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A multi-objective optimization model for the design of an effective decarbonized supply chain in mining

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ABSTRACT

In this work, a three-objective optimization model for the design of an effective decarbonized supply chain in mining is proposed. It considers the installation and transport costs as the economic objective, the environmental objective through emissions from transport and operations, and the efficiency of the processing plants as the technological objective. We suggested a Pareto-based algorithm, which is a Multi-objective Hybrid Particle Swarm Optimization metaheuristic, for solving the problem. Using six metrics, many categorized instances are given to compare the performances of our algorithm, with those of an epsilon-constraint based algorithm (AUGMECON). The computational experiments show that the proposed metaheuristic is better than AUGMECON when it comes to metrics related to diversity and the distribution of solutions in the Pareto front.

1. Introduction

The impact of climate change on businesses and society has been highlighted as one of the major challenges that researchers, practitioners and policy makers have faced in the last decades. The increasing volume of carbon dioxide equivalent (carbon - CO_2e) accumulated in the atmosphere is one of the main contributors to climate change. In 2010, the world total emissions of carbon were 48,629 $MTCO_2e$, where the industrial sector is principally responsible for those emissions (Chaabane et al., 2012; den Elzen et al., 2013; Blanco and Sheffi, 2017) and the mining industry is an important participant, (Li et al., 2011; Norgate and Haque, 2010; Aguirre-Villegas and Benson, 2017). International organizations and governments are setting stringent legal constraints to reduce carbon emissions. In addition, the environmental awareness of customers is pressuring companies to adopt more environmentally friendly practices such as reducing their carbon emissions to the atmosphere. The mining industry is one of the major carbon emitters, just losing to the cement and the electricity industry. In this global setting, mining companies are looking for strategies to reduce their carbon emissions. They realized that supply chain management can provide a systemic view of their entire operations and thus an opportunity to redesign their global operations to achieve economic and environmental objectives. The network design of a supply chain (SCND) with the objective of minimizing cost (or maximizing profit) is a well-known strategic problem. In that problem, the optimal location, the capacity and the number of facilities to open (close) and the flow of raw material/goods through the network are defined (Simchi-Levi et al., 2007). The SCND is a hard combinatorial optimization problem and solution methods should be developed to address real supply chain problems (Melo et al., 2009; Santibanez-Gonzalez and Diabat, 2013; Simchi-Levi et al., 2007). Since changes to the network configuration are very costly, SCND is a key decision constraining the subsequent tactical and operational decisions (Devika et al., 2014; Chaabane et al., 2012).

Closed-loop supply chains (CLSC), which integrate the typical forward flows and the reverse flows of returned/used products, are a SCND problem that have received increased attention in the last years. This is supported by the number of papers compiled by (Agrawal et al., 2015; Govindan et al., 2015b; Souza, 2013) among others. Consumer returns and end-of-use returned products are some examples of the reverse flows of this type of supply chain (Souza, 2013). The companies have to deal with the undesirable returned products and the environmental regulations governing the operations of industries such as electric waste, electronic equipment and auto-makers. In this line, the works by (Tuzkaya et al., 2011; Kannan et al., 2012; Seuring, 2013; Diabat et al., 2013; Devika et al., 2014; Eskandarpour et al., 2015; Barbosa-Póvoa, 2014) proposed mixed integer linear programming (MILP) mathematical models and some others (Santibanez-Gonzalez and Diabat, 2013) developed heuristic approaches for solving a complex combinatorial optimization problem. A few researchers proposed heuristic approaches to solve CLSC problems. One example is Soleimani et al. (2013). They

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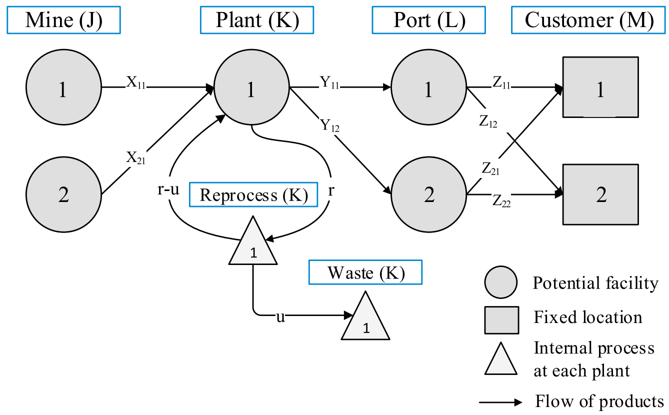

Fig. 1. Example of the SCN.

Table 1
Example of the content (%) of some ore quality parameters in mines and requirements of each product as a goal (%) of quality parameters.

		Quality Parameter				
		Fe	SiO_2	Al_2O_3	*Mn*	*P*
Mine	M1	64	4.0	1	0.80	0.06
	M2	45	5.0	3	0.50	0.05
Product	P1 (sinter)	64	4.0	1	0.80	0.06
	P2 (sinter)	50	2.0	5	0.13	0.05
	P3 (pellet)	64	1.0	5	1.50	0.01
	P4 (pellet)	69	0.9	10	3.00	0.06

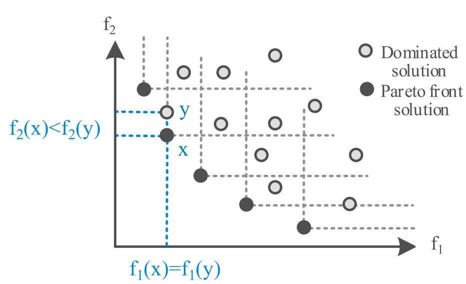

Fig. 2. Pareto dominance in a bi-objective minimization problem.

proposed a multi-echelon multi-period and multi-product CLSC model using a GA. They solved the model using CPLEX optimization software and compared it with the GA by using a set of large-size instances. The results proved the acceptable performances of the proposed GA and its applicability in real-size situations. For a detailed review of this line of research, the papers by (Govindan and Soleimani, 2017; Rajeev et al., 2017; Souza, 2013) are recommended.

In comparison to the typical stream of work on supply chains governed by economic objectives, only very recently the SCND problem with environmental and economic objectives has attracted the attention of both research and professional communities (Chaabane et al., 2012; Govindan et al., 2014). One example of this work is by (Akgul et al., 2012). They propose a multi-period, multi-product MILP model for the optimization of a biofuel supply chain regarding cost and environmental issues. All stages of the biofuel life-cycle, such as cultivation, transportation and production, are integrated into the proposed model. As part of the increasing environmental concern, the problem of designing a network to reduce carbon emissions along the whole (closed-loop) supply chain have been addressed by few researchers (Seuring and Müller, 2008; Seuring, 2013; Govindan et al., 2015b). This problem is also known as the problem of designing a decarbonized supply chain network.

Several authors have stressed the importance of designing a decarbonized supply chain network as a strategy that companies can use to help reduce carbon emissions to the atmosphere and mitigate climate change. This can be observed in the papers by (Chaabane et al., 2012; Diabat et al., 2013; Kannan et al., 2012; Ramudhin et al., 2010) to name a few. These papers propose a MILP-based model and, in almost all of them, a commercial standard package is used to solve the proposed model. In addition, both heuristic and metaheuristic approaches have been developed to solve closed-loop or decarbonized SCND problems. For example (Devika et al., 2014; Govindan and Soleimani, 2017; Soleimani and Kannan, 2015).

In the same context, to balance environmental and economic objectives that are sometimes in conflict when designing a decarbonized supply chain network, multi-objective mixed-integer linear programing models have been proposed. To solve them, classical approaches such as Epsilon-constraint (Mota et al., 2015; Zhang et al., 2014), Goal programming (Ramudhin et al., 2010; Chaabane et al., 2011) and Weighted sum (Galante et al., 2010; Amin and Zhang, 2013) have been used. Furthermore, many works have been developed in Swarm intelligence and Evolutionary algorithms (Tuzkaya et al., 2011; Zhang et al., 2013; Govindan et al., 2014, 2015a; Shankar et al., 2013; Chen et al., 2017). Due to the computational complexity of the resulting real MILP models, the authors highlight the necessity to develop heuristic/metaheuristic approaches for obtaining good solutions in a reasonable computing time.

In the mining industry, the research on SCND problems with environmental concerns is scarce. Pimentel et al. (2016) analyzed the literature focused on the development and application of quantitative methods for the decision support systems with sustainability concerns in the mining industry. They emphasized a lack of significant development in this area. According to the paper of McLellan et al. (2009), the mining industry can be seen 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. In the same line, Pimentel et al. (2010) emphasized the significant environmental and social negative impacts which could be generated along the chain. Chaabane et al. (2011) proposed a bi-objective optimization model for the design of a decarbonized SC. The model was applied to a Canadian firm that produces steel products with high levels of GHG emissions and that is subject to a regulation that caps carbon emissions. In a very recently published paper, Sauer and Seuring (2017) analyzed desirable connections between SCs and sustainable SCM and suggest future research work.

Our work enlarges and contributes to the existing body of research in three fundamental lines: (a) we propose a multi-objective optimization model for designing a decarbonized supply chain in the mining industry. The design problem considers decisions about the optimal localization of plants and the assignment of flows for a supply chain comprised of four echelons, several facilities, products and preprocessing flows. The different objectives consider the economic and environmental dimensions of the sustainability and the efficiency of the processing plants; (b) considering the computational complexity of the multi-objective optimization model, we design a multi-objective hybrid particle swarm optimization algorithm (MOHPSO), which is able to find feasible solutions; (c) In addition, to validate our model and the proposed algorithm, extensive computational experiments were conducted to analyze the quality of the solutions obtained by the proposed algorithm. We compared the results obtained by our proposed algorithm against an exact algorithm, AUGMECON.

The paper is structured as follows. In section 2 the problem and the optimization model are explained. Section 3 shows the characteristics of the proposed algorithm. Section 4 presents computational experiments comparing the performance of the algorithm with an existing procedure by using several standard criteria. Section 5 is dedicated to the analysis of the solutions obtained by the algorithm, and in section 6, the main conclusions and future work are presented.

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