



Engineering complex systems applied to risk management in the mining industry



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ABSTRACT

Related to complexity, there is a wide diversity of concepts, ranging from “systemic” to “complex”, implying a need for a unified terminology. Per different authors, the main drivers of complexity can be found in human behaviour and uncertainty. This complexity, structural or dynamic can be organizational, technological, or nested in their relationship. ISO international standard 31000:2009 definition of risk management “coordinated activities to direct and control an organization with regard to risk”, when applied to economic sectors, industry, services, project, or activity, it requires the use of models or theories as guidelines. Therefore, as its basic elements comprehend human behaviour and/or uncertainty, risk management to be effective and adapted as much as possible to reality, must be operational within complex systems, as already demonstrated in different R&D environments. Risk management faces demanding challenges when approaching specific and endogenous needs, such as the mining sector. This paper presents a multivariable function analysis methodology approach based on complex system modelling and through real data corresponding to a risk management tool in the mining sector.

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1. Introduction

Currently risk management is perceived as a tool for any business sector. In an economy of global scale and high volatility due to uncertainty of the markets, risk management is critical for decision makers to obtain high productivity gains.

In certain industries, risk management should be given careful attention due to the potential impact of project failure on public safety or the environment, e.g. in the mining sector due to risk perception, feasibility decision making and uncertainty.

Traditional risk management systems tend to lack full response to the specific challenges of the mining industry e.g. human capital, climate changes and new technologies. In this sense, new approaches must be found to obtain an overall answer. In a technology transfer offshore wind energy project, there was evidence, that complex systems are well-adapted models for risk management.

Technical and socioeconomic complexity and organizational culture are amid the main characteristics of complex systems. In the same sense, the mining sector is in its nature complex, encompassing major hazards, socioeconomic impacts, and resource nationalism.

International Labour Organization Convention concerning Safety and Health in Mines establishes “that workers have a need for, and a right to, information, training, and genuine consultation on and participation (...) concerning the hazards and risks they face in the mining industry”.

Mining is a complex system, as it includes human, organizational, and technological issues.

In such context, risk assessment of integrated operations, can be improved by complex risk models and dynamic environments. Hence, complex systems can provide decision makers a supporting tool comprising a three axes analysis model. Each axis (X, Y and Z) comprehends a multivariable function (f_i): X: (f_1) (management variables related to mining); Y: (f_2) (risk management systems variables) and Z: (f_3) (complex systems variables). Such a proposal comprehends designing, developing, and testing a risk management decision making model within complex systems, transversal to other hazard sectors of economic activities. Validation through real data may provide organizations with sustainable and integrated risk management indicators.

2. Method

The review for the present paper is mostly based on several resource databases and scientific journals through Exlibris Metabibis. Research was conducted related to three main topics, that is,

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Table 1
Objectives of complex thought.

ID	Description
1	Understand and learn to live with uncertainty
2	Learn to deal with paradoxes and situations that cannot be solved by the binary logic
3	Provide people more thinking flexibility
4	Understand life better, nature systems and man-made systems
5	Provide people a better relation in the natural world
6	Understand the ego better and learn how to deal with it in a less self and hetero destructive mode

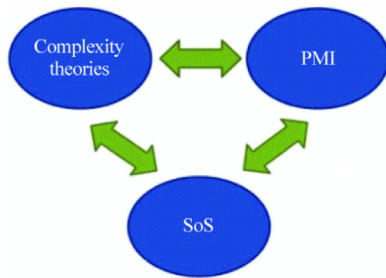


Fig. 1. Representation of the schools of complex thought [5].

risk and risk management, complex systems, and mining industry. Also, a brief understanding of the theory of complex systems through literature review on the field is presented. A systematic approach is intended with the resulting topics: complex thought, complexity as a diversity of concepts, complex systems and complex projects and risk management within complex systems. To support the presented algorithm with multi variable functions and modelling, mathematical references were also used. Published case studies and previous research works are included in the review procedure, namely the published offshore wind energy project.

3. Literature review

3.1. Complex thought

Complexity thought can be defined as “more a way of thinking about the world than a new way of working with mathematical models” [1].

Complex thought is an instrument of change and resilience and it is a method in the sense of Descartes and its main objectives are embodied in Table 1 [2].

The dimensions of the complex thought are structural complexity, uncertainty, and socio-political environment and in a dynamic, ever-changing, and multi way world, in contrast to human mental models support decisions, making processes normally tied, conservative and narrow-minded and “like organisms, social systems contain intricate networks of feedback processes, both self-reinforcing (positive) and self-correcting (negative) loops” [3,4].

Today complex thought is gathered in three schools: Complexity Theories School, Project Management Institute School, and System of Systems School [5]. The Complexity Theories School comprises complexity, adaptive self-organization, co-evolutionary, social organizational, contingency, constraints, systems, network theory, nonlinearity and chaos. The Project Management Institute (PMI) School focuses on structural complexity, uncertainty, and socio political complexity dimensions. The School of System of Systems (SoS) emphasizes autonomous and independent systems, and the problem of not being capable to control them. A diagram of such

relations is shown in Fig. 1, with different characteristics according to Table 2.

3.2. Complexity as a diversity of concepts

Complexity is far from being a simple concept or a single point of view; from the Santa Fe Institute, “systemic” designation, through the Morin’s “complex” classification, to the need of a unified terminology claimed by Mariotti, complexity overlaps multiple labels and approaches [6,7]. Complexity must be perceived as a fabric of heterogeneous inseparable associated constituents when trying to understand complex and complexity [6]. In general complexity is defined in terms of potential states in a system or the number of components and what is particularly important to identify, is the origin of complexity, its level, and its implications [4,8].

As noted in Fig. 2, the diagram shows the main impediments to learning. Arrows indicate causation.

Complexity within collaborative design includes the interaction of many participants, working on different elements of the design, such as in diverse economic activity sectors e.g. mining sector [9]. Human behaviour and uncertainty are the touchstone to complexity basic research as established by many authors.

3.3. Complex systems and projects

In physical sciences when joining or connecting many systems, the macroscopic or collective properties of the outcoming system are not generally related with the properties of their individual constituents. In this case, the resulting system is a complex system. A complex system implies software, cultural and political issues and obviously, people and organizations that are able to affect the whole or a part of a system [10].

The more complex a system is, the more controlled must the local environment be and knowing the nature and shape of complex systems in organizations can be an important tool for the managers [11,12]. Each different context, simple, complicated, complex, chaotic, requires different managerial response [1]. Such is the case in “soft” systems thinking, better adequate to fuzzy ill-defined situations when people and cultural background are concerned [13].

Organizational behaviour and individual’s emotional intelligence may support studies concerning the complex interconnection between individuals in an organization or a project team

Table 2
Characteristics of the schools of complex thought [5].

Complexity theory	PMI	SoS
Edge of chaos		Non-linear
Tiny initiating events		Autonomous systems
Contingency		Flexible
Power laws and Paretian distributions		Uniqueness
Control parameters	Difficulty	Adaptive cycles
Scale laws	Multiple stakeholders	Aren't built for the same purpose
Coarse-graining	Uncertainty	Fitness landscape
	Changing projects governance	Unclear and unfixed boundaries
	Technology newness	Fractals
	Trust	Chaotic behaviour
	Indirect communication	Share and acquisition environment
	Megaprojects	Self-organization
	Context dependence	Emergent
	Ambiguity of features	
	Capability	

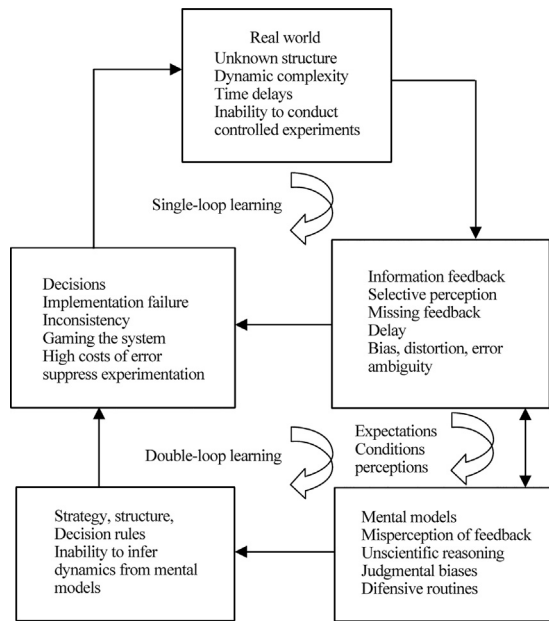


Fig. 2. Feed-back process of learning [4].

and its impact on competitiveness [14]. The cognitive systems engineering maintains that “a cognitive system is as able to control its behaviour using information about itself and the situation, where the information can be prior information (knowledge, competence) situation-specific information (feed-back, indicators) and constructs (hypotheses, assumptions)” [15]. The discussion of the complexity behaviour of a system at different scales does not explain why the systems should be simple or complex but a “profile” that quantifies the relationship between independence, interdependence and scale of collective behaviour may provide help to this response [16].

When a complex system adapts to disruptions and changing conditions, that is, what it is called resilience, also understood as an emergent property of the complex system [17]. In a context of safety management, resilience engineering provides actors with a way to deal with complexity in an environment of under pressure to achieve success through diagnostics, recognition and preparedness in safety breakdowns [18].

To understand the complex systems approach in the design and implementation phases, one must recognize the many differences between the traditional practices of engineering and the natural evolutionary process [19]. Social organizations regarded as complex in management procedures tackle social complex problems, thus finding solutions to such problems in hierarchical decision making structures; and standard planning can be considered insufficient and scarce [20].

A systemic methodology based on negotiation and argumentation to help in the resolution of complex issues and to facilitate evaluation options during design of such systems is proposed by Marashi and Davis [10]. The decision-making processes when supported in the quantification of complex areas become reinforced, because they help set priorities and direct management efforts [21].

To deal with ambiguity and interdependency, individuals seek a sense to resolve plausibly and move on, that they call moments of sense making [22]. The multiple perspectives of complex situations are supported in terms of decision by the combination of two methods: “multiple criteria decision making” and “techniques from soft systems” [23].

It was proved that the complexity of the projects is imperative to establish exceptional preventive measures [24]. To obtain a measure of the project complexity, the variables such as time, cost, and quality, and the three in combination, were studied and proved that the project complexity can have a logical and valid representation [25].

On the other hand, other researchers present the technical, organizational, and environmental framework for project complexity. In such three part framework risk is understood as a feeding-factor project complexity [26].

3.4. Risk management within complex systems

The main contribution of complexity theory to management has been demonstrating its effectiveness in planning and analysis of several organizational problems [12].

Complexity offers an interesting theoretical framework to the obligatory interdisciplinary studies of integrated safety management and risk management methods [27]. The focus of engineering is on the risk factors, the development and implementation of the measures of control, from design, construction, operation processes, systems maintenance and operation limit states, such as emergencies and starting and stop processes [28]. A common definition of risk is set of triplets, scenarios, likelihoods and consequences [29].

The traditional risk analysis is not sufficient to recognize the heterogeneity of the input criteria (wildness in wait) because it does not recognize the difference between the assumptions aimed at emerging order nor the possibility of heterogeneity of the criteria to be incorporated in such apparent order and “risk assessment (as part of Governance) should be recognized as a (social) knowledge practice” [30].

The link between uncertainties and risk management introduces a new perspective on uncertainties in projects and how to manage them. Traditional risk management assumes risk as uncertainty. The authors understand risk as one of the implications of uncertainty. They define uncertainty as “a context for risks as events having a negative impact on the project’s outcomes, or opportunities as events that have beneficial impact on project performance” [31].

Risk management needs to be thoroughly defined; such is the case in ISO international standard 31000:2009; “refers to a coordinate set of activities and methods that is used to direct an organization and to control the many risks that can affect its ability to achieve objectives”. In a similar context, an important change related to risk perception can be found in ISO international standard 9001:2015. Risk management integration approach, more than the traditional view as an aspect of quality, is now a major component of the organizational culture.

When considering the risk of change (related to social elements), from the system point of view, taken as an imbedded behaviour component, it could come up, due to the fact of its permanent interaction with its neighborhoods. According to the degree of the mentioned interaction, the safety level of the system itself can be questioned. If the processes are in a steady state, the system can thus be considered in a safety scenario. The dynamics of the change rate, lead to an approach to complexity, not a linear manner, but in a multiple levels mode [32].

In prevention domain, the most effective elements of a safety program are: the support of top management the selection of human resources (own or outsourced) and strategic management. In turn, the least effective factors are the records, accident analysis and planning of emergency [33]. The specifications in the oil refining industry highlight the need for training within the role of safety technicians about the impact of maintenance activities in this major hazard industrial process [34].

To demonstrate how risk can be managed in high risk workplaces, one way might be through the analysis of communication gaps [35].

Risk management should have a strategy-based project management approach, using life cycle objective functions, and must be developed to identify as many potential risks as possible, as the main drivers for risk reduction and value addition. This is crucial information for the identification of threats and vital elements for decision making. Systematic management of complex projects requires important information skills and decision support systems which can combine the management of “hard” and “soft” aspects, and facilitates decision evaluation on a real-time basis [36].

4. Discussion

4.1. Risk management

Risk management guidelines require the support of models and/or theories in every sector, industry, services, organization, or project. Thus, to achieve effectiveness and adaption to real workplace environment as much as possible, risk management because of its basic elements, human behaviour and/or uncertainty, must be operational within complex systems, as already inferred in different R&D environments. Risk management faces challenges when approaching specific needs, such as the mining sector: “that workers have a need for, and a right to, information, training and genuine consultation on and participation in the preparation and implementation of safety and health measures concerning the hazards and risks they face in the mining industry”, established by the International Labour Organization (ILO) Safety and Health in Mines Convention. The same ILO regulation furthermore recognizes that “it is desirable to prevent any fatalities, injuries or ill health affecting workers or members of the public, or damage to the environment arising from mining operations”. In such a sense, risk assessment of integrated operations, can be enhanced by complex risk models and dynamic environments [30].

The mining sector faces unprecedented challenges due to unexpected internal factors (lack of trained people or frequent equipment failure) and external factors (mineral commodity prices, market volatility, increasing regulations, dwindling profits and changing global demand). Inadequate risk management can lead to failure in production and sometimes serious personnel injuries in and environmental issues. Such issues can interrupt projects and even the complete loss of the business [37].

To integrate OHS into industrial project risk management is a complex challenge and the interdisciplinary of this problem must be the starting point of any research [38].

Likewise, from the point of view of emergent properties, the mining industry remains a complex system for it encounters human, organizational, and technological factors where uncertainty and human behaviour are present. Mining industry is complex due to the numerous and different operations, so that, its principal concern is safety. The performance of a health and safety management system in an organizational context is a critical and demanding topic, and studies recommend reports based on three metric categories: organizational performance, worker performance and interventions [39]. The principal environmental stressors in this field are: human intrusion in ecosystems, gas emissions, noise and dust in the air, soil disturbance and contamination, linear infrastructure, traffic and solid waste in land and water pollution. These vectors must be considered for any risk management analysis in mining industry [40].

4.2. Decision making tool

Therefore, decision makers may find in complex systems a supporting tool. In this sense, there is a range of alternative strategies or solutions in a complex system, which could lead to diverse scenarios [41]. A risk management decision making model designed, developed, and tested within complex systems, aimed at being transversal to other sectorial hazards in any economic activity, may provide sustainable and integrated risk management indicators to organizations.

Such supporting tool (complex systems) to decision making has already been used in an innovative construction project, related to offshore wind energy [24]. This prototype leads to a specific and unique case of prevention. The identification, systematization, and conception of a classification structure of complex projects, are framed in the perspective of the prevention management and to implement a system of professional risk management.

Complex systems present a demanding and highly efficient management response to an equally laborious economic activity such as the production, storage, utilization and distribution of hydrogen that sets a technological and economic challenge to decision makers in global energy market [28]. Sustainable solutions aggregate multi criteria approaches: social issues, health and safety prevention procedures environmental concerns and legal and regulatory frameworks. Thus, a complex equation is launched when designing management systems to tackle hydrogen life cycle. Some authors revealed the need for new theories to explain accidents [42].

For effective risk assessment, there is a shortage of conceptual frameworks to properly explain two of its dimensions: knowledge and surprise [43].

Safety comprises many inherent variables, both as inputs as well as outputs; thus it is complex to assess in a objective manner the impact of the inputs and output ratios [44].

Establishing a safety management system comprises mainly perfection of safety in: supervision organization, rules and regulations, investment, training, and technique, as well as cooperation bodies amid third parties (government, investors and workers) [45].

The approach of prevention and security through complex systems intends to provide a complete answer to the identification, evaluation, and control of the risks in the mining sector to achieve the goal of zero accidents.

4.3. Algorithm proposal

In this sense, an algorithm proposal is designed based upon a three-axis (X , Y , Z) analysis model that allows to predict future behaviours. Each of the three axes is a multi-variable function f_i :

X : f_1 is the mining management variables; Y : f_2 is the risk management systems variables; and Z : f_3 is the complex systems variables.

4.3.1. Vector analysis

The criteria of the vector analysis are defined based on literature review supporting data from different researchers and evidence that converges to the indicators in discussion.

The three axes supporting the algorithm proposal must accommodate the mathematical equivalent of qualitative variables from management. This may be achieved through reason scaling of the mentioned axis allowing for non-uniform range for the qualitative variables.

X : f_1 represents mining management variables is a function evaluated by the following criteria, and x_1 is the major hazard industry.

Real work context data is critical to validate the proposed mathematical algorithm into a management model.

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