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ORIGINAL RESEARCH PAPER

Towards better understanding of the complex industrial systems: Case of production systems

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ABSTRACT

Growth of the world population and the globalization of trade are the origins of the fourth industrial revolution, called "Industry 4.0". What engineers call systems are becoming more and more complex as businesses strive to stay competitive and meet ever-changing demand. While automation and information digitization and transmission technologies are increasingly becoming major assets in modern industries, the changes they bring are having an impact on the management of occupational health and safety.

The aim of this article is to provide an overview of the progress achieved in the understanding of complex systems and to test some of the published theory by comparing it to a case study. The major scientific databases were searched to retrieve the literature on complexity, and a large company in the steel products business was queried to determine how its complexity as perceived by its managerial staff compares to the theory of complex systems.

Our main conclusion is that, based on the data gathered in the case study, the perception that the managerial staff has of the company corresponds closely to the current definition of complex systems as proposed by researchers. However, it remains to be determined whether this correspondence holds over the range of business sizes.

KEYWORDS

complexity, systems, complex system, steel company, production systems

1. INTRODUCTION

World population growth and demographic shifts combined with increasing standards of living remain a major driver of technological and scientific development as needs change and new markets emerge. Modern living is becoming increasingly complex and is creating demand for ever more sophisticated systems of production and distribution of goods and services. Definitions of what constitutes a system (physical, biological, social) abound in the scientific literature. Some authors consider a system as a functional unit composed of interrelated elements, actions or individuals that interact with each other and with their environment, or as a combination of interacting elements forming a collective entity, or as a coherently organized and interconnected set of elements constituting a model or structure and producing a set of characteristic behaviors [1–3]. Interactions, more than analysis of isolated elements, are the key to true understanding of a system [4], and may be physical, informatic, and/or information-exchanging [2].

However, systems are becoming more complex not just as a response to growth and diversification of human needs but also to meet the demands of the never-ending competition for market share. Throughout history, civilization has undergone many transformations, one of the most profound being the industrial revolution, starting in the first half of the 18th century, as mechanization of certain production methods and techniques became

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feasible. Thus began the replacement of artisanal workshops by mass production in steam-powered factories. A second wave of the revolution then occurred as the wide distribution of electrical energy became practical. The third wave took place during the second half of the 20th century as automation became widespread, and digitizing electronics made possible the convergence of communications and information technologies. Today, the world faces a fourth wave, called industry 4.0, or intelligent production, in which machinery is programmed to produce not only according to specifications but also according to demand, and software monitors not only raw material and finished product inventories but also distribution, generating so-called "big data" for market strategy and management [5–9].

Systems are now so complex that a new field of study has emerged, called complexity science. Although no formal definition of a complex system has been adopted universally, most researchers agree that a system is complex when it comprises numerous interacting elements and its overall behavior includes what are called emergent components, meaning behavior that cannot be predicted from the sum of the functions of the constituent elements of the system [10]. Although such sophisticated systems can be highly efficient, the difficulty of predicting their behavior under all conditions is a drawback and can have and does have consequences for occupational health and safety (OHS).

Integration of modern digitized production systems and generalization of real-time process monitoring, control, and communications along with the resulting big data promise huge gains in productivity. All this interconnectivity will have an impact on OHS. For example, short-term reorganization of manufacturing areas involves changes in equipment configuration and movement, each potentially requiring reevaluation of workplace OHS status and hence raising the issues of worker adaptability and the assiduity with which OHS obligations are managed by companies and their employees [11].

This article describes a segment of a broader research project focused on developing an OHS performance evaluation tool better adapted to complex systems in the Industry 4.0 context. The advantages and drawbacks of the tools described in the literature have been discussed in an earlier article [12]. In order to achieve the overall objective of the project, the following question must first be answered: what is a complex system and what are its criteria that must be taken into account in the evaluation of their OHS performance? To answer this question, the article aims to provide an overview of the complexity for a better understanding of complex industrial systems. This work provides an overview of the progress made in understanding complex systems by citing previous research on this topic. Indeed, the added value of this research can be summed up in the comparison of the results drawn from the literature with those obtained following an analysis of data from a field study carried out on the production systems of a large steel company. We begin here with a detailed formal overview of the various aspects of complex systems. Some real industrial cases are included to support salient findings in this field. Our bibliographic research methodology is described in section 2 below, followed by a summary of the published literature in section 3. Our findings based on the literature and the limitations of our study are discussed in section 4. Our conclusion is provided in section 5.

2. RESEARCH METHODOLOGY

Our overall procedure is summarized in Fig. 1. The theoretical framework was derived from relevant articles retrieved using keywords to query databases. The practical perspective came from the industrial partner in this study, in the form of data gathered in the field. The third part of the study was devoted to contrasting the theory with the practice to provide validation of the former.

2.1. Bibliographic research

The publications examined for the purposes of this hybrid research methodology (literature review and case study) were obtained in two steps. The first was retrieval of published documents from the database Scopus and using the search engines Google and Google Scholar with keywords in French and English (complexité, complexity, système complexe, complex system, système sociotechnique, socio-technical system, and entreprise, but not business or company). The searched fields of text included primarily document titles, abstracts, and keyword lists. We thus screened memoirs and theses, review articles, conference proceedings, books, and reports for relevance to our topic. Grey literature was excluded. Documents were retained for consideration based on the apparent quality and the credibility of the sources.

The second step consisted of tracking down documents of interest mentioned in the documents retrieved initially, whenever such documents were mentioned more than twice. These were deemed relevant to our review of the literature and added to the list.

2.2. Gathering of field data

To provide validation for the theories expressed in the literature, we applied a methodology based on action research. The participation of the Tunisian steel company Elfouladh in the study made this approach possible, thus providing means of checking claims made in the literature about various aspects of the complexity of complex systems. It is necessary to mention that the study was made on the production systems of the partner company in order to better address the subject of complexity. Action research has been used widely to explore human social phenomena, since it allows stakeholders to become involved and to commit to promoting lasting changes [13].

Action research has been categorized in four ways, each with different emphasis [14, 15]. The first of these considers two elements: 1) balancing of research and action, 2) the type of intervention [16]. A second categorization distinguishes three action research subsets [17]. However, three

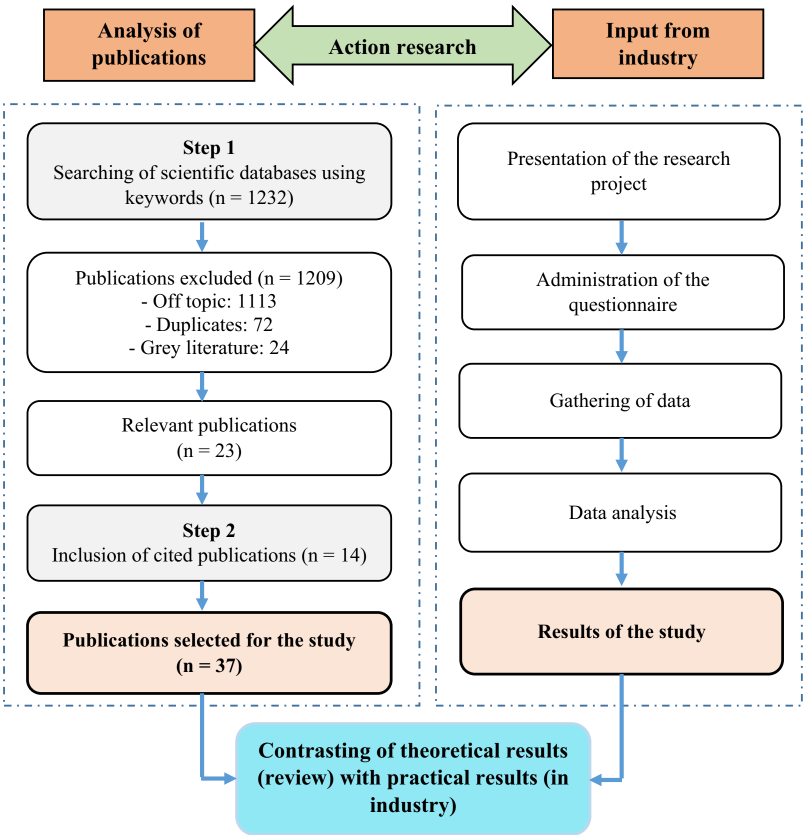

Fig. 1. Research methodology

categories had been proposed previously, based on participation [18]. These are: 1) study of the action, but without action, 2) the industrial partner presents the problem, and the researcher proposes solutions, and 3) total commitment of the partners to the search for solutions. In the fourth categorization, five types of action research are defined [19].

The action research used for the purposes of the present study is based on participation type 1 above, which involved gathering data to characterize the complexity of the industrial partner's business but without introducing and monitoring changes in company procedures or policy.

The questionnaire used as the principal means of gathering the data used to test the theories on system complexity was intended for the company managers and supervisors, these individuals being considered best suited to providing helpful answers to questions asked in a research context. To obtain a representative sampling of the targeted employee category, 60 questionnaires were administered, distributed throughout all production units in the company. After meeting with the production unit directors, we were authorized to communicate with managers and supervisors to explain the project and the importance of their voluntary participation in data gathering. In fact, the questionnaires were administered at the end of the meeting, at which point the informed consent forms were signed. Prior to our beginning the study in the workplace setting, our reference documentation received validation from the UQTR research ethics committee (approval number CER-21-278-07.10).

2.3. Contrasting of bibliographic research results with field reality

Based on the consensus found in the published literature, 10 characteristics define a company as a complex system. Support for this list of characteristics may be found in practice, as we did in our quantitative analysis of a real company in the steel products business. Each characteristic was scored in terms of a percentage of the responses to each survey question, and the overall score was used to evaluate the extent to which the company qualified as a complex system.

3. RESULTS

3.1. Theory of complex systems, based on the literature

3.1.1. What is a complex system?. According to the science of complexity, interactions between the various elements of a system give rise to complex behaviors [1, 20]. To understand the concept of a complex system, the notion of complexity itself must first be understood. Something is *complicated* if it is composed of many elements and is difficult to comprehend or perform. In contrast, *complex* means composed of different elements combined in a manner that is difficult to analyze [1]. The Latin word *complexus*, generally refers to the whole, to the number of elements that comprise the system under study, and to the number and variety of interactions between these elements [21].

Complexity is a relatively new field of study that began in the 1980s at the Santa Fe Institute of New Mexico to build an epistemology to define the interrelations, interactions and connectivity of the elements within a system and between a system and its environment [22]. The word is often used without explanation to describe concepts or contexts, and it still has no consensus definition. As a study, it is usually focused on behavior and interactions inherent in a system as whole, rather than on constituent elements [1]. Other authors treat complexity in terms of the quantity of information required to describe a system and as a function of the number of elements as well as the number and nature of the interconnections within the system [23]. Complexity is also considered as a property of any system comprising a diversity of interacting elements [24].

For the purposes of the present study, the complexity of a system refers to the number and variety of constituent elements as well as the interrelations, interactions and interconnexions between these elements.

Several definitions of a complex system are proposed in the literature, for example, “contains many components and layers of subsystems with multiple non-linear interconnections that are difficult to recognize, manage and predict” [25], or composed of numerous elements (agents) that interact with each other, with their environment and with emergent phenomena created by these interactions, the agents being of varied nature, including persons, groups of persons, components, machinery, a production unit, and so on [10, 20, 26]. An agent behaves according to rules that define the stimuli (excitation) it emits to other agents as a function of the stimuli it receives from other agents and its environment.

Another expression proposed is “mutual dependencies” of elements [27]. The behavior of a complex system is unpredictable since it emerges from the interactions of the elements [3]. The system is a set that is not decomposable to separate elements or to independent processes, because of the nature of the interactions and/or exchanges between elements. The evolution of any complex system is determined by its dynamic and non-linear interactions [28].

Despite the absence of consensus on the definition in the literature, there seems to be some agreement that a minimal requirement for system to warrant the adjective “complex” would be to consist of a plurality of elements that interact and to be characterized by feedback loops and various other dynamic and emergent behaviors.

In the literature, some authors consider that a sociotechnical system is a complex system. According to Hettinger et al. [29], a sociotechnical system is considered a complex system thanks to its emergent properties, its associated phenomena which can have multiple causes and (often unforeseen) consequences, and the non-linear relationships between its constituent elements. A sociotechnical system is also considered as an example of complex adaptive systems, since it comprises several dynamically interacting elements (social and technical) whose emergent characteristics can be described as a non-linear function of its integrated activities [29, 30].

However, the distinction between a simple system and a complex system is also important. This distinction is a function of our distance from the system (the quantity of information needed to describe the system), since complexity is the result of interactions between the constituent elements and cannot be found at any specific and identifiable site within the system [31]. Table 1 lists some of the differences between simple and complex systems.

3.1.2. Aspects of complexity and characteristics of a complex system. No consensus has been reached among authors on the definition of complexity as a topic of study. Some continue to recognize the four conventional central aspects, namely: self-organization, non-linearization, chaos, and emergent behaviors, whereas others more recently have pointed out that these four aspects do not provide sufficient description. Table 2 lists the different aspects of complexity cited in the literature.

Also based on the literature, a system can qualify as complex in theory, based on its possession of the characteristics listed in Table 3 below. This list of characteristics was taken from the literature following a keyword searching. The choice of these characteristics was motivated by the consensus established by four recent publications [32–34] that talk about the same subject.

Table 1. Comparison of simple and complex systems

Aspect	Simple	Complex
Theory	Linear	Non-linear
	Adaptation occurring in a static environment	Interactions in a dynamic environment
	Solution is outside the system	Solution is part of the system
Causality	Simple	Mutual
	Deterministic	Probabilistic
	Certain	Uncertain
	Emphasis on the function of individual components	Emphasis on relationships between components
Justification	Reductionism (analysis of individual components)	Holism (analysis of the system as a whole)
	History unknown, since the systems tends towards equilibrium	Change and evolution based on past states (history is important for evolution)
Planning	Convergent thought	Divergent thought
	Deductive characteristics	Emergent characteristics
	What is at stake is proportional to how much change occurs	Butterfly effect (what is at stake does not determine how much change occurs)

Source: Glouberman & Zimmerman, 2002 cited by [1].

Table 2. Theoretical aspects of complexity

N°	Aspect	Description	References
1	Chaos	The implicit capacity of a system to exhibit linear and non-linear behaviors	Sharif and Irani (2006) cited by [1]
2	Emergent behaviors	Non-linear, self-organized or chaotic interactions resulting in emergent properties and complex behaviors	
3	Self-organization	The complex system tends to react to perturbations by organizing itself autonomously to eliminate or at least reduce the consequences of the perturbation.	Sharif and Irani (2006) cited by [1] Rzevski and Skobelev [27]
4	Non-linearization	The behaviors and responses are not deterministic and are influenced by the presence of non-linear relationships and feedback loops.	
5	Connectivity	The complexity of the system increases with the number of connections between its elements. The weaker the connections, the easier it is to break them and create new ones, which increases complexity.	Rzevski and Skobelev [27]
6	Autonomy	The elements have some behavioral freedom (autonomy) always limited by standards, regulations, or law. Increasing the autonomy of the elements increases complexity.	
7	Emergence	The behavior of the system overall emerges from interactions among its elements. Emergent behavior is unpredictable but not random.	
8	Imbalance	Remains subject unpredictable perturbing events, which limits the capacity of the system to return to an equilibrium between two perturbing events.	
9	Co-evolution	Changing as the system environment changes and in turn changes the environment. Co-evolution is irreversible.	

Table 3. Theoretical characteristics of a complex system

N°	Characteristic	Description
1	Involves many elements	Element behavior may be describable while the number of elements remains small. However, beyond a certain number, comprehension of the system or even of elements within it becomes difficult.
2	Elements interact dynamically	Elements being numerous is a necessary but not sufficient condition for a system to qualify as complex. The elements must interact, and this interaction must be variable.
3	Richness of interaction	Interaction is rich, meaning all elements influence and are influenced by a plurality of other elements.
4	Non-linear interactions	Element failure may have disproportionate consequences (larger or smaller than the relative volume of information normally processed by that element)
5	Interactions occur generally on the short term	Interactions occur mostly over relatively short distances, that is, through information obtained from close neighbors. Long-range interaction is possible if the path between elements is covered in few enough steps. Influence is thus modulated in transit, and may be eliminated, modified, or improved.
6	Negative and positive feedback loops	The effect of any activity can have repercussions on the system, instantaneous or delayed. These can reinforce or stimulate (positive) or inhibit or harm (negative) the overall system performance.
7	Open system	A complex system is generally an open system, meaning that it interacts with its environment. In fact, it is often difficult to define the boundaries of a complex system.
8	Function far from equilibrium	The functioning of a complex system does not approach any equilibrium.
9	Evolving history	A complex system has a history. It not only evolves over time, but its previous states continue to have a major impact on its present behavior.
10	Individual elements that are unaware of the behavior of the system as a whole	At least one element responds only to the information it obtains from its immediate surroundings and is oblivious to the system behavior and orientation. This is a crucial point, since if each element “knew” what was happening overall, the entire complexity would have to be present in each one.

Source: [31–34].

3.2. Field study

The field study took place in the production systems of a Tunisian steel company called EL FOULADH, a large public corporation created in 1962 under the auspices of the ministry of industry, energy, and mines. The company converts scrap iron to steel billets (for subsequent transformation, e.g., by forges) long rods (concrete reinforcing, merchant bars, etc.), extruded products (all-purpose wire, specialty wire, galvanized wire, etc.) and hot-dip galvanized metal structures (hydro pylons, metal frames and scaffolds). It employs about 1000 persons, including 70 managers and directors assigned to its various production units.

We used the example of this company to test the complex systems theory described in the published literature. The type of information that we obtained for this purpose is gathered normally using sociological data collection tools, that is, questionnaires, surveys, observation, interviews, analysis in groups, and content analysis [15]. We used a questionnaire, which gave us access to much company staff and increased data reliability by uniformizing the responses obtained [35].

We were able to obtain 30 completed questionnaires, which corresponded to 50% of the respondents. The details of their experience and level of education are shown in Figs 2 and 3. Sixty-four percent had more than 20 years of experience and 63% were university graduates.

The respondents were all company managers or directors. Based on their answers to the questionnaire, we obtained the scores shown below in Fig. 4 for the characteristics listed in Table 3, to determine whether the company EL FOULADH is a complex system.

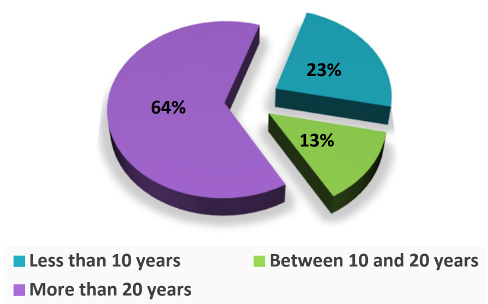

Fig. 2. Years of experience in EL FOULADH among the respondents

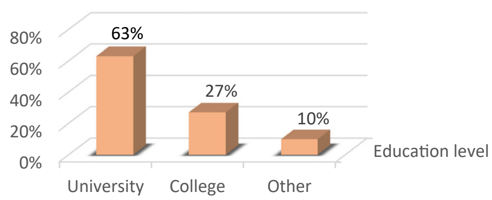

Fig. 3. Education level of the respondents working for EL FOULADH

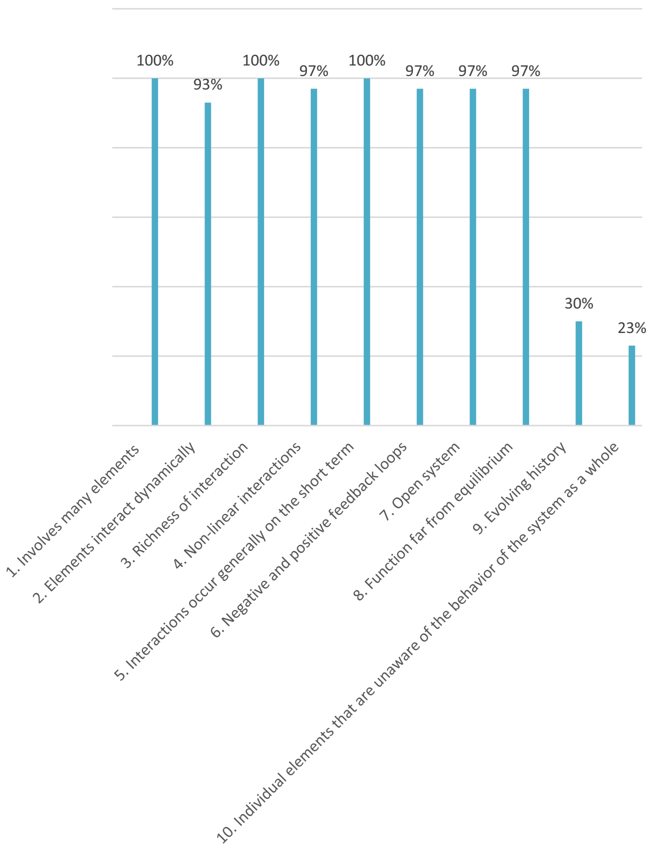

Fig. 4. Scores obtained from questionnaires completed by EL FOULADH managerial staff for each company characteristic associated with complex systems

4. DISCUSSION AND LIMITATIONS

The increasing complexity of the world has given rise to the study and hence the science of complex systems. Understanding of complex systems requires first understanding complexity. Based on the definitions that appear in the published literature, the complexity of system refers to the number and variety of its constituent elements as well as the connections, interactions, and interrelations between these elements. A system is complex if its elements and their interactions are multiple and give rise to feedback loops as well as a diversity of dynamic and emergent behaviors. Researchers have established a list of characteristics that may be checked to confirm whether a system is complex or not (Table 3).

The validity of this list of characteristics was tested using the responses to a questionnaire administered to the managers and directors of EL FOULADH, a Tunisian steel manufacturing company. The questions were formulated to allow us to obtain a score for each characteristic.

Both the theoretical study and the field observations confirmed that this company displays to a large degree all 10 of the characteristics described in the literature. On this basis at least, EL FOULADH constitutes a complex system. The scores, as well as details of the way this company displays the characteristics (based on the answers and comments provided by the respondents) are shown in Table 4.

Table 4. Characteristics of complexity exhibited by EL FOULADH managerial staff

N°	Characteristic	Explanations	Score
1	Involves many elements	EL FOULADH is made up of several departments (logistics, purchasing, sales, administration, production, etc.), various production lines (foundry, extrusion, sheeting) and other operations such as energy recovery.	100%
2	Elements interact dynamically	Each workshop interacts with the sales department, and the workshops interact with each other (e.g., the foundry supplies the other production lines) to meet demand.	93%
3	Richness of interaction	Each shop interacts with the other departments: purchasing, sales, administration, and so on.	100%
4	Non-linear interactions	Certain activities involve the use of dangerous chemicals (acid, flux, and borax), and poor control of process parameters can cause major losses (material and human).	97%
5	Interactions occur generally on the short term	The production units procure raw materials and replacement parts mainly from local suppliers. They may interact with remote suppliers through the purchasing department or otherwise.	100%
6	Negative and positive feedback loops	A good maintenance strategy in production units can lead to better yield (positive feedback) but too much downtime can lead to intermediate or finished product shortages (negative feedback)	97%
7	Open system	The national economy (fluctuations of purchasing and sales prices, product inventory subject to market demand), international relations (trade balance) and other environmental influences weigh in constantly on operations.	97%
8	Function far from equilibrium	Since the activities of EL FOULADH are subject to supply and demand dynamics, they can never reach an equilibrium. The company can grow or shrink but not stagnate.	97%
9	Evolving history	Company history has a strong influence, for example, forecasts of annual production and sales are all based on previous performances.	30%
10	Individual elements that are unaware of the behavior of the system as a whole	Each workshop is focused on a main objective (e.g., daily yield or productivity) by acting only on the information that is relevant to achieving that objective. The managers do not necessarily know what other departments (purchasing, sales, logistics, etc.) are doing.	23%

Of the 10 characteristics, 8 received unequivocally high scores (93–100%), indicating that such characterization of the Tunisian steel manufacturing company is very likely accurate. For each of the last two characteristics on the list, the score was too low to be taken as an indication that the characterization is applicable. However, analysis of the respondents' answers suggests that these low scores were due to poor understanding of the concepts contained in the questions. The meaning of "the evolving history of the company" or "individual elements unaware of the behavior of the system as a whole" was apparently unclear.

Based on these results, the practical side of our study does provide support for the theory of complex systems as expressed in the literature. We also conclude that the company EL FOULADH meets the criteria for being characterized properly as a complex system. In order to generalize this conclusion, this partnership can be followed by others. We are still far from generalization.

4.1. Limitations of this study, future research

By examining only documents retrieved from databases, we limited our analysis to articles published in scientific journals. Other types of literature (e.g., governmental reports, unpublished internal reports, patent literature, etc.) were not taken into consideration. It is therefore possible that some approaches to analyzing the complexity of systems were neglected.

By dealing with the subject of complexity, complexity theory deals in general with abstract systems. However, every real system is complex. So, the distinction between a real system and an abstract system was not discussed. This distinction is important in order to better understand and analyze the complexity of systems.

Action research has advantages and drawbacks. Its main advantage is the inclusion of direct and presumably reliable input from the business that researchers wish to inform regarding processes or performance criteria (e.g., OHS) subject to complex social influences [36]. Field studies provide more complete and precise description of the realities of actual problems and thus the possibility of narrowing the proposed solutions down to one or two that have a better chance of working in practice. However, the effectiveness of a proposed solution may be influenced by (or depend on) the culture of the business partnered with the research team. In addition, the solution may be too specific to be applied elsewhere, and the results obtained therefore difficult to generalize [37].

Another consideration is the extent to which the results of the practical study were influenced by the process of gaining the cooperation of some participants. Half of the questionnaires administered were not useable for analysis. In this sense, the study had a low yield. Although the quantity was disappointing, the data obtained did provide unequivocal results for the purpose of testing the theory against the reality found in the case study. However, our conclusion regarding the system complexity of this company cannot be generalized.

The theoretical characteristics chosen to define complex systems were those found applicable to large businesses, which the industrial partner in this study is. A case study was planned for a small Tunisian business to give us some idea of how generalizable our conclusion might be. However, this initiative never came to fruition because of the sanitary measures imposed in response to the SARS-Cov-2 pandemic, which prevented productive visits, even virtual ones. We hope to proceed with such a study in the future to see to what extent smaller businesses also may be considered complex systems.

5. CONCLUSION

As the global population and international trade grow and commerce becomes increasingly complex, not only to meet demand but also to maintain business competitiveness and market share, single companies become more difficult to model and understand in terms of systems. Complex systems have therefore become the subject of much research, and the various aspects of this new complexity have been described in articles published in scientific journals. The characteristics exhibited by a system that can be considered complex have at least been listed.

In this study, we searched Google, Google Scholar, and Scopus to provide an overview of complex systems and describe their various characteristics and attempted to validate these descriptions in a case study by applying action research. We broadened our search to include memoirs, theses, reviews, conference proceedings, books and reports deemed relevant to the research topic. The action research was conducted through an internship in a large Tunisian company that manufactures steel products. The data were gathered in this real industrial setting using a questionnaire. Analysis of the responses allowed us to confirm that this company exhibits eight of 10 characteristics widely considered in the literature to indicate that a system is properly described as complex.

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