-making processes pertinent to mining operations, we identify several opportunities for advancing research and practice. In particular, we find important gaps in elements such as project portfolio optimization, operations and waste management, and mine closure and rehabilitation, and even more so when social targets and impacts are considered. It is our belief that insights from this discussion could be of significant value to both academics and practitioners interested in promoting sustainable socio-economic development throughout the mining industry.

Contents

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1. Introduction

The core characteristics of the mining industry — the long term planning horizon, the need for both skilled and unskilled labour, and the challenging requirements of regional services and infrastructure — call for a broad, responsible approach to achieving challenging economic targets while contributing to social development and ecosystem integrity (ICMM, 2012). Moreover, not only are those issues key aspects of a truly sustainable economy, but also, the ability to adequately taking them into account when designing, operating and closing mining projects has become a primary prerequisite to support business feasibility.

Sustainability, in this paper, is based on the Triple-Bottom-Line structure, which refers to the approach of measuring the success of an organization's activities according to its social and environmental performance in addition to the traditional financial performance (Glac, 2015). On the economic dimension, an increasingly competitive, global market imposes strong pressure over costs, productivity and delivered value. On the environmental dimension, mining ventures must deal with ever-stricter requirements involving the efficient consumption of energy, water and natural resources, the reduction of carbon emissions and process wastes, as well as effective land rehabilitation upon closure. On the societal dimension, although mining projects are, by definition, temporary ventures, the economic impact they generate should be able to induce long-term sustainable social development for the communities along the value chain. In fact, by often being located in remote areas, mining can provide a unique means for stimulating significant economic development (Kondo et al., 2002). However, local cultural and environmental implications can result in major socioeconomic challenges.

Mining and sustainable development are intrinsically and complexly interconnected. History has shown several examples of a *commodity curse*, through which nations richly endowed with natural resources prove unable to effectively transform those into long-term prosperity (Kasprzyk, 2011), typically experiencing slower growth, lower economic diversification, more corruption, oppression and government opacity, and greater exposure to economic volatility. In fact, these characteristics threaten the establishment of long-term societal benefits, while also posing obvious environmental challenges. Though not universal (and examples from the United States, Norway, Australia support this notion), the commodity curse prospect calls for a mature, systematic approach to the strategic management of natural resources. Specifically, managerial decision-making processes should aim at — besides optimizing resource allocation and usage — building the resource sector's institutions and governance, developing infrastructure, ensuring robust fiscal policy and competitiveness, supporting local content, deciding how to spend resource windfalls wisely, and transforming resource wealth into broader economic development (Dobbs et al., 2013).

This paper aims at providing an overview of the relevant literature and case studies of Operations Research and Management Sciences in the domain of sustainability in the mining industry. From a broad analysis, we also identify challenges and opportunities for future research and application development. We focus mainly, but not exclusively, on techniques and models from optimization and mathematical programming (Bradley et al., 1977), as these constitute the main disciplines over which decision-support systems and tools for complex systems such as the mining industry can be developed.

This paper is organized as follows. Section 2 discusses the specific challenges of the mining industry concerning sustainable development and managerial action. The reviewing methodology and organization are presented in Section 3. Section 4 then proposes a framework for analysis and discusses the literature on decision-support tools for sustainability with a focus on mining operations. From that discussion, Section 5 presents a set of challenges and open problems for both researchers and practitioners. Finally, Section 6 concludes the paper and establishes the motivation for a continued discussion on this important topic.

2. Mining and sustainability

Strictly speaking, mining *cannot* be a sustainable activity, in the sense that its operations have a finite lifespan, and humanity's dependence on nonrenewable resources cannot go on indefinitely (Sterman et al., 2012). However, building on the International Council on Mining & Metals' thesis (ICMM, 2012), mining *can* contribute to sustainable development in the sense that, if well-managed, it can provide lasting opportunities for economic growth and development.

In recent years, the broad concept of Corporate Social Responsibility has evolved into the more specific one of a *social licence to operate*, which is based on the idea that mining companies need not only government permits, but also a “social permission” to develop their projects. However, a granted social licence must not act in the way of de-prioritizing a company's engagement on core development issues (Owen and Kemp, 2013). In fact, according to Laurence (2011), a sustainable mining operation must be safe, demonstrate leading practice in environmental management and community engagement, be economically robust and, most importantly, use the mineral resource as efficiently as possible. If those criteria are met, the life of the mining project will be optimized (and optimized earnings should follow), the community benefits maximized (thus perpetuating the social licence to operate), and the industry itself will enjoy wider community acceptance.

From a broader perspective, one can view the mining industry as a long-term networked value chain, which begins with the exploration of mineral resources, moving on to site design and construction, operation, final closure and rehabilitation, covering a time span that may range from 10 to 100 or more years (McLellan et al., 2009). The operation phase is usually the longest, and the one which is often focus of environmental efficiency efforts. In open-pit mines, exploitation is commonly performed by heavy-duty, off-road trucks and shovels that remove the run-of-mine and feed it to processing plants where ore quality is enhanced by classification and concentration processes. Final products are then delivered to customers through roads, railways, ducts, or ocean carriers (Pimentel et al., 2010). Each of those stages, at every phase of development, may create significant environmental and social negative impacts that must be balanced by counteracting investments with long-term benefits.

It is important to emphasize that mining is an extremely capital-intensive industry. In this quintessential commodity market, costs, operational efficiency, and discipline in capital allocation have become of paramount importance — in fact, recent studies have shown that the escalating capital expenditures and operating costs have had a major impact on mine productivity (Lala et al., 2015). That is the core characteristic on which we base our argument for an integrated perspective of sustainability goals in strategic, tactical and operational decision levels. That means environmental and social (limited) resource allocation decisions must be analyzed in an integrated, transparent manner alongside with the inherent economic targets.

Such a scenario motivates the following research questions:

1. How are the three dimensions of sustainability addressed by decision-support models and tools in the mining industry?
2. Which physical processes, value chain stages, and mine life cycle phases receive the most attention from research and practitioners, and which still lack formal, quantitative approaches to sustainability?
3. What are the key theories, technologies and methods that must be further developed in order to make long-term, sustainable progress in decision-making processes in mining?

From a broad literature review, we hope to establish an assessment of current developments, as well as a discussion on the main challenges and opportunities not yet addressed at their best efforts.

3. Methods

We conduct the review according to a content analysis methodology (Mayring, 2003). Given an expectation of a small number of articles on the topics of interest, we do not limit a time window for selecting relevant papers. Hence, we include literature ranging from as early as 1949, and as recent as 2015. We do constrain our analysis, however, to papers focused on the *mining* industry, and which report or promote the development of formal sustainability decision-support models. Search was mainly conducted as a structured keyword search in major databases, also including cited references when appropriate. The main sources include: *Computers and Chemical Engineering*, *Industrial Engineering and Chemical Research*, *International Journal of Surface Mining, Reclamation and the Environment*, *International Journal of Sustainable Engineering*, *Journal of Cleaner Production*, *Journal of Environmental Management*, *Minerals Engineering*, *Resources Policy*, *Transactions on Ecology and the Environment*, as well as more specific managerial fora such as the *European Journal of Operational Research*, *Interfaces*, *International Journal of Production Economics*, *Journal of Operations Management*, *Management Science*, among others.

Fig. 1 evidences an increased publication rate since 2006, which can be explained both by the demand side, such as regulations and increased control and awareness, and the supply side, such as availability and diffusion of impact assessment methodologies. This is in accordance to the findings presented on the surveys by Seuring (2013) on sustainable supply chain management, and McLellan et al. (2009) on design of mineral processing operations. However, given the relevance of the subject, the absolute figures are still rather small, with only a handful of papers being published each

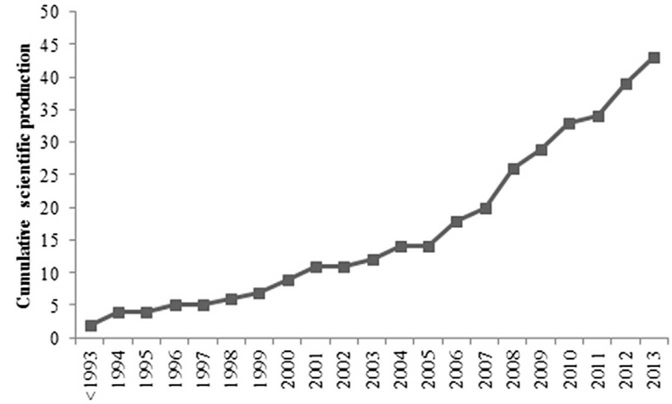

Fig. 1. Cumulative scientific production on sustainable mining networks.

year, which suggests the need for an increased focus by the mining industry to address sustainable development goals in a more strategic, objective decision-making perspective. Nevertheless, the discussion on gaps and challenges in Section 5 brings to the table several other papers that, though not directly related to mining, do provide important support to the characterization of research and application development opportunities.

Large-scale mining firms are often organized according to a supply chain structure — a theme that has become an important focus of sustainable operations management research. Thus, although many of the advances reported on *sustainable supply chain management* can be broadly applied to the mining industry, we do not include the whole of that literature in this paper. The interested reader is referred to a very interesting paper by McLellan et al. (2009), which is focused on a Design for Sustainability approach to minerals processing. In our present work, we build on by expanding the analysis to all phases of the mining life cycle, and by including a broader discussion on open problems and challenges. Of particular interest are the decision-making models and tools that support sustainable practices in traditional supply chain functions — procurement, transformation, delivery, product use and recycling — and how each function addresses issues related to environmental and social impacts (Hassini et al., 2012).

There are many different dimensions to support the categorization of this literature review. Possible approaches might reflect the mining supply chain stages (Pimentel et al., 2010) (mine, railway, port and customer), or the mining project life cycle (exploration, design, operations, closure and rehabilitation), or even a decision-level (Anthony, 1965) organization (strategic, tactical, and operations control). One could also observe the whole process from a sustainability-based, life-cycle assessment point of view, considering all infrastructure, suppliers and technology providers engaged on the flow of minerals from mines to users.

In this survey, we build on those ideas and propose a specific analysis framework that encompasses the main structural concepts related to the management of sustainable mining networks. The core idea within it is that the complex characteristics of the mining industry—in particular, the long-term impact of its massive capital expenditure decisions, the intricate interactions between different stakeholders in government, industry, local communities, and regulatory agencies, and the relentless uncertainty associated with global commodity markets — require the development of specific metrics and valuation methods to support robust decision making. Those metrics and methods would then permeate both project, portfolio, and operations management decisions and their corresponding impacts on economic, environmental and social performance throughout the life cycle of a mining venture.

It is important to notice that, as pointed out by Rosenhead and Mingers (2001), formal approaches to natural resource management must deal with complex challenges such as *comprehensive rationality*, which unrealistically presumes to substitute analytical results and computations for judgement; the creative generation of alternatives is de-emphasised in favour of presumably objective feasible and optimal alternatives; misunderstanding and misrepresenting the reasons and motivations for public involvement; and a lack of value framework beyond the typical *utilitarian precepts*. Building on that argument, the sheer complexity of the mining industry, even when analyzed at a regional level, imposes additional challenges to decision-support models that must deal with inherently participatory planning and decision environments where (often) conflicting interests of a network of numerous, diverse stakeholders must be balanced (Mendoza and Martins, 2006). The proposed analysis framework attempts to address this issue by providing a deeper understanding of the mining industry dynamics, which pervades through and influences metrics, methods and specific modelling approaches observed in both research and application.

4. Literature review

In this section, we analyze the contents of the selected papers that characterize the development of formal models and tools to support sustainability decisions in mining networks. The organization reflects the structure proposed in Fig. 2.

4.1. Mining industry dynamics

The mining industry is an extremely complex, dynamic system. Immersed in a market characterized by a large number of stakeholders with often conflicting goals, the industry has been evolving rather erratically, in amidst of cycles of booming and instability (Carter, 2012). In a comprehensive report, Hopwood (2014) identified the main issues affecting mining performance:

1. low levels of productivity, with high input and production costs;
2. highly unstable commodity prices, affecting the growth trajectory of many developing markets with high exposure to international trade;
3. an innovation imperative, with a more integrated approach to mine design and planning, and attention to energy supply and demand;
4. higher debt levels, and a trend for market consolidation;
5. questionable capital allocation practices;
6. intensifying demands from communities on the *social license to operate*;
7. rising hostility in government relations;
8. ever-stricter regulatory environments;
9. a zero harm to zero fatalities imperative;
10. a significant gap in talent acquisition and retention.

Furthermore, many mining ventures may need structural changes towards feasibility, through cost reduction, focus on productivity and returns on shareholder value, discipline in capital allocation, and by embracing new forms of innovation — including new approaches for dealing with local communities, governments and regulatory bodies. The industry is past a phase of strong prices and opportunistic pursuit of volume, and must hence regain focus on business fundamentals and a long-term, sustainable perspective of the commodity markets.

Mining is probably one of the industries where economic, environmental and societal decision variables are most closely interdependent. The last decade has seen a rise in volumes and dividend yields, but with a recent trend of falling commodity prices. The scenario is one of lack of confidence that costs can be controlled, capital discipline will occur, returns on capital will improve, and resource nationalism will not turn promising projects into poor bets (Gravelle and Rajaratnam, 2013). To make matters more complicated, many commodities suffer from persistent cyclical instability in prices, production, profitability, and investment, what can be rather costly for the corresponding stakeholders. In fact, the amplitude of the fluctuations tends to increase significantly as they propagate from manufacturers to steelmakers to miners, and to mining suppliers, with each upstream stage lagging behind its immediate customer (Ballmer, 1949).

In such a capital-intensive, slow dynamics industry, sustaining long-term investments in supporting assets such as innovation and sustainability can be rather challenging. Since there seems to be a never-ending conflict between short- and long-term goals, care must be taken against the possibility of *decision implementation failure*, when the need to maintain performance overrides the need to learn about a given enterprise — the *worse-before-better* paradigm can be especially troublesome in such settings (Sterman et al., 2015). Such organizational barriers may even affect the implementation of cleaner production practices, which fundamentally depend on a consistent strategic commitment of both firms and regional governments (Hilson, 2000).

One could always argue that adopting the values of sustainable development implies an increase in the industry's costs. However, history has shown that past increases in environmental and social

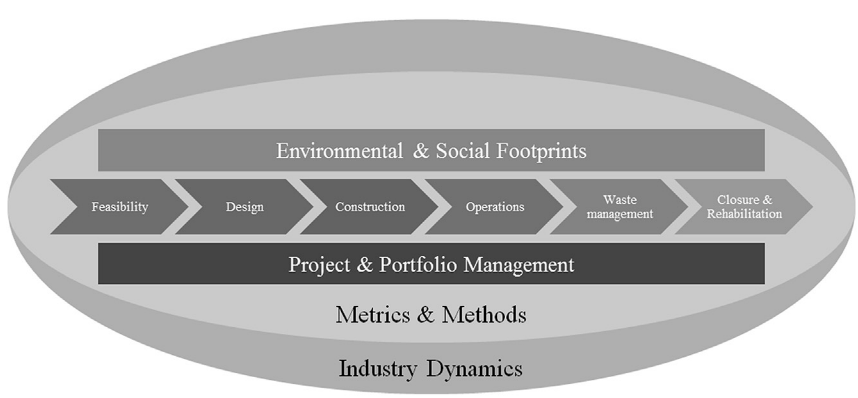

Fig. 2. A framework to analyze sustainability decision-support models in the mining industry.

costs have been more than offset by developments in productivity (Humphreys, 2001). In fact, improving returns to capital is and probably will always be in order for the mining industry — yet another market-pull for formal, quantitative, applied decision-support methods for driving effective project design, resource allocation and operations management (Lala et al., 2015).

4.2. Metrics and methods

The development of consistent metrics to feed sustainability decision-support models is a fundamental challenge for each decision level and every stage of mining value chain. However, in a recent survey, Hassini et al. (2012) stated that none of the studies covered had comprehensively addressed the three dimensions of sustainability. In general, the literature on sustainability metrics show that either the chosen metrics are not truly reflective of all three aspects of sustainable development, or they are too many and, consequently, difficult to apply, or both (Martins et al., 2007). Additionally, Nikolopoulou and Ierapetritou (2012) argue that the focus of the academic community on sustainability issues is somewhat concentrated on the integration of economic and environmental considerations, with a smaller concern on the social aspects, while the industry seems to be more focused on the constraints imposed on the use of limited resources such as energy and water, as well as managing waste and reducing emissions. Our research agrees with those findings, and also evidences that efforts to develop sustainability metrics for the mining industry roughly concentrate around four main topics: frameworks of metrics, project valuation, operations, and closure, which are further discussed below.

A number of authors have proposed frameworks for establishing metrics that encompass one or more of the three dimensions of sustainability. Roca and Searcy (2012) analyze the contents of recent sustainability reports from Canadian organizations, showing that the indicators disclosed were relatively evenly distributed along the triple bottom line of sustainability — though only a third of the reports included items explicitly identified as Global Reporting Initiative (GRI) indicators (GRI, 2014). In that study, the mining sector is represented by 16 companies (17% of the sample) presenting metrics organized around categories related to employees, health and safety, and emissions and effluents. Examples of highly cited social indicators include: "lost time injury frequency", "all injury frequency number", and "funding, donations and sponsorship". It is interesting to note, however, that only a handful of corporations publish *targets* for their sustainability indicators. Azapagic (2004) addresses the development of a GRI-compatible framework as a tool for reporting, performance assessment, and improvement. Economic, environmental, social, and a suite of integrated indicators are proposed based on a systems thinking analysis of the relevant stakeholders of the mining industry. That comprehensive framework provides a consistent means to support decision-making and evaluate positive and negative impacts. Basu and Kumar (2004) also present a sustainable performance management framework which requires a set of indicators for measuring, monitoring and reporting progress. The authors argue that *regional* sustainability requires that institutions exhibit *corporate* sustainability, which in turn depends on satisfying local sustainability goals through specific, well-managed projects. That argument emphasizes the importance of integrating strategic goals among different stakeholders within the mining networks.

Project and portfolio valuation is also a sensitive, data-dependent process. Several authors have studied the development of specific valuation methods for sustainability investments in the mining industry. In this context, Damigos (2008) presents an interesting overview of environmental valuation processes, as well as practical applications in mining. Two important categories stand out: a social cost-benefit project appraisal, and an assessment of natural resource damages. The author points out that due to the potentially significant legal and financial risks involved, the importance of such methods to mining firms is paramount. However, one should note that the economic valuation of environmental damages in such complex systems may be seen as an oversimplification of the actual negative outcomes (Martinez-Alier, 2001), and hence should be approached with scientific caution.

Land use, conservation and rehabilitation are among the most important environmental investments made by mining firms. In particular, the ability to allocate realistic economic values to biodiversity assets within conservation areas has significant strategic importance. Pearce and Moran (1994) argue that the issue must be addressed in a way as to demonstrate the economic value of conservation *relative to the returns from land development*; and to construct mechanisms for the appropriation of those values — meaning that the decision rule should favour the comparison of the *total economic value* over a simple trade-off of the direct use of land versus the opportunity costs. The authors proceed with a discussion of modelling guidelines for establishing the economic value of biological assets in conservation or common-pool areas. Although not being applied to specific mining conservation sites, the guidelines build on a series of efforts to quantitatively evaluate investments in environmental assets.

On the social dimension, Gregory and Keeney (1994) argue that stakeholders in a strategic decision process involving economic and environmental trade-offs have a right to be involved, and should have substantial early input in framing the decision process itself, and identifying its main objectives. The authors present an approach to valuate social trade-off decisions based on three steps: setting the decision context, specifying the objectives to be achieved, and identifying alternatives to achieve those objectives. A case study of a mine drilling permit in Malaysia is used to evaluate the effectiveness of the proposed process, showing a straightforward and transparent approach to elicit and analyze multiple, often conflicting, stakeholder objectives.

A fundamental discussion — and clearly related to the goals of this paper — regards evaluating the benefits of the development of innovative technologies for sustainability in the minerals industry. Indisputably, research and development efforts always come with a certain degree of uncertainty over the expected results, and thus demand specific methods of valuation and value assessment. McLellan et al. (2007) propose a four-stage methodology to assess minerals processing R&D projects, based on (i) a characterization of impact categories, (ii) a quantification of the lowest-unit-level change in impact to each category, (iii) an extrapolation of the results from the lowest-unit-level to the highest potential for implementation, and (iv) valuation, monetary or not. Results of applying the methodology to research projects in comminution, geo-polymers, and biomass illustrate the applicability of the model.

Mining industry operations are both a source and a consumer of sustainability-related metrics. For instance, Mudd (2008) assesses and quantifies the total amount of water required to produce various mineral commodities. Data from 36 mining companies shows that there is wide variation in the embodied water for the 13 mineral commodities considered, as well as for the same commodity. There is little evidence for economies of scale (in embodied water) in base metals and bulk minerals, though for precious metals (gold, platinum), greater throughput does tend to lead to greater efficiency. Mudd and Diesendorf (2008) analyze sustainability metrics such as energy and water consumption, and carbon emissions for uranium production. Data from Australia, Canada, and Namibia points out that the extent of economically recoverable uranium is clearly linked to exploration effort, technology, and economics, but nevertheless closely associated to environmental costs such as energy, water and chemicals consumption, greenhouse gas emissions, and broader social issues. The study also shows a strong sensitivity of those costs to ore grade, which further calls for an integrated perspective of sustainability-related metrics to support operations management.

Of particular importance to our work, evaluating the choice of cleaner technologies is key in strategic decision-making processes. Driussi and Jansz (2006) survey various pollution minimization techniques adopted in mineral processing operations. Those typically include environmental management systems, advanced pollution control technologies, environmental awareness training for employees, and requirement, from company stakeholders, for increased accountability of environmental impacts. Data from six major mining companies depict programmes and technologies aimed at improving environmental performance measured by indicators on water and energy efficiency, greenhouse and other negative emissions, as well as renewable energy use and land rehabilitation rate.

A very small number of papers discusses indicators aimed at assessing performance and impact of the closure and post-closure phases. A particularly interesting article by Worrall et al. (2009) argues that, while mining operations generally work within strict guidelines and have significant available resources to tackle sustainable development issues, legacy mine land sites (which include abandoned, derelict, or orphan sites in need of remedial work) often present unsatisfactory mining practices, and have unclear or disputed ownership. A set of 14 criteria and 72 indicators covering environmental, social-political and economic dimensions of post-closure are proposed and discussed in light of an Australian case study. The authors estimate that potentially millions of legacy mine sites exist in the world, what calls for consistent, effective managerial efforts form both governments and organizations.

4.3. Mining project & portfolio optimization

Project portfolio selection and prioritization are among the most important decisions in mining organizations. As stated before, discipline in the allocation of capital, especially in such a capital-intensive industry, has been consistently demanded by shareholders (Hopwood, 2014). Yet, this is the function directly responsible for assuring that coherent investments in sustainable development be *timely* included in a firm's investment portfolio. Conflictual decisions such as “spending more on technologies with higher environmental performance” are thus typical of such settings.

Most technologies developed to reduce environmental impact may indeed require significant investment levels, thus increasing operating costs and/or reducing the nominal throughput — often seen as irreversible investments under output price uncertainty. Real Options theory (Trigeorgis, 1996) allows evaluating decisions contingent on the particular realizations of one or more relevant random variables, being particularly suitable to analyze investments under managerial flexibility. Cortazar et al. (1998) present an example of such an approach, where a copper mining and processing firm is confronted with environmental regulation schedule linking maximum production levels and operating costs to the level of environmental investment. Results show that firms require significantly high output prices to be induced to invest in environmental technologies. That is in accordance to what is observed in practice, especially considering that firms optimally would not choose to commit to a significant irreversible investment that could prove unprofitable in the event of a price fall. The mining industry dynamics and the dynamics of the mineral commodity markets pose additional challenges to making decisions under those conditions (Ballmer, 1949).

In an attempt to balance economic and environmental goals, Gomes et al. (2013) propose a multi-criteria portfolio selection method for a Brazilian mining company. The method initially applies the Analytic Hierarchy Process (Saaty, 2005) to determine the relative importance of GRI environmental indicators according to the company's strategy. The priorities are then used as weights in a goal programming model to optimize a project portfolio aimed at improving the company's environmental performance compared to a synthetic benchmark. Projects selected under this exercise included investments to address direct and indirect energy and water consumption, as well as water recirculation targets.

4.4. Mining life cycle

Different opportunities, risks and investment levels are required in different phases of a mine project's life cycle. The following sections detail relevant work found in our survey.

4.4.1. Feasibility and design

McLellan et al. (2009) pose that the biggest opportunity for reducing the environmental and social impacts of mining operations lies in the design phase, rather than in operation or post-closure. In their extensive survey, the authors review tools and approaches for integrating sustainability principles into mineral processing design. On the formal, quantitative decision-support side, the paper elaborates on such methods as Life Cycle Assessment, real options, externality analysis, multi-criteria decision analysis, among others.

Specific optimization approaches may be employed to address the design of industrial processes particular to mining operations. Bagajewicz et al. (2000) propose a mathematical programming approach to determine a network of interconnections of water streams among water-using and water-disposing processes so that the overall annualized capital and operating costs are minimized, and water quality is ensured. Pokrajcic and Morrison (2008) present a simulation study to assess the performance, and support eco-efficient modifications on a comminution circuit. Modifications involved employing more efficient grinding elements, and including an additional griding stage to target finer materials. The authors report impacts on both direct and indirect energy usage, reaching as much as 14% savings on total power consumption. Zhang (2011) presents an interesting approach to the design of sustainable supply chains. A *Sustainable Function Deployment* technique quantitatively derives priorities among economic, environmental and social objectives, and then feeds those priorities into a mixed-integer programming model that selects an optimal configuration for a general supply chain network.

4.4.2. Construction

Establishing a new mining operation incurs on significant environmental and social impacts on the construction site and surrounding communities. Although we have not been able to find specific papers on formal models for supporting decisions on the construction phase of mining operations, we point out a few articles which illustrate important issues that must be integrated into the present discussion, especially in terms of the management of the related environmental and social impacts.

Ortiz et al. (2009) present a review of recent research on Life Cycle Assessment applied within the building sector, and establishes the basis for a thorough discussion on the role of the construction industry in improving the social, economic and environmental indicators of sustainability. As it will be presented in following sections, LCA is a consistent method to better understand the most relevant decision variables in a construction project. It is also important to consider the various impacts that the construction of a new mining operation may have across mine service towns. In such situations, the characteristics of the project, the structure and history of the community, and the extent to which a non-resident workforce is involved are key factors in assessing the magnitude of the social impacts and the ways to manage them (Petkova et al., 2009). Faniran and Caban, (1994) address the issue of waste in construction sites, and point out that there exists a potential scope for improving the effectiveness of waste minimization at source by addressing the sources of all waste generated during the construction phase of a project.

4.4.3. Operations

The operations phase is probably the longest and the most intensive in environmental and social impact, thus requiring special attention and decision-making support. Conversely, Newman et al. (2010) reveal a lack of specific studies that incorporate sustainability goals in typical decision-making processes supported by operations research. Integrating sustainability to mining operations requires a systematic and rigorous process of identification and qualification of issues and opportunities in each technical stage (Tuazon et al., 2012). In that sense, van Berkel (2007) proposes a framework for eco-efficiency in mineral processing that covers process design, input substitution, plant improvement, good housekeeping, and reuse, recycling and recovery — this last one with five resource productivity themes: resource efficiency, energy use and greenhouse gas emissions, water use and impacts, control of minor elements and toxins, and byproduct management. It is worth to notice that the classification proposed by van Berkel is focused on a single company, thus falling short to the integration of supply chain management concepts. Caldentey and Mondschein (2003) develop a mathematical model that has two components: (i) a nonlinear integer model to describe smelter operations including the investment decisions in pollution abatement plants, and (ii) a network flow model to describe the economic behaviour of the associated byproducts. The objective is to maximize total expected profit from the copper production process, discounted over the planning horizon, subject to technical, environmental, and market constraints.

Gunson et al. (2010) propose a linear programming model to minimize the energy requirements of the water processing network in a hypothetical copper mining firm. Freitas and Magrini (2013) propose a multi-criteria approach to address the problem of selecting sustainable water management strategies for a mining complex located in Brazil, thus integrating social (partially represented by corporate image) and environmental aspects into the decision-making process. Some of the alternatives included: installation of an end-of-pipe system to treat the total dam overflow rate, reuse of part of the effluent from the dam in processes at the beneficiation plant which can handle the untreated water, and treatment of the remainder flow rate of the dam in an end-of-pipe treatment plant.

Besides the commonly disclosed benefits of reducing the *per tonne* impact of mining operations by achieving economies of scale in haulage, handling and transportation activities, as well as improving the efficiency (including energy-related) of production assets (Kolonja et al., 1993), which could also be primarily motivated by productivity and cost concerns, less evident gains on the sustainability performance of mining operations must also be discussed. Everett (1996), for instance, uses a simulation model to reduce fluctuation in iron ore composition by employing intelligent ore stacking and recovery procedures. Besides improving product quality, his model also allows reducing about 60% of the space dedicated to stockpiles, while at the same time decreasing rehandling — both creating significant environmental value due to the use of smaller stockpiles, and decreased dust pollution and land degradation. Sahoo et al. (2010) present an optimization model to minimize the specific fuel consumption of dump trucks in open pit mining operations according to different operational conditions. The authors report energy savings of up to 15%.

4.4.4. Waste management

With a much smaller representation in our sample, mining waste management still configures an important field to the development of decision-support models and tools. Haibin and Zhenling (2010) discuss a case study of coal mining waste management process, from the recycling economy perspective. Though not converging the approach into a formal mathematical model, the discussion covers several investment options to create value from coal mining waste. Bian et al. (2008), additionally, provide an impact assessment of coal mining wastes, and argues about the importance of the transportation and accumulation of those contaminants over time on the environment and farmland.

4.4.5. Closure and rehabilitation

The International Council on Mining & Metals (ICMM, 2008) argues that mine closure is mainly a *managerial challenge*, since the technical activities to meet closure requirements are relatively straightforward. The harder issues involve “aligning, scoping, implementing, reviewing and adjusting the closure plan to provide a sustainable exit strategy”. Nevertheless, the Council proposes a discussion on *planning for closure*, which entails designing a mine operation observing closure constraints, such as re-vegetation of tailings facilities, or designing infrastructure considering the requirements of neighbouring communities.

A discussion on sustainable closure plans can also be found in the work of Robertson et al. (1998). The authors emphasize that the mining industry can (and should) provide motivation and guidance to assist in the rationalization of the uncoordinated administration and control of post mining sustainable land-use. In particular, a set of arguments for sustainability attainment through closure are presented, which include: taking into account the effects of multiple projects in a given area; expecting realistic, long-term maintenance costs; changes in regulations and societal pressure; new land use requirements; among others.

On a more quantitative perspective, Moel and Tufano (2002) analyze the effects of market parameters (price, volatility, interest rates, etc.) as well as operational parameters (fixed and variable costs, and reserves) on the decisions of opening and closing gold mines. From a data set of several North American mines, the authors conclude that a real options model can be used to describe and predict a mine's opening and shutting decisions. Also, the closure decision seems to be related to firm-specific managerial factors, most notably the profitability of other mines in the firm's portfolio.

4.5. Environmental & social footprints

Among the numerous approaches to quantitatively address sustainability issues, Life Cycle Assessment (LCA) has been widely accepted as a well-established methodology to assess and compare the environmental impact of products and processes, as well as a way to identify valuable insights for a number of both simple and complex process improvement initiatives (Azapagic and Clift, 1999). Our interest in LCA is thus twofold: (i) identifying energy consumption, greenhouse gas emissions, embodied water, wastes, among other environmental aspects pertinent to mining projects, and (ii) providing coherent metrics to assess the corresponding environmental performance. Also, although LCA has been primarily focused on the environmental dimension, some attempts at including the social impact have been addressed recently and show promising research directions (Finnveden et al., 2009).

The mining industry has received increasing attention from LCA practitioners (Norgate and Rankin, 2000; Stewart et al., 2006a; Mangena and Brent, 2006), with the availability of consistent, representative models and databases configuring the major development challenges (Stewart et al., 2006b). Durucan et al. (2006) address this issue by developing a comprehensive LCA model integrating mine production, processing, waste treatment and disposal, rehabilitation and aftercare, allowing spatial and temporal impact assessments.

Mineral commodities vary in respect to their environmental impacts and even to the stages that correspond to the largest contributors. Norgate and Haque (2010) carry out a LCA assessment of iron ore, bauxite and copper concentrate, and compare those minerals according to total greenhouse emissions and embodied energy. Results show that loading and hauling make the largest contributions to the total greenhouse gas emissions for iron ore and bauxite, whereas crushing and grinding represent the largest contributions to the total greenhouse gas emissions for copper. Besides creating a consistent impact inventory, the results help prioritize efforts to reduce the corresponding environmental footprints.

On a more strategic perspective, Northey et al. (2013) use data from sustainability reports of several mining companies to estimate a global footprint of primary copper production in terms of energy, greenhouse gas emissions, and water intensity. Another interesting work is presented by Memarya et al. (2012), where LCA is applied to estimate impacts from the five largest Australian copper mines, incorporating changes in ore grade and differences in technologies and regional energy sources. Annualized results from years of copper production suggest the importance of considering time-series-based LCA models to assess future technology and energy options in the mineral sector. It is interesting to notice, however, that the available data is somewhat sparse in assessing the impact of mining tailings. In a more specific study, Reid et al. (2009) use LCA to compare different management and closure scenarios for a tailing site of an underground copper mine in Canada. The case study establishes the inventory of these management scenarios from design to post-closure in order to assess the corresponding environmental footprints, and to emphasize the importance of the land-use impact category for the mining industry.

An important convergence of LCA and decision-support methods is discussed by Azapagic (1999). The author reviews several applications of LCA in process industries, and points out advances and opportunities of incorporating LCA into system optimization problems, usually through: (i) carrying out a Life Cycle Assessment study, (ii) formulating a multi-objective optimization problem in the LCA context, and (iii) solving the multi-objective problem and selecting the best compromise solution. Often (conflicting) economic and environmental objectives can be addressed within a single Pareto analysis.

Despite the large opportunities for scientific and practice initiatives, the assessment of the *social* impacts of mining activities is still in its infancy. Solomon et al. (2008), on a literature review, highlight some of those gaps as being: social performance, mine site functional roles, industry work and working conditions, Indigenous employment, gender equality, public participation, and community development. Several challenges on developing social indicators and measurement methods still demand significant attention from academics and industry.

4.6. Sustainable mining networks

Global mining networks are complex systems comprised of integrated facilities designed to process, using a variety of production techniques, and distribute, using a variety of transportation modals, bulk ore products from mines to customers, which can be (and usually are) at significant geographic distances (Pimentel et al., 2010). However, when the *sustainability* perspective is incorporated, the management function must also address the diverse interests and characteristics of suppliers, governments, communities, as well as the environmental and social footprints attributed to each echelon of the supply chain. Table 1 summarizes the review according to the framework proposed in Fig. 2.

Actually, one of the most challenging changes in the way companies work with sustainable development is the shift of focus from their particular operations towards the improvement of the performance of their entire supply chains. The adoption of sustainability targets in traditional supply chain decision-making processes is usually related to three main drivers: increased regulation and legislation pressures (Xu et al., 2013), customer awareness and the social licence to operate (Thun and Muller, 2010), and marketing, efficiency and performance requirements (Hart and Ahuja, 1996). Nevertheless, from the previous surveys of Linton et al. (2007), Seuring and Muller (2008), Gunasekaran and Spalanzani (2012), Hassini et al. (2012), Tang and Zhou (2012), Seuring (2013), and Brandenburg et al. (2014), we can infer that the scientific literature has been devoting very little attention to quantitative approaches on sustainable *mining* supply chain management.

Nevertheless, Muduli et al. (2013) propose a graph theoretic and matrix approach to identify and assess the adverse impact of factors hindering the adoption of green supply chain management practices in the Indian mining industry. Results show that capacity constraints have more adverse impacts than other issues in the case of large mining companies, whereas poor legislation produces a more adverse impact on green supply chain management practices in small scale mines. In a similar approach, Govindan et al. (2014) addresses the barriers and drivers for implementing, respectively, green and corporate social responsibility practices in the Indian mining value chain. Both propose models that, though not supporting decision-making endogenously, may be useful in providing information to decision makers interested in developing strategies for addressing environmental and social issues in their companies.

One final comment on the nature of decision-making problems in natural resource management is in order. This review has shown that the complexity of the mining industry imposes additional challenges to decision-support models that must deal with inherently participatory planning and decision environments where conflicting interests of diverse stakeholders must be balanced. In those cases, as pointed out by Mendoza and Martins (2006), the decision analytical framework may benefit from Soft-OR techniques that allow modelling qualitative requirements pertaining to the social aspects of the decision problem, coupled with a more quantitative, structured approach of formal, traditional models.

5. Research gaps and challenges

The previous sections helped building a broad perspective on the available research and applications of quantitative, formal methods to supporting sustainability-related managerial decisions in the mining industry. From that perspective and according to the framework proposed in Section 4, we analyze existing research gaps, directions, and open challenges.

Table 1
Grouping papers according to the analysis framework.

Component	Related papers
Environmental & social footprints	(Norgate and Rankin, 2000; Stewart et al., 2006a; Mangena and Brent, 2006; Stewart et al., 2006b; Norgate and Haque, 2010; Northey et al., 2013; Memarya et al., 2012; Reid et al., 2009; Azapagic, 1999; Solomon et al., 2008)
Mining life cycle	
Feasibility & design	(McLellan et al., 2009; Bagajewicz et al., 2000; Pokrajcic and Morrison, 2008; Zhang, 2011)
Construction	(Petkova et al., 2009)
Operations	(Tuazon et al., 2012; van Berkel, 2007; Caldentey and Mondschein, 2003; Gunson et al., 2010; Freitas and Magrini, 2013; Kolonja et al., 1993; Everett, 1996; Sahoo et al., 2010)
Waste management	(Haibin and Zhenling, 2010; Bian et al., 2008)
Closure	(Moel and Tufano, 2002)
Mining Project Portfolio Optimization	(Cortazar et al., 1998; Gomes et al., 2013)
Metrics & methods	(Hassini et al., 2012; Roca and Searcy, 2012; Azapagic, 2004; Basu and Kumar, 2004; Damigos, 2008; Martinez-Alier, 2001; Pearce and Moran, 1994; Gregory and Keeney, 1994; McLellan et al., 2007; Mudd, 2008; Mudd and Diesendorf, 2008; Driussi and Jansz, 2006; Worrall et al., 2009)
Mining industry dynamics	(Gravelle and Rajaratnam, 2013; Ballmer, 1949; Hilson, 2000; Humphreys, 2001)

Generally speaking, the integration of the inherent trade-offs between sociopolitical, environmental, ecological, and economic factors is one major source of complexity in the decision-making processes of mining projects. Typical challenges include condensing multiple criteria into monetary value, and dealing with the inevitable difficulty of addressing conflicting stakeholder preferences. As we have seen throughout the discussion of Section 4, and more specifically in Section 4.5, the combination of impact assessment methods, multi-criteria decision analysis (Kiker et al., 2005), and multi-objective optimization does seems to be a promising framework (Zhou et al., 2000; Ferretti et al., 2007), despite the added complexity (Nikolopoulou and Ierapetritou, 2012), as depicted in Fig. 3.

Undoubtedly, the internalization of externalities (Bithas, 2011) is a major challenge in developing sound decision-support tools for sustainable mining networks, since the associated costs may be quite relevant compared to market prices (Steen and Borg, 2002). In fact, recognizing the relevant social and environmental impacts along the full project life cycle — from exploration through operations, to the long post-closure period — in a mine's design and financial analysis would reflect a major evolution in the way capital investments are made (ICMM, 2012).

The literature on sustainable supply chain management is vast, but only a small portion applies quantitative methods, and an even smaller number of papers attempt to address the social dimension of sustainability (Seuring, 2013). Clearly the mining industry could be one of the major agents in transforming this scenario, especially considering the multitude of sensitive issues inherent to its projects (Kitula, 2006; Watch, 2013).

We organize the following discussion according to a decision-level structure (Anthony, 1965), also extending an integrated perspective on existing opportunities for sustainable mining networks.

5.1. The strategic perspective

The strategic decision level deals with long-term decisions involving managerial policies and resource development. Recent history has shown how decisions on capacity expansion and mining network design may be influenced by commodity and economic cycles. However, it is also important to fathom their impact on the establishment and maintenance of consistent sustainability strategies (Aldy and Stavins, 2012). In fact, the short- and long-term variations in mineral commodity prices must be seen as a fact of life for mine project planning and for those concerned with community and regional development (Kondo et al., 2002). The corresponding impacts have to be taken into account when designing irreversible environmental and social investments which unarguably depend on the productive investments (and eventual divestiture) (Pimentel et al., 2013).

Optimizing project and portfolio selection through the balancing of economic, environmental and social targets is one of the main opportunities for developing decision-support models and tools for mining firms. Multi-criteria decision analysis seems well-suited to support prioritizing conflicting goals, and multi-objective optimization methods can be applied to the project selection problem, thus providing decision-makers with a clearer view on the triple-bottom-line trade-offs. Nevertheless, it is important to remember that uncertainty and risk are an integral part of this process. Real options theory may be useful in addressing the managerial flexibility of managing exposure to risk in investment portfolios (Tufano, 1998). Also, the multi-objective portfolio selection problem may find additional robustness in stochastic programming methods (Abdelaziz et al., 2007).

Waste management and recycling planning also lack broader applications in mining. One should notice that *waste* should be

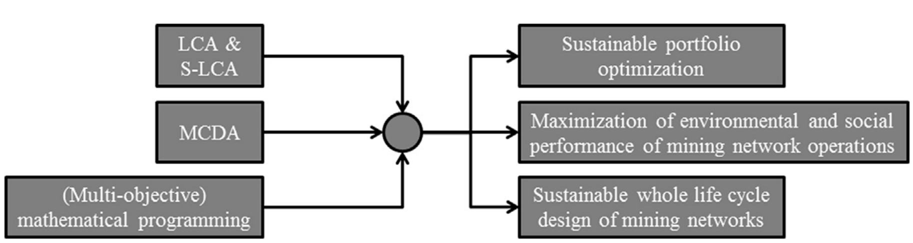

Fig. 3. The combination of life cycle analysis, multi-criteria decision analysis, and mathematical programming approaches to support sustainable performance in mining.

viewed as both the overburden or byproducts of ore beneficiation, and the typical industrial and urban residues. Actually, some mining companies do invest in establishing the required infrastructure for waste logistics, destination and recycling (for instance, of truck tyres, lubrication oil, etc.), which could also be a focus of facility location and network design studies. Sustainable mining network design also means addressing recycling economy issues at design time in order to convert process waste into wealth and social development (Haibin and Zhenling, 2010).

Finally, it is important to note that, as pointed out by McLellan et al. (2009), several opportunities exist for mining firms to incorporate sustainable development targets in their network design efforts. Besides the direct benefits gained from deciding on the optimal investment portfolios, such approaches might also facilitate the social and regulatory licences to operate, which clearly configure an important competitive advantage.

5.2. Tactical and operational perspectives

The tactical decision level seeks effective resource allocation to satisfy demand requirements and operation constraints on a given time horizon, while operations control is concerned with short-term decisions, usually involving low-level programming and scheduling. Clearly, the efficient use of production and transportation assets will always be in the decision deck of mining operations, bringing positive environmental impacts, beyond the obvious economic directive (Absi et al., 2013). As pointed out by Newman et al. (2010), operations research-based tools supporting mine production planning still fail to incorporate sustainability goals. For instance, in open pit mines, the ability to optimally schedule mine production to account for overburden hauling in a way as to minimize the size of waste stockpiles would present evident environmental and economic benefits. Also, open pit operations that run on large off-road trucks may be interested in optimizing not only distance travelled and productivity, but also specific energy consumption and emission targets. The same approach could be envisioned for railroad ore transportation operations and traffic scheduling (Australia, Case Study, 2014). In fact, sustainable vehicle routing (Lin et al., 2014) is an important trend for both research and practice on mining operations.

Effective resource allocation also means developing or acquiring *effective* technologies. According to the framework proposed by Blok et al. (2013), the sustainability of new technologies should be assessed through the impact on human health, the impact on social well-being, the impact on prosperity, the impact on the natural environment, and the impact on nonrenewable resources. The integration of such technologies within a consistent design approach is the focus of *sustainable process design* methods, which stand for multi-objective optimization problems in which the manufacturing costs must be minimized while improving all other sustainability indicators (Sikdar, 2003). Such a process may even include the optimal selection of technology and service providers under environmental efficiency targets and constraints (Yeh and Chuang, 2011).

Environmental impacts associated to energy and water use are among the most important issues for the mining industry. Several opportunities thus exist to develop analytics-based approaches to optimize water networks, recirculation and regeneration (de Faria et al., 2009), including the proper selection of available technologies (Dharmappa et al., 2008). Also, since many minerals are declining in average ore grade, the sensitivity of embodied water to ore grade provides yet another major sustainability challenge (Mudd, 2008).

Managing biodiversity assets in conservation areas protected by mining firms can also benefit from quantitative approaches, such as the protocol proposed by Joseph et al. (2009), in which project management parameters (costs, benefit, and probability of success) and species parameters (taxonomic distinctiveness and threat status) are used to optimally allocate constrained financial resources from conservation funds in New Zealand.

In recent years, several different approaches towards Social Life Cycle Assessment (SLCA) have been developed (Kloepffer, 2008), though its widespread adoption still demands considerable research (Benoit et al., 2010). Societal indicators present themselves according to impact categories in Human rights, Labour practices and work conditions, Society, and Product Responsibility (Jorgensen et al., 2008). However, there is still a large gap, and equally important challenges, of applications in the mining industry.

5.3. Integrated perspectives

Supply chain design problems have recently incorporated sustainability-related decision variables pertaining to environmental concerns, such as carbon and waste management, and social concerns, which seem rather difficult to capture and quantify in mathematical terms. The literature has evidenced three main trends in methods supporting sustainable operations: whole life cycle assessment, multi-criteria decision analysis, and integrated systematic methodologies (Liu et al., 2011). In effect, given the global nature of modern mining networks, the focus on achieving adequate sustainability performance should be expanded to encompass production, consumption and recycling, while connecting social, ecological, technological, economic and governance domains across local and regional scales (Giurco and Cooper, 2012).

The *sustainable mining network design problem* would require not only minimizing the total costs associated with construction and operation, but also minimizing the carbon equivalent emissions associated with its various activities (Nagurney and Nagurney, 2010). Given the inherent uncertainties in the life cycle inventory of the network operation, stochastic approaches would allow maximizing a project's net present value, while at the same time minimizing the corresponding environmental impacts for a given probability level (Guillén-Gosálbez and Grossmann, 2009). Furthermore, taking into account the carbon emissions incurred in logistics, suppliers and sub-contractors selection, decisions on technology acquisition and the choice of transportation modes could mean significant environmental performance (Chaabane et al., 2011). Given the continued discussion on carbon prices and emission trading schemes, mathematical formulations could incorporate investment decisions addressing strategies specific to global mining networks (Ramudhin et al., 2010).

Ore transportation plays a significant role in the environmental (and some times social) impacts of mining. Investment and network design decisions on large scale transportation modes — such as railroads, ore ducts and ocean carriers — could be more deeply analyzed according to their trade-offs on cost, productivity, energy and water consumption (and water displacement), and overall equivalent carbon emissions. The challenge of covering all relevant (and potentially geopolitical diverse) subsystems would most likely bring additional complexity into an already difficult optimization problem.

Again, the social aspect of sustainable supply chains still demands further research, especially keeping in mind that supply chain structures do play a fundamental role in the creation of social welfare (Vachon and Mao, 2008). For instance, promoting strong competition among agents within mining networks, and creating a demanding customer sustainability culture would not only promote fair wage and human rights within firms, but also create incentives to addressing society well-being through investing in local communities. Analogous to a environmentally efficient technology portfolio, one could envision a portfolio of social investments that could relate to the improvement of measurable impacts on human development indexes (McMahon and Moreira, 2014). Also, given the capillarity of typical mining networks in remote areas, one should not take for granted the opportunities of implementing plans and the additional capacity to support disaster recovery and humanitarian logistics (Altay and Green, 2006).

In summary, we argue that the development of decision-support tools with sustainability considerations for mining should be based on the following premises:

1. Economic goals should aim at maximizing the net present value of the entire mining network throughout its whole life cycle, as well as minimizing the corresponding operational costs. That may be achieved by optimally locating facilities and networks, selecting cost-effective process technologies, and optimizing lot-sizing and scheduling decisions.
2. Environmental directives are threefold. Firstly, they should drive the selection of appropriate process technologies so as to minimize water and energy consumption, as well as waste and equivalent carbon emissions in both production and transportation activities. Secondly, they should guide the investment on biodiversity assets, such as the establishment of protected areas according to their Total Economic Value. Thirdly, investments in the closure and post-closure stages of the mining enterprise should be evaluated not only as a compulsory business requirement, but also as an opportunity to further improve the company's biodiversity assets, and its institutional presence in the host communities.
3. Societal drivers must also be related to tangible perspectives. The most basic is the contribution to the household income of direct and indirect workers. Additionally, governments of host countries should benefit from royalties and taxes, hence further improving their GDP per capita. In a more sustainable sense, however, specific investment in the development of local suppliers could improve supply chain performance as well as economic and social indicators. Furthermore, the established service infrastructure should not only enable mining operations, but also improve quality of life by providing local communities with energy, transportation, health care, and education services. Long-term social development strategies should support the evolution and diversification of local economies in order to reduce its often exclusive dependence on the core mining operations.
4. The short- and long-term variations in market prices and demand are inherent challenges of strategic planning, and should be treated as intrinsic stochastic parameters.

6. Conclusion

This paper provides a broad review of the literature devoted to the development of formal, quantitative methods for incorporating sustainability targets into decision-making processes in the mining industry. Having established a framework covering the whole mine life cycle, as well as the necessary conceptual support, we also present a discussion of important research gaps and development opportunities.

Often located in remote areas, mining can provide a unique means for stimulating local economic activity. However, social and environmental implications are significant and can result in major socio-economic challenges. Usually, mining networks present themselves in complex configurations where many diverse relationships affect the operational, tactical and strategic choices made by firms, governments, and users. That fact clearly demands an integrated perspective that encompasses as many stages of the supply chain as possible in order to avoid unintended effects caused by the inherent interconnectedness of managerial decisions (Matos and Hall, 2007). Hence, in setting successful policies for sustainable development, researchers, policymakers, and practitioners should take into account the various linkages between economic actors responsible for the channels through which sustainability efforts can be developed and disseminated (Boons et al., 2012).

From our discussion, it is clear that the small number of papers presenting formal models devoted to sustainable mining networks indicates several opportunities for research and application. That is especially true for the Mining Project Portfolio Optimization, Operations, Waste Management, and Closure elements, and even more so when considering social targets and impacts. Of course, sustainability performance indicators and metrics are a fundamental necessity to any consistent approach involving those aspects. As we have noted, LCA-based methodologies seem to be one of the most popular techniques to address this need; integrating LCA with mathematical programming, and/or multi-criteria decision methods is a promising approach.

Any mining activity should only be undertaken if a net positive long-term contribution to human and ecosystem well-being can be produced. Although incorporating environmental and societal issues into quantitative decision-making processes may be rather challenging, it is our belief that such an approach could deliver significant value to industry, government and communities.

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