Modeling or dynamic simulation: a tool for environmental management in mining?*

S. B. Mondoukpè Lagnika, Robert Hausler and Mathias Glaus

construction engineering Department, École de Technologie Supérieure, Montréal, Canada;
Station expérimentale des procédés pilotes en environnement (STEPPE), Montréal, Canada;
École de Technologie Supérieure, Montréal, Canada

ABSTRACT
The buoyancy of the minerals market, due to price and demand continually rising, maintains an increased interest for investors in mining. However, it is a sector particularly facing many negative environmental impacts, technical and environmental conditions to which are added the meeting of financial and production goals. Nevertheless in lockstep together, risk management of these extractive activities on environment – in this age where the society’s level of awareness in ecological balance has evolved – continues to fuel discussions and interventions. Therefore, it becomes unavoidable to manage more effectively the environmental factors around mines. This study aims to propose the integration of environmental management (EM) tools based on dynamic simulation (DS) for mining. This research is structured in four main topics: (1) the dynamics of open-pits system, (2) the management of their environmental effects, (3) the EM tools at the disposal of managers and (4) the proposed EM by DS. The results show that the challenges are numerous and the volume of DS approaches in mining is constantly growing, even if only few are directed towards EM. Some approaches of DS in a few open-pits with the proven effectiveness, show a new opportunity to investigate.

1. Introduction
Environmental management (EM) has become an important preoccupation, and thus, industries for which the scientific community strives to develop appropriate tools knowing that the reduction of environmental risks (ERs) requires the integration of various coupled parameters. In recent years, many studies integrated modeling tools for the management of their diversified business sectors. Indeed, for Hines et al. (2011), simulation models can be useful in many areas of management science, but also often expensive, time consuming, and challenging to develop. In fact, modeling has gradually evolved from a simplified graphical representation into a...
dynamic digital representation where users monitor their systems, directly observing operations or dynamic functioning of the components that constitute operations. The interaction stemming from socio-economic development and technology contributed to advancements in technology, namely the development of increasingly-powerful tools transforming static modeling into dynamic modeling. However, advancements in database management with computer/software engineering now greatly affect simulation processes, artificial intelligence and the development of support tools. The mining industry is one that stands out with respect to a range of applications where the EM process is still only partially addressed. The mining sector is an important contributor to economic development.

This article includes a literature on dynamic simulation (DS), its application for the mining industry and methods of management of environmental problems and risks upon integrated implementation. The present paper also analyses the progress aspects of simulation digital existing tools and the benefits of its use for EM activities. It is also a critical analysis of the existing data to help in understanding EM practices related to mining engineering, to highlight the limitations of current tools and the importance of simulation software such as Vensim. This contribution will lead to the development of key solutions in the ever-changing area of mining environmental management (MEM) research.

To achieve this, the remainder of the document has been organized into seven sections. The organization of this research and objective of the study are described in Sections 1.1 and 1.2. Sections 2 and 3 provide a detailed overview of the research methodology and materials in academic and mining industry perspectives with known and emerging ERs. Section 4 focuses on the differences on intermixed terms taken into account in modeling and simulation. Then, main results obtain using those methods are summarized in Section 5. In Section 6, a non-exhaustive list of tools currently used in EM, the progressive integration of DS in EM and the challenges of MEM are discussed. Then, the critical assessments of management approaches have generated other questions on links between MEM and DS before concluding in Section 7. Far from being exhaustive, this work intends to provide an overview of the application of this technology in many industries including mining and to point out his absence in MEM.

1.1. Organization of the research

For each basic study with respect to the required data, keyword groups or semantic equivalents for critical review are integrated in Table 1.

Next, this critical review of literature was organized in different stages as shown in Figure 1.

Contributions from the various chosen publications show a particular pattern of dynamic systems usage linked to one of the many existing issues in the mining industry. For example,

Table 1. Keywords used for information research and related objectives.

| Keywords used | Objectives |
|---------------|------------|
| (open-pit mining) + simulation + management | Know the history and evolution of modeling and dynamic simulation in open-pits mines (OPMs) practices |
| (open-pit mining) + (dynamic modelisation) + management | Know the existence or not of simulation as an environmental management tool |
| (dynamic simulation) + (environmental practices) | Know the existence or not of simulation as a tool in environmental management in mining industry |
| (mining NOT data) + simulation + (risks management)/(environmental risks) | |


the contributions can be divided in three categories: (1) financial profitability as dominant model within covered scientific publications; (2) production optimization or the planning related to extraction procedures; and, (3) as aid in decision-making or other solutions related to risks. Without a doubt, this research activity has contributed in: (1) organizing, viewing, analyzing and summarizing important elements of the research on DS or modeling; (2) showing the evolution of software for this digital approach within the mining industry; and (3) highlighting potential links with EM. DS is synonymous with dynamic modeling for many scientists as detailed later in Section 4.1, however, throughout this text, the term ‘DS’ will be used.

1.2. Research objectives

The objectives of this research are to:

(1) summarize and discuss the evolution of DS and software in the mining industry; and
(2) promote research on DS as an EM tool in the mining industry.

2. Research methodology

2.1. Process and materials

Nine databases have been considered for the collection of a substantial volume of articles: Compendex & Inspec, ScienceDirect, Scientific.net, Taylor & Francis online, Wiley & Son, IEEE xplore, Springer, Hindawi and Google scholar. The use of digital simulation in management approaches, optimization schemes, existing and emerging issues whether unresolved or resolved in mine management are analyzed during this research. Furthermore, the volume of databases was increased upon review of selected bibliographies of the articles, leading to the collection of relevant peer-review articles mainly on open-pit mines (OPMs).
2.2. Types of mines

Different mining extraction practices determining various types of mines, exist worldwide which are define by circumstances and elements types (Gratzfeld 2004). According to Samimi Namin et al. (2011), several factors including: economic, spatial characteristics of deposits, geological and hydrological conditions, geotechnical properties, technological and environmental aspects, are considered in determining the mode of extraction. They are generally of the following two categories: OPMs and underground mines. OPMs allow the extraction of minerals near surfaces, while underground mining are extractions of deposits below the surface. In addition, the latter requires special facilities: a network of wells and galleries linking to the surface and allowing the circulation of personnel and transportation of equipment and ore. All such excavations are equipped by supply systems that need to be effective regarding ventilation, water, electricity and compressed air (Armstrong & Menon 2000).

These extraction methods are similar everywhere despite the differences in work techniques and ore types. However, this research mainly focuses on OPMs operations and related ERs due to their high number in comparison to underground mines (NIOSH 2011).

3. Mining industry and ERs

Lagnika (2009) defines the risk as an uncertain occurrence and, if present, affected entities bearing the risk. Thus, as frequency and effects characterize the risk, any activity can lead to risks of external or internal nature. Among others, mining corporations have their environmental impacts analyzed (Lagnika 2004; Panov et al. 2011; Bhatasara 2013; Nadeau et al. 2013). Mining sector as an important contributor to economic development around the world is favourably considered. It generates significant economic benefits, facilitates the design of numerous products as well as the transformation or processing of a variety of industrial products into useful products. The Canadian government (2000) recognizes the importance of metals and the mining industry for the economy (income) and for the population (employment). But, the negative impacts associated with these activities are considerable.

Highlighting aspects of extracting non-renewable natural resources by various industrial operations, Godrej and Forbes (2012), have again confirmed ERs associated with the mining industry. It is an industry in which coexist several subsystems such as: production, technology, environment, human resources and markets. And these impacts on natural elements belonging to their biophysical, geological, geographical or social environments in turn become sources of ERs. Underground or OPMs are regularly subject to anthropological and technological influences as evidenced when also considering these characteristics (Ramani 1995; Donoghue 2004; Dhillon 2009; Radosavljević & Radosavljević 2009).

There were numerous ERs identified in the literature associated with the operation of OPMs: loss of soil fertility for agriculture, air pollution, noise, vibrations, waste-water discharge, groundwater destabilization, wildlife destabilization, geomorphologic changes, soil and flora changes, soil and vegetation contamination from dust (soluble and insoluble) and water acidification (Lagnika 2004; Agbo & Honkpehedji 2009; Kříbečka et al. 2014). Moreover, the type of ore and the geological formation coupled to the various mining activities (digs, sampling, spraying, drilling and blasting) and enrichment of deposits such as gold (with mercury, cyanidation, etc.) are also other serious sources of contaminant emissions (MAC...
Thus, impacts from the mining industry on the environment, health and safety, which are considerable, further induce scientific research (Nadeau et al. 2013). There are still lacks however, in information related to the different risks, especially with those emerging risks highlighted in the (ILO 2010) report which increase the uncertainty for industrial operations to master. In addition, high-tech equipment, including biotechnology equipment, is also identified as a contributor to numerous emerging risks like contamination by fine particles size fraction (Müezzinog’lu 2003; Donkor et al. 2005; Paruchuri et al. 2010; Csavina et al. 2011). And with this increase of such ERs, numerous interventions and ideas have been developed all over the world on optimal design of mine structures and sustainability into the design process for example (Kambani 2003; Odell 2004; Fleurisson & Grenon 2014). Albeit the concept of prevention and the laws or regulations related to EM promote the reduction or elimination of risks at the source (Environmental Compliance 2003), an integration of various affected parameters such as current legislation, the economy, technologies, methods of extraction and EFs is still required. A management method which requires the development and use of appropriate tools (Gendron 2004).

3.1. Environmental factors related to mining process

Section 3 includes information related to the different ERs stemming from mining operations. However, following literature review, environmental factors linked to mining operations are important to note, which include human, economic, wildlife, floral, atmospheric, soil, hydrological, geomorphologic and geological factors. But it’s important to mention that Canadian technical reports for mining commonly called National instrument (Ni) 43 101 and the environmental impact assessments (EIAs) do not account for EFs in the same way (Genivar 2008; ELAW 2010; BAPE 2013; Redwood 2013; Gervais et al. 2014). Specific to mining, Ni 43–101 summarizes the core elements of the project before its completion and is comparable to the Joint Ore Reserves Committee Code in Australia. This report provides the preliminary economic analysis and all technical data except sensitive (e.g. mineral content) without further analysis of the environmental effects. That is why it differs from EIAs because he is the only one to evaluate in depth the effects of the operations on environmental factors by proposing mitigation measures. The following summary as shown in Table 2 lists the environmental parameters accounted for in the Ni 43–101 reports, EIAs and other works systematically integrating sustainability aspects for mining projects. However contents of this outcome here serve in validating the link of such factors to mining operations.

3.2. ER factors related to mining process

To prevent or manage any type of pollution, risk factors need to be understood by studying the cycle and interactions between system elements and then controlled. Recent work from Huisman and Wood (1974) describe the environment as a geological matrix and system represented by its topography and geomorphology comprising minerals with certain permeability properties. With water being essential for most living organisms, the system represents a natural receptacle of all flows above and below ground. With mining, purification process explained by Mballo (2012) during operations to obtain a higher concentration of the ore (e.g. copper), contaminants and reactions with subsoil materials (exposed to light and air) can change water composition risking to make it unusable. ERs thus become part
Table 2. Summary of environmental factors related to mines in literature.

| Environmental factors linked to OPMs | Biophysical profile | Flora and vegetation | Fauna | Climate | Geochemistry | Hydrogeology | Hydrology | Economy | Geology | Ground | Geotechnic | Social profile |
|-------------------------------------|---------------------|----------------------|-------|---------|--------------|--------------|-----------|---------|---------|--------|-----------|----------------|
| NI reports                          | ★★★                | ★★★                 | ★★★  | ★       | ★★★         | ★            | ★         | ★★★    | ★★★    | ★★★    | ★★★★★☆    | ★★★            |
| EIAs and 301 reports                | ★★★                | ★★★                 | ★★★  | ★★★     | ★★★         | ★★★         | ★★★       | ★★★    | ★★★    | ★★★    | ★★★★★★☆  | ★★★            |

✦✦Informations on this factor largely addressed and detailed; ★Informations on this factor slightly addressed; Factor not accounted.
of a dynamic where elements interact so as to negatively affect other elements, living organisms and compositions of the surrounding environment. That is the reason EM systems came into existence through various tools.

### 3.3. Environmental management

EM is now widely applied as part of the planning and management of human activities in order to reduce EIs as well as negative social impacts. Boiral (2005) has explained how EM today is a major preoccupation for industrial organizations. According to Boiral (2005), their legitimacy or economic survival are affected by external pressures and increasing regulatory requirements. Such organizations must now balance economic viability, social progress and environmental requirements (Labonne 1999; Zeng et al. 2010). Two frequently-used systems have been highlighted here: EIAs and environmental management systems (EMSs) in the form internal environmental policies for organizations. However, these are not quite enough in solving existing environmental problems for the following reasons: (1) high number of issues or problems (2) intertwined or interlinked factors, and (3) processes according to Mermet et al. (2005) that negatively affect or destroy ecosystems are still ongoing.

### 4. Introduction to dynamic systems and simulation

#### 4.1. Modeling and simulation

Apart from the fact that a model is a representation for an individual or element as an ideal, an example or a reference, there are several definitions with respect to lexicographical references. In an epistemological context or reference however, Birou (1966) defines a model as ‘a physical or mathematical system, or rationalization representing essential structures of a reality’ and the fact of being able to dynamically reproduce and explain its functional aspects constitutes the modeling of phenomena or interactions within the system. But, Giraud et al. (1971) define modeling as ‘a process by which is established the model of a complex system to facilitate study of the system and to measure the effects of variations with respect to integrated elements.’ Then dynamic reproduction constitutes the confounding boundary between modeling and simulation but, in this paper, the concept of ‘modeling’ is equated with ‘simulation’.

According to Centeno (1996), simulation is more like an iterative process in which a model is designed, one or more scenarios are defined, temporal-space components are defined from zero time to infinity, results are analyzed, several experiments are performed, and so on. Such modeling considers the work environment and can apply for a variety of industrial environments. Within expected logical and efficient syncing, with the organization of all mining operations being essential to production, such modeling requires interaction aspects between all elements of the system. This is because of these interactions and the number of elements involved (natural, technical, economic and social) that such a system, according to Sterman (2000) and Bérard (2009), is considered dynamic and complex. For example below, the Figure 2 illustrates a general model simulation of an OPM.
4.2. Dynamic systems

According to Rosnay (1975), a system is a set of dynamically interactive elements organized to achieve a goal. The degree of complexity, the organization of relations between elements, the whole that all system components represent, and the interactions between elements are the properties of such a dynamic system (Poussin 1987). Thus, the mining industry is a complex and dynamic system subject to changes where all components are in a perpetually interactive state or configuration with respect to each other. However such related complex issues of mines will not be discussed here. Csavina et al. (2011) recommended futures studies to better integrate modeling to predict environmental health risks associated with mining operations. So, DS could be a solution for more effective management of ERs in mining industry? The Figure 3 achieved by DS software represents a simple sequence of production of an ore to show the possibility.

5. Results

5.1. Challenges in MEM

There are numerous challenges varying in complexity often specific to each environment and method of extraction namely in industrial, independent/artisanal and semi-industrial mines. However in this research, only some of the general challenges of EM related to OPMs
Table 3. Environmental challenges and issues covered by selected authors.

| Issues and challenges of MEM | Authors, publication year |
|-----------------------------|---------------------------|
| Soil degradation            | Butaré and Keita (2010), Dato and Filifi (2008), Edwards et al. (2013), Keita (2001), and Lagnika (2004) |
| Noise and vibrations        | Cloete et al. (2012), Lagnika (2004), Qing-gui et al. (2012), and Samimi Namin et al. (2011) |
| Particles emissions (dust or contaminants) | Donkor et al. (2005), González-Carrasco et al. (2011), Meech et al. (1998), and Oyarzun et al. (2009) |
| Water pollution and waste water management | Csavina et al. (2011), Gratzfeld (2004); Hall (2013), Mballo (2012), Mirchi et al. (2012), Mousavi et al. (2011), Prikryl et al. (1999), Ravengai et al. (2005), and Skousen and Vance (2003) |
| Safety                      | Samimi Namin et al. (2011) and Lagnika (2004) |
| Changes in flora and topography | Samimi Namin et al. (2011) and Genivar (2008) |

are presented in Table 3. These are: soil degradation, noise, vibrations, particle emissions (dust or contaminants), safety, waste management (various forms), water pollution and changes in flora and topography.

Among these works, there have been attempts at utilizing DS and loop diagrams with the objective of resolving certain issues such as wastewater management (Prikryl et al. 1999) or safety (Li et al. 2013). However, these attempts remain isolated solutions amongst all environmental issues to resolve.

5.2. Current EM tools and systems

Section 3.4 covered a few of the EM systems commonly used in the mining industry. However, they are not the only tools or systems considered in this industry. Referring to covered publications from 1999 to 2014, five dominant systems and tools are generally used by managers: (1) EIAs; (2) EMSs; (3) life cycle assessments (LCAs); (4) environmental technical reports (ETNs); and, (5) environmental accounting (EA).

5.2.1. Environmental impact assessments

Defined as the study of the management of an activity (at the project stage) that can potentially affect the surrounding environment, it facilitates decision-making on project feasibility. It also serves as a set of guidelines for project planning for approved projects.

5.2.2. Environmental management systems

It is an internal control system for operations specific to the environment. It consists of internal EM policies regularly applied to activities and reinforced by effective communications on the risks to the public, stakeholders and employees at all levels with an objective of continuous improvement. Within most mining companies, EMSs are often used in addition to EIAs completed beforehand in order to demonstrate the use of green practices (Evangelinos et al. 2014).

5.2.3. Environmental technical reports

These technical reports vary according to publication context. Among them are mandatory publications, corporate discretionary and non-discretionary publications required for obtaining certain certifications or for other legal or contractual purposes. According to Sinding (1999), these publications do not always link to the environmental, social and economic aspects to
address or solve, but more often contain content on compliance level or performance with respect to the management of social and economic aspects. Over time, this system adds a significant volume of publications with costs that are also significant to previous systems and tools.

5.2.4. Life cycle assessments
Assessments of impacts generated at various stages by the production of ore from its extraction stage to its procurement. Risk identification occurs from all impact zones (including input products, equipment used, etc.), with an evaluation and report on mitigation measures at each stage of production. The particular aspect of this system is that the data obtained increases with the complexity of the final product, and analyses are carried out individually for each finished product for every organization. Results are compiled in documents intended for stakeholders and increase the volume of publications within these organizations.

5.2.5. Environmental accounting
Refers to the identification of risks that are further described through cost analyses of incurred Ers. In addition to focusing on the satisfaction of stakeholders, absolute measurements of contaminant emissions and their financial impacts greatly affect decisions. With financial aspects being essential to the viability of mining companies, this system is consequently often used.

Evangelinos et al. (2014) identified 15 systems and tools available to mining industry managers, in addition to a conclusive ‘eco-conscience’. Numerous EM techniques may be available, but aside from the fact that they can be used to implement EM policies and eliminate or reduce Ers, they have helped increase awareness of the significance of Ers that each management system or tool addresses. However they do not bring about sufficient global solutions related to the three aspects to consider. Since Rist’s 1961 publication, a new management technique using DS has gradually emerged. Used mostly in scientific applications and management, the technique goes beyond a graphical representation to identify interactions, problems and provide solutions through visual databases.

### Table 4. Simulation software used in the mining industry from 1961 to 2005.

| Software                  | 1961 | 1961–1970 | 1970–2005 | 2005 and + |
|---------------------------|------|-----------|-----------|------------|
| SPS                       |      | ✔         | ✔         |            |
| SNOBOL                    |      | ✔         | ✔         |            |
| GPSS                      |      | ✔         | ✔         |            |
| GASp                      |      | ✔         | ✔         |            |
| SIMSCRIPT                 |      | ✔         | ✔         |            |
| SIMULA                    |      | ✔         | ✔         |            |
| ARENA                     |      | ✔         | ✔         |            |
| SIMSCRIPT II (MODSIM)     |      | ✔         | ✔         |            |
| SLAM                      |      | ✔         | ✔         |            |
| SIMPLE + extend           |      | ✔         | ✔         |            |
| PROMODEL                  |      | ✔         | ✔         |            |
| POSES ++                  |      | ✔         | ✔         |            |
| AUTOMODELSIM              |      | ✔         | ✔         |            |
| GPSS/H                    |      | ✔         | ✔         |            |
| MATLAB                    |      | ✔         | ✔         |            |
| AUTOMOD                   |      | ✔         | ✔         |            |

The significance of the indicators ‘♦’ is to confirm the presence of simulation software in years between 1961 to now.
5.3. History of mining dynamic systems and completed research

According to Sturgul (2001), DS is one of the most widely used techniques in management science since its first use in the mining sector in 1961. It has consequently evolved and has been used in other areas and to solve different problems. Focusing on its use today in mining and OPMs, this work outlines the exponential increase in software used for digital simulations. Table 4 lists sixteen software applications, including the now archived Symbolic programming system language (SPS) (Rist 1961) which was the first application used for digital simulation. Automod and GPSS/H are among the most widely used simulation applications, with Vensim gradually gaining in popularity in the mining industry since its introduction in 2013 (Sturgul 1997; Yuriy 2005; Li et al. 2013).

Publications on DS and risk management approaches for the mining industry highlight several specific objectives and research areas. Most of them are focused on: (1) the control of geological uncertainties in the aim of maximizing mineral production or profits; (2) the interrelated multiple sequential mining operations; (3) production scheduling; and, (4) lowest possible cost of the ore exploitation. Such objectives have favored the operations in the following research areas: (1) production optimization (Ramazan & Dimitrakopoulos 2007; Dimitrakopoulos & Ramazan 2008; Osanloo et al. 2008); (2) optimization using dynamic geometric representations (Huang & Espley 2005; Askari-Nasab et al. 2007; Duncan & Rahman 2013; Xiao-ping et al. 2015); (3) decision-making and risk management aids (Huang & Espley 2005; Mirchi et al. 2012; Araz 2013; Li et al. 2013); and, (4) dynamic modeling integrating economic analyses (Turner 1999; Ghoddusi 2010; Montiel & Dimitrakopoulos 2015). Allowing for the observation of their contributions in part and related to key applications such as: (1) modeling of operations; (2) decision-making and multi-criterion aids; (3) risk or problem solving and identification; (4) DS of mining processes; (5) dynamic modeling for the creation of mines or pits; (6) modeling for mining scheduling with geographical data; and (7) production with profitability optimization in Figure 4. Then, simulation based on stochastic calculations in combination with artificial intelligence seem to provide powerful tools but limited against the type of ore, the environment, the random field of production planning and dynamic processes in open pit mines.

As shown in Table 5 in the shaded gray column, no research has been done on the use of DS on these mining processes since 1961. However, these research results show...
opportunities for improvement of existing EM systems and tools if they are associated with DS systems.

6. Discussion and future direction

With the objective of proposing an EM approach through digital technology, this article examines the results from partial practical implementations and literary reviews. Sections 5.1 and 5.2 pertaining to mining industry Els describe the challenges the industry faces and the management systems and tools available for EM in the last decades. To further understand existing MEM challenges, this research has shown EFs linked to OPMs, and the resulting ERs from production processes. Consequently, ER management is of great importance during OPM operations. Works of Morteza and Mahdi (2014) on mine design considering sustainability aspects as well as research done by Pokhrel and Dubey (2013) or Prikryl et al. (1999) on ERs resulting from mining practices further demonstrate the urgency to reduce these risks during mining operations. Results here have shown that the five most frequently used EM systems and tools (from 1999 to 2014) help in the management and reduction of certain impacts affecting ecological and social structures. For example, an EIA lists all possible impacts according to operation type and specifics on surrounding environment while EMSs specify only certain risks identified during operations while considering EIA results as well. EA is a relevant system, but does not always reflect the level of activity at production sites. Yet from the perspective of reinforcing environmental protection practices and legislation, the mining industry has an obligation to promote continuous observation of environmental, social and economic components which must generate fewer and fewer risks over time. This analysis thus helps to better redefine their respective purposes and applications. By observing on one hand such challenges with the technical aspects of production, this article helps in reinforcing not only the importance of EM systems and tools, but also the need to update such systems and tools for continuous improvement. On the other hand, the literature effectively shows the profound awareness on the problems. For example, they have a lack of linking to all technical aspects, which nevertheless unfailingly support operations of the mining industry. This raises a fundamental question about the effectiveness of these systems and tools and the consistency of their roles in environmental protection. In addition, the proliferation of tools, EM practices since 1992 and the volume of publications required has made their use difficult and cumbersome for managers which has encouraged actions such as the integration of management systems supported by several authors (Zeng et al. 2007; Almeida et al. 2014). So, it is within this state of affairs of resolving certain critical issues on wastewater management, safety and production performance (financial analyses and production optimization), where impacts are significant (for sustainability) which prompted the mining industry to use other systems and tools. Among these tools is the progressive presence of DS following its proven effectiveness in solving several problems in many areas such as economics, health and safety.

Results from the review of: DS history in the mining industry, evolution of simulation software and publications or scientific contributions as shown in Figure 4 and Table 4, were provided for the progressive use of this new tool. After compiling a list of sixteen software applications used since 1961, with fifteen still used today in the mining industry, it was evident that DS is gradually becoming the tool of choice for mining engineers. This interest is characterized by organizational profitability needs or requirements of managers or
Table 5. Summary of DS research areas covered in the literature.

| Data base          | Peer-reviewed scientific papers                                | Modeling of operations | Decision-making aids for multi-criterion conditions | Conceptualization and solving problems/risks | DS of mining processes | Dynamic modeling for the design of mines or pits | Modeling for mining scheduling and GIS/geomatic data | Production and profitability optimization |
|--------------------|-----------------------------------------------------------------|------------------------|----------------------------------------------------|------------------------------------------|-----------------------|------------------------------------------------|------------------------------------------------|-----------------------------------------------|
| Inspec & Compendex | Série de publication de «Australasian Institute of Mining and Metallurgy» |                        |                                                    |                                          |                       |                                            |                                               |                                                |
|                    | SGEM 2013 Conference Proceedings                               |                        |                                                    |                                          |                       |                                            |                                               |                                                |
|                    | Technical TMS Annual Meeting                                  |                        |                                                    |                                          |                       |                                            |                                               |                                                |
| Scientific.net     | Applied mechanical & materials                                |                        |                                                    |                                          |                       |                                            |                                               |                                                |
| Springer           | Mining technology (Institute of Materials, Minerals and Mining) |                        |                                                    |                                          |                       |                                            |                                               |                                                |
|                    | Proceedings of 4th International Asia Conference on Industrial Engineering and Management Innovation |                        |                                                    |                                          |                       |                                            |                                               |                                                |
| Taylor & Francis   | International Journal of Mining, Reclamation and Environment  |                        |                                                    |                                          |                       |                                            |                                               |                                                |
|                    | Journal of the Chinese Institute of Engineers                 |                        |                                                    |                                          |                       |                                            |                                               |                                                |
|                    | Journal of Systems Science and Systems Engineering            |                        |                                                    |                                          |                       |                                            |                                               |                                                |
|                    | First International Symposium on Mine Simulation               |                        |                                                    |                                          |                       |                                            |                                               |                                                |
| IEEE Xplore        | Proceedings of the 2012 Winter Simulation Conference (WSC)    |                        |                                                    |                                          |                       |                                            |                                               |                                                |
| Hindawi            | Discrete Dynamics in Nature and Society                       |                        |                                                    |                                          |                       |                                            |                                               |                                                |
| Wiley & Son        | Environmetrics                                                  |                        |                                                    |                                          |                       |                                            |                                               |                                                |
| Google Scholar     | Scottish Journal of Political Economy                          |                        |                                                    |                                          |                       |                                            |                                               |                                                |

The significance of the indicators ‘◊’ is to confirm the presence of dynamic simulation (DS) research specific areas in each peer review papers.
investors. About 40% of the covered publications center on: (1) financial profitability through meeting of performance targets or optimization techniques and (2) decision-making aids (multi-criterion) required by managers due to the multidisciplinary nature of the mining sector. However, there are still some simulation software applications such as Vensim by Yu et al. (2003), which remain unknown within the mining industry. A dominant amount of information concerning DS within the mining industry for multiple areas is found within the literature. Aiding in research for a variety of publications on decision-making, modeling of operations, mine pit design and risk resolution rarely linked with the environment and mining industry planning. Moreover content on DS used in general operations of OPMs was not found, however works of Bouloiz et al. (2013) provide an overview of DS for an organization and its related environment. The benefits are numerous, including: (1) monitoring of all system components, (2) aid in decision-making, (3) detailed analysis of influencing factors (IFs) as well as interactions and implementation of best practices. Important elements known to be also unavoidable key factors aspects for EMs systems. Such a management system includes the planning of activities according to established environmental policies and implementation while regularly monitoring the effectiveness and results of actions. Following that train of thought, DS can serve as a basic platform beneficial to a mining company’s EM system needing further development. This approach is supported by a publication from Yu et al. (2003) who used the Vensim simulation software to develop a dynamic model on the sustainable use of land resources. Upon completion of their work, in addition to having identified the potential interactions in the system, determined the variables or indicators for aids in decision-making, the simulation helped in identifying the relevant components for the sustainable management of land resources. It adds up to the possibility of being able to use DS as a complementary system to existing EM systems and tools. DS, unlike other existing systems and tools, is more comprehensive because it not only considers the issues, but also all connected and interacting elements and thus serves as a multidisciplinary toolbox also used for multi-division collaborations. This system also allows for real-time risk management through its interfaces and consequently in a reduction of reports to write.

Following related analyses and the results of Yu et al. (2003), a single-sequence representation of an OPM extraction process was completed through Vensim in a loop diagram to confirm theory. The diagram showed that the extraction process has negative impacts on the environment but is nonetheless conditioned by an extraction rate regulating the production of minerals. Thus, the elements of a system may be further broken down in order to reveal IFs, interactions between elements, illustrated processes, and to perform detailed analyses.

7. Conclusion

Far from being a comprehensive exercise, the main objective of this article is to provide a representative overview of the latest research in the application of DS within the mining industry. This article has presented and exposed the reasons of the MEM with the existing advantages and the weaknesses of the approaches of management tools for this business sector of intense activity. Moreover, DS was identified following literature review as a management tool increasingly used in other areas, which may also contribute to the EM field. Yet, there are already several management systems and tools in a variety of industries to
address environmental problems, however with remaining challenges with respect to their implementation and resolutions for environmental issues to date.

The majority of scientists focused on production optimization through pit design or dynamic geometric representations, decision-making aids, employees or population safety and particularly on financial aspects. And their management application within industries including mining has been useful. DS can certainly support EM, which requires more appropriate tools in line with continuous improvement. Not to be ignored moreover is the absence of dynamic models in mine operation representations within specific environments and in MEM following this study.

Considering research results, the following must also be considered:

1. All environmental issues related to the mining industry must be identified, documented and updated.
2. Coordinated extraction and production processes would include integrated EM that takes into account all mining operations, links to operations, interactions between internal or external factors, and stakeholders.

An in-depth study on this proposed approach would be welcomed to confirm hypotheses and develop new or more appropriate EM tools adapted to OPMs. The mine configuration may be an OPM or underground mine, but although seeming vastly different, similarities emerge when considering individual components.

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ORCID

S. B. Mondoukpè Lagnika http://orcid.org/0000-0001-7306-1363

References

Agbo SJA, Honkpehedji RN. 2009. Analyse des déterminants de la production des cultures vivrières au Bénin: cas du maïs et de l’igname [Mémoire. En ligne] [Analysis of the determinants of food crop production in Benin: case of maize and yam [Memory Online]]. Abomey-Calavi: Université Abomey-Calavi (UAC); p. 75.

Almeida J, Domingues P, Sampaio P. 2014. Different perspectives on management systems integration. Total Qual Manage Bus Excellence 25:338–351.

Araz OM. 2013. Integrating complex system dynamics of pandemic influenza with a multi-criteria decision making model for evaluating public health strategies. J Syst Sci Syst Eng. 22:319–339.

Armstrong J, Menon R. 2000. Les mines et les carrières [Mines and quarries]. In: Organization IL, editor. Encyclopédie de sécurité et de santé au travail [Encyclopedia of Safety and health at work]. 3e édition ed. Genève: International Labour Organization; p. 74.1–74.61.

Askari-Nasab H, Frimpong S, Szymanski J. 2007. Modelling open pit dynamics using discrete simulation. Int J Min Reclam Environ. 21:35–49.

BAPE. 2013. Projet d’ouverture et d’exploitation d’une mine d’apatite à Sept-Îles [Project to open and operate an apatite mine in Sept-Îles]. Québec: Office of public hearings on the environment (BAPE). Rapport 301 du BAPE [Report 301 of BAPE]. En ligne.

Bérard C. 2009. Le processus de décision dans les systèmes complexes: une analyse d’une intervention systémique [The decision-making process in complex systems: an analysis of a systemic intervention] [Doctorat en administration, Thèse]. Montréal: University of Quebec in Montreal (UQAM).
Bhatasara S. 2013. Black granite mining and the implications for the development of sustainability in Zimbabwe: the case of Mutoko communities. Environ Dev Sustainable J. 15:1527–1541.

Birou A. 1966. Vocabulaire pratiques des sciences sociales [Vocabulary of the social sciences]. Paris: Édition les ouvriers [Publishing the workers].

Boiral O. 2005. Compte rendu d’un ouvrage recensé [Proceedings of a book reviewed]. Relations industrielles [Ind Relat]. 60:392–394.

Bouloiz H, Garbolino E, Tkiouat M. 2013. Modeling of an organizational environment by system dynamics and fuzzy logic. Open J Saf Sci Technol. 3:96–104.

Butare I, Keita S. 2010. Environmental aspects related to the development of the mining sector in west Africa. Dakar: International Development Research Center (IDRC).

Canada. 2000. Suppliers of mining goods and services in Canada: link between Canadian mining company and selected sectors of Canadian economy. Ressources Naturelles Canada.

Centeno MA. 1996. An introduction to simulation modeling. In: Charnes JM, Morrice DJ, Brunner DT, Swain JJ, editors. WSC ’96 Proceedings of the 28th conference on Winter simulation; 8–11(12), 1996. Coronado, CA: SCS International; p. 15–22.

Cloete S, Zupanc C, Burgess-Limerick R, Wallis G. 2012. Steering performance and dynamic complexity in a simulated underground mining vehicle. In: Wile C, editor. Proceedings of the human factors and ergonomics society annual meeting 2012. Boston: Sage publications; 22–26 October 2012.

Csavina J, Landázuri A, Wonaschütz A, Rine K, Rheinheimer P, Barbaris B, Conant W, Eduardo Sáez A, Betterton E. 2011. Metal and metalloid contaminants in atmospheric aerosols from mining operations. Water Air Soil Pollut. 221:145–157.

Dato P, Flifli V. 2008. Policy for the sustainable management of non-renewable natural resources in Benin: the case of gravel mining in the commune of Dogbo [Research memory]. Abomey-Calavi: University of Abomey-Calavi (UAC).

Dhillon BS. 2009. Mining equipment safety: a review, analysis methods and improvement strategies. Int J Min Reclam Environ. 23:168–179.

Dimitrakopoulos R, Ramazan S. 2008. Stochastic integer programming for optimising long term production schedules of open pit mines: methods, application and value of stochastic solutions. Min Technol. 117:155–160.

Donkor A, Bonzongo J-C, Narrey V, Adotey D. 2005. Heavy metals in sediments of the gold mining impacted Pra River Basin, Ghana, West Africa. Soil Sediment Contam Int J. 14:479–503.

Donoghue AM. 2004. Occupational health hazards in mining: an overview. Occup Med. 54:283–289.

Duncan EE, Rahman AA. 2013. 3D GIS for mine development – integrated concepts. Int J Min Reclam Environ. 29:3–18.

Edwards DP, Sloan S, Weng L, Dirks P, Sayer J, Laurence WF. 2013. Mining and the African Environment. Conserv Let, Pol Persp. 7:302–311.

ELAW. 2010. Guide pour l’valuation des EIE de projets miniers [Guidelines for EIA evaluation of mining projects]. Eugene, OR: Environmental Law Alliance Worldwide (ELAW).

Environmental Compliance. 2003. Prevention better than cure [mining industry]. Mater World. 11:29–30.

Evangelinos KI, Allan S, Jones K, Nikolau IE. 2014. Environmental management practices and engineering science: a review and typology for future research. Integr Environ Assess Manage. 10:153–162.

Fleurisson J-A, Grenon M. 2014. Conception géomécanique de talus de mines à ciel ouvert. Conception géomécanique de talus de mines à ciel ouvert [Geomechanical design of open-pit embankments – Geomechanical design of open pit embankments]. Hal 65–84.

Gendron C. 2004. La gestion environnementale et la norme ISO 14001 [Environmental management and the ISO 14001 standard]. Presses de l’Université de Montréal.

Genivar. 2008. Projet minier Canadian Malartic: Étude d’impact sur l’environnement (EIE) [Canadian Malartic Mining Project: Environmental Impact Statement (EIS)]. Malartic: Genivar. Rapport principal. En ligne No. AA106790.

Gervais D, Roy C, Thibault A, Pednault C, Doucet D. 2014. Technical report on the mineral resource and mineral reserve estimates for the Canadian malartic property (compliant with National Instrument 43-101 and Form 43-101F1). Malartic: Iamgold, Yamana Gold. Technical report.

Ghoddusi H. 2010. Dynamic investment in extraction capacity of exhaustible resources. Scottish J Political Econ. 57:359–373.
Giraud J, Pamart P, Riverain J. 1971. Les mots «dans le vent» [The words “in the wind”]. Paris: Larousse.

Godrej SJ, Forbes N. 2012. Report of the working group on “Effectively Integrating Industrial Growth and Environment Sustainability”. Twelfth Five Year Plan (2012–2017). New Delhi: Planning Commission. En ligne.

González-Carrasco V, Velasquez-Lopez P, Olivero-Verbel J, Pájaro-Castro N. 2011. Air mercury contamination in the gold mining town of portovelo, ecuador. Bull Environ Contam Toxicol. 87:250–253.

Gratzfeld J. 2004. Industries extractives dans les zones arides et semi-arides: planification et gestion de l'environnement [Extractive industries in arid and semi-arid Areas: Planning and management of the environment]. Gland: IUCN.

Hall EP. 2013. Pollution from mine drainage. In: Pfafflin JR, Ziegler EN, editors. Encyclopedia of environmental science and engineering. Boca Raton (FL): CRC Press Inc.

Hines J, Malone T, Goncalves P, Herman G, Quimby J, Murphy-Hoye M, Rice J, Patten J, Ishii H. 2011. Construction by replacement: a new approach to simulation modeling. Syst Dyn Rev. 27:64–90.

Huang Y, Espley S. 2005. A 3D mine simulation model for decision-making in mine design and production. Int J Surf Min Reclam Environ. 19:251–259.

Huisman L, Wood WE. 1974. Slow sand filtration. Genève: World Health Organization: WHO. Report.

Kambani SM. 2003. Small-scale mining and cleaner production issues in Zambia. J Cleaner Prod. 11:141–146.

Keita S. 2001. Study on artisans mines and small scale mining in Mali. London, UK: IED and WBCSD. Report No. 80.

Kříbeka B, De Vivob B, Davies T. 2014. Special issue: impacts of mining and mineral processing on the environment and human health in Africa. J Geochem Explor. 144:387–390.

Labonne B. 1999. The mining industry and the community: joining forces for sustainable social development. Nat Resour Forum. 23:315–322.

Lagnika SB. 2004. Contribution à l’élaboration d’une base de données informatisées pour l’analyse et la gestion environnementale des exploitations minières au Bénin [Mémoire de fin de formation de 1er cycle] [Contribution to the development of a computerized database for the analysis and environmental management of mining operations in Benin]. Abomey-Calavi: Abomey Calavi Polytechnic School; p. 112.

Lagnika SBM. 2009. La gestion des risques environnementaux au sein des entreprises immobilières [Mémoire] [Environmental management risks in real estate companies]. Montréal: University of Quebec in Montreal; p. 131.

Li X-G, Song X-F, Li X-C. 2013. System dynamics modeling in coal mine safety. In: Qi E, Shen J, Dou R, editors. Proceedings of 2013 4th International Asia Conference on Industrial Engineering and Management Innovation (IEMI2013); Taipei: National Taiwan University, Springer; p. 823–833.

MAC. 2010. A report on the state of the Canadian mining industry: Facts + Figures 2010 [A report on the state of the Canadian mining industry: Facts + Figures 2010]. Ottawa: Mining Association of Canada.

Meech J, Veiga M, Tromans D. 1998. Reactivity of mercury from gold mining activities in darkwater ecosystems. Ambio, J Hum Environ. 27:92–98.

Mbollo B. 2012. Impacts possibles des activités minières sur les ressources en eau en Afrique de l’ouest: cas des mines aurifères du Burkina Faso [Mémoire] [Possible impacts of mining activities on water resources in west Africa: Case of the gold mines of Burkina Faso]. Ouagadougou: International Institute of Engineering, Water and Environment (2IE); p. 74.

Mermet L, Billé R, Leroy M, Naryc J-B, Lice X. 2005. L’analyse stratégique de la gestion environnementale: un cadre théorique pour penser l’efficacité en matière d’environnement [Strategic analysis of environmental management: A theoretical framework for thinking about environmental effectiveness]. Nat Sci Soc. 13:127–137.

Mirdiri A, Madani K, Watkins Jr. D, Ahmad S. 2012. Synthesis of system dynamics tools for holistic conceptualization of water resources problems. Water Resour Manage. 26:2421–2442.

Montiel L, Dimitrakopoulos R. 2015. Optimizing mining complexes with multiple processing and transportation alternatives: an uncertainty-based approach. Eur J Oper Res. 247:166–178.

Morteza O, Mahdi R. 2014. Mine design selection considering sustainable development. In: Drebenstedt C, Singhal R, editors. Mine planning and equipment selection. Springer International Publishing; p. 151–163.
Mousavi A, Chavez RD, Ali A-MS, Cabaniss SE. 2011. Mercury in natural waters: a mini-review. Environmental Forensics. 12:14–18.

Müezzinog‘lu A. 2003. A review of environmental considerations on gold mining and production. Criti Rev Environ Sci Technol. 33:45–71.

Nadeau S, Badri A, Wells R, Neumann P, Kenny G, Morrison D. 2013. Sustainable canadian mining: occupational health and safety challenges. In: Carswell C. Melody, editor. Proceedings of the Human Factors and Ergonomics Society 57th Annual Meeting; 2013 Sep 30 –Oct 4; San Diego (CA): Sage; p. 1071–1074.

NIOSH. 2011. Underground surface mining facts – 2008. Pittsburgh, PA: Mine Safety and Health Administration (MSHA). Statistique Report.

NMA. 2010. The economic contributions of U.S. mining in 2008. Washington (DC): National Mining Association. Report.

Odell CJ. 2004. Integration of sustainability into the mine design process [Thesis]. Vancouver: University of British Columbia; p. 279.

ILO. 2010. Risques émergents et nouvelles formes de prévention dans un monde du travail en mutation [Emerging risks and new forms of prevention in a changing world of work]. Genève: International Labor Office (ILO).

Osanloo M, Gholamnejad J, Karimi B. 2008. Long-term open pit mine production planning: a review of models and algorithms. Int J Min Reclam Environ. 22:3–35.

Oyarzun R, Cubas P, Higuera P, Lillo J, Llanos W. 2009. Environmental assessment of the arsenic-rich, Rodalquilar gold–(copper–lead–zinc) mining district, SE Spain: data from soils and vegetation. Environ Geol. 58:761–777.

Panov Z, Ristova E, Stefanovska L. 2011. Environmental strategies in the mining: the importance of development and implementation national environmental strategy for waste treatment. Paper presented at 11th International Multidisciplinary Scientific GeoConference SGEM2011. Albena, Bulgaria.

Paruchuri Y, Siuniak A, Johnson N, Levin E, Mitchell K, Goodrich JM, Renne EP, Basu N. 2010. Occupational and environmental mercury exposure among small-scale gold miners in the Talensi, Nabdam District of Ghana’s Upper East region. Sci Total Environ. 408:6079–6085.

Pokhrel LR, Dubey B. 2013. Global scenarios of metal mining, environmental repercussions, public policies, and sustainability: a review. Crit Rev Environ Sci Technol. 43:2352–2388.

Poussin JC. 1987. Notion de système et de modèle [Concept of system and model]. Note. Cah Sci Hum. 23:439–441.

Prikryl P, Cerny R, Havlik V, Segeth K, Stupka P, Toman J. 1999. Deposition of waste water into deep mines. Environmetrics. 10:457–466.

Qing-gui C, Ye-jiao L, Qi-hua S, Jian Z. 2012. Risk management and workers’ safety behavior control in coal mine. Safety Science (Special Issue on the first international symposium on mine safety science and engineering). 50:909–913.

Radosavljević S, Radosavljević M. 2009. Risk assessment in mining industry: apply management. Serb J Manage. 4:91–104.

Ravengai S, Love D, Mabvira-Meck M, Musiwa K, Moyce W. 2005. Water quality in an abandoned gold mining belt, Beatrice, Sanyati Valley, Zimbabwe. Physics and Chemistry of the Earth. 30:826–831.

Ramani RV. 1995. Mining disasters caused and controlled by mankind: the case for coal mining and other minerals. Nat Resour Forum. 19:233–242.

Ramazan S, Dimitrakopoulos R. 2007. Stochastic optimisation of long-term production scheduling for open pit mines with a new integer programming formulation. Orebody modelling and strategic mine planning, uncertainty and risk management models. 2nd ed. Perth (WA): Australasian Institute of Mining and Metallurgy Publication Series; p. 385–391.

Redwood SD. 2013. Technical report of the San Matias project technical report Cordoba Minerals Corp. Córdoba: Cordoba Minerals Corp. Technical Report. En ligne.

Rist K. 1961. The Solution of a transportation problem by use of a Monte Carlo technique. Mining World; p. 1–15.

Rosnay J. 1975. Le macroscope: vers une vision globale [The macroscope – Towards a global vision]. Persée. 32(6):1319.
Samimi Namin F, Shahriar K, Bascetin A. 2011. Environmental impact assessment of mining activities. A new approach for mining methods selection. Gospod Surowcami Miner. 27:113–143.
Sinding K. 1999. Environmental impact assessment and management in the mining industry. Nat Resour Forum. 23:57–63.
Skousen JG, Vance GF. 2003. Surface water pollution by surface mines. In: Stewart BA, Howell T, editors. Encyclopedia of Water Science (Print). New York, NY: CRC Press; p. 956–960.
Sterman JD. 2000. Business dynamics: systems thinking and modeling for a complex world. Columbus (OH): Irwin-Mcgraw-Hill Higher Education.
Sturgul J. 1997. History of discrete mine simulation. In: Panagiotou GN, Sturgul JR, editors. First International Symposium on Mine Simulation (MINESIM ’96); 05. 1997; Rotterdam: Balkema Publishing Company; p. 27.
Sturgul JR. 2001. Modeling and simulation in mining – its time has finally arrived. Simulation. 76:286–288.
Turner RJ. 1999. Simulation in the mining industry of South Africa. Int J Surf Min Reclam Environ. 13:47–56.
Xiao-ping B, Yu-hong Z, Ya-nan L. 2015. A novel approach to study real-time dynamic optimization analysis and simulation of complex mine logistics transportation hybrid system with belt and surge links. Discrete Dyn Nat Soc:8.
Yu CH, Chen CH, Lin CF, Liaw SL. 2003. Development of a system dynamics model for sustainable land use management. J Chin Inst Eng. 26:607–618.
Yuriy GM. 2005. Discrete-event simulation of mine equipment systems combined with a reliability assessment model. Sudbury: Laurentian University/Université Laurentienne; p. 93.
Zeng SX, Shi JJ, Lou GX. 2007. A synergetic model for implementing an integrated management system: an empirical study in China. J Cleaner Prod 15:1760-1767.
Zeng SX, Tam CM, Tam VWY. 2010. Integrating safety, environmental and quality risks for project management using a FMEA method. Econ Eng Decis. 21:44–52.