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Model-based Sustainability Assessment – an enabler for Transition to Sustainable Manufacturing

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Abstract

The "sustainable manufacturing" concept has been discussed by researchers and manufacturers for decades. Still, a transition to sustainable manufacturing is limited due to constraints such as the lack of a practical definition of sustainable manufacturing, shortcomings of existing sustainability assessments, and an uncertainty of the effect of actions on the organization. This paper investigates the potential to study sustainable manufacturing through the prism of a complexity theory. The model of sustainable manufacturing based on the ideas of complexity theory is proposed. The use of the model as a foundation for sustainability assessments is suggested as an enabler for the transition to sustainable manufacturing.

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Keywords: complexity theory; sustainable manufacturing model; sustainability performance; sustainable manufacturing definition.

1. Introduction

Sustainable manufacturing is a hot topic for both practitioners and researchers. Plenty of sustainability practices have been developed and tested, different sustainability assessment methods have been proposed, and numerous case studies have been carried out. However, a transition to sustainable manufacturing is still limited due several challenges. Particularly, many definitions of sustainable manufacturing exist (see e.g. [1-4]), but no unified understanding has arisen. Among others, Garetti and Taisch [5] define sustainable manufacturing as "the ability to smartly use natural resources for manufacturing, by creating products and solutions that, thanks to new technology, regulatory measures and coherent social behaviors, are able to satisfy economic, environmental, and social objectives, thus preserving the environment, while continuing to improve the quality of human life."

Another challenge lies in the inability of most sustainability assessments to provide any practical approach for the companies to identify improvement areas and possible actions. Despeisse et al. [6] argued that "the literature and the case studies fail to provide the means by which improvements can be identified for more sustainable manufacturing." Similarly, Smith and Ball [7] revealed that there is no evidence of a systematic analysis of manufacturing companies that can assist with the identification and selection of improvement opportunities. Granly [8] also indicated that many manufacturing companies lack information on how to implement a sustainability concept, and how to identify existing practices and adapt them to company's needs.

Since sustainability is not a destination but a journey, transition to sustainable manufacturing can be viewed as any plan-do-check-act (PDCA) cycle. Thus, transition to sustainable manufacturing can be defined as a process that turns manufacturing company into sustainable one through the continuous process that consists of: (1) an assessment of current sustainability performance; (2) an identification of improvement areas; (3) a suggestion of specific actions across the company; and (4) an implementation of these actions.

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Transition to sustainable manufacturing requires cooperation among researchers and practitioners from different domains, e.g. sustainable practices, sustainability assessment. Despite the comprehensive research in these domains, there is little evidence of bringing these domains together. One attempt was made by Yuan et al. [9] who combined sustainability performance assessment, identification of improvements areas, and suggestion of sustainability practices. Although this approach is focused only on the environmental aspect of the manufacturing system, it provides an example of a possible interdomain study.

Sustainability assessment is a means to get a comprehensive and reliable analysis of current sustainability performance of manufacturing organization that enables an identification of improvement areas. However, Moldavska and Welo [10] show that existing sustainability assessments of manufacturing organization identify improvement areas in an organization at too general level (e.g. social aspect, water management). This may limit an identification of specific actions and, thus, transition to sustainable manufacturing. A study of Moldavska and Welo [11] indicates that applicability of existing sustainability assessment methods is currently limited. One of the underlying reasons is that sustainability assessment fails to capture a complexity of sustainable manufacturing—relationships between sustainability issues and interlinkages between elements of the organization,—due to a widely used reductionist approach. The need to shift a view on the world from reductionism to complexity has been stressed already by different researchers, see e.g. [12]. This idea was supported by Halog and Manik [13] who argue that sustainable development is a complex phenomenon that cannot be fully covered by the reductionist-oriented tools.

All in all, transition to sustainable manufacturing is constrained by the lack of a practical definition of sustainable manufacturing, shortcomings of existing sustainability assessments to present sufficiently current conditions of an organization, and by the uncertainty of the effect of actions proposed by decision makers based on the result of a sustainability assessment. Thus, the objective of this paper is to investigate the potential of complexity theory to help in overcoming these constraints. First, a brief overview of the idea of sustainability assessment is presented. Second, the application of key ideas of complexity theory to sustainable manufacturing is examined. Then, a complexity-based model of sustainable manufacturing is proposed; the use of the model as a foundation for the sustainability assessment tool is suggested as an enabler for a transition to sustainable manufacturing.

2. Sustainability Assessment in manufacturing

Due to the pluralism inherent in the sustainable development concept, different definitions of sustainable manufacturing have been proposed, e.g., [14]. While some researchers stress the need for establishing a clear understanding of sustainable manufacturing [15], others argue that it is necessary to move from trying to identify sustainable manufacturing toward developing tools for measuring achievements [16]. Sustainability assessment with the overall goal of measuring the achievements of manufacturing organization toward sustainability can be such tool for measuring achievements of organizations.

Bond *et al.* [17] stress that the ecological, social, political and cultural pluralism provides a plural context for sustainability assessment. Moreover, Cashmore and Kørnøv [18] outline two dimensions of plurality; plurality of theoretical perspectives on sustainability assessment, and plurality of stakeholders with multiple perspectives. Due to the plurality of sustainability assessment, “no single, definitive and globally agreed sustainability assessment process is likely to emerge beyond some basic steps” [19]. However, according to Marsden *et al.* [20], an incomplete definition of sustainability assessments leads to inability of current methods to capture the full range of concerns.

Since the concept of sustainable development is central to sustainability assessment, pluralism of sustainable development has led to a diversity of definitions of sustainability assessment [21-25] and approaches to assessment, see e.g. [11, 21, 25-29]. The variety of viewpoints on what sustainability assessment is and how to perform resulted in a vast number of sustainability assessment tools. The term “sustainability assessment” is used as an umbrella for different procedures, practices, processes, methodologies, methods, frameworks, and tools that focus on measuring or promoting sustainability at different levels, e.g., country, city, and organization.

According to the categorization framework proposed by Morrison-Saunders *et. al.* [30], sustainability assessment tools can be placed within three dimensions: (1) underpinning sustainability discourses, (2) representations of sustainability within the assessment process, (3) the decision-making context.

To foster sustainable development and address global sustainability challenges, manufacturing organizations need to make decisions taking into account a series of complex social, economic, and environmental issues simultaneously. This makes sustainability assessment an essential aid for decision-making in sustainable development [31-33].

3. Sustainable Manufacturing through the prism of complexity theory’s ideas

According to Nooteboom [34], “there is no complexity theory but a number of consistent publications”. Complexity theory is not a single idea, theory, or technique; it is an umbrella for a variety of ideas, hypotheses, metaphors, theories, and modeling and simulation techniques [35-37]. The focal point of the complexity theory is not to study complexity, but to understand the behavior of complex systems, such as manufacturing organization.

Complexity theory consists of the variety of concepts such as emergence, uncertainty and unpredictability, non-linearity, diversity, networks, self-organization, relationships, sensitivity, feedbacks and recursion, open systems, holism, dynamical systems, distributed control, adaptation, conflict, leverage points, non-equilibrium, recursive causality, e.g. [38-40]. Utilization of these concepts to study sustainable manufacturing can enable the transition of manufacturing organizations to sustainable ones. The use of some ideas of complexity theory to study sustainable manufacturing is reviewed in this section. As it was indicated above, no unified definition of sustainable manufacturing exists. This is one of the challenges when one tries to put the theoretical concept of sustainable manufacturing into the practice. Thus, to study sustainable manufacturing through the prism of complexity theory may assist in better understanding of sustainable manufacturing and transition to sustainable manufacturing.

3.1. Relationships

A complex behavior of any system is influenced by the state of the system elements, their number, and relationships between them [41]. The behavior of a manufacturing organization should be studied by analyzing the conditions of its sub-systems or parts simultaneously with the relationships between them.

One of the shortcomings of existing sustainability assessments is an inability to address cause-effect relationships between different sustainability and organizational aspects. Hon [36] analyzed performance measurements of manufacturing and argued, “ideal local and global measures of manufacturing system should exhibit a direct cause-and-effect relationship, not a correlation relationship.”

Although the need for the identification of relationships between the indicators to learn about the behavior of the system was stressed decades ago [42], the majority of assessment tools do not take into account linkages between indicators and the interactions between metrics [13]. Kelly [42] stated that “a failure to capture information about the structure and behavior of the system in which development decisions are being made will most likely lead to ineffective policy design.” Gasparatos et al. [43] concur that at this moment none of the existing popular assessment methods can encompass a consideration of a plethora of social, economic, and environmental issues simultaneously due to the use of the reductionist approach.

3.2. Non-linearity

Many cause-effect relationships in complex systems are nonlinear, i.e. one action can cause more than one consequence, and one consequence can be caused by more than one action. Thus, sustainability assessment of manufacturing should indicate these non-linear relationships. The result of overlooking such nonlinearities may mislead the conclusion, made based on the sustainability assessment, and constrain the transition to sustainable manufacturing.

3.3. Feedbacks

Innes and Booher [44] argue that any complex system (e.g. manufacturing organization) can become sustainable if system’s agents share a general purpose and get feedback from their actions so that they can act differently. Hjorth and Bagheri [45] support this idea and state that planning for sustainable development depends on the identification of the viability loops in the system and keeping them functional. Mayer et al. [46] stress the importance of the feedbacks in understanding of the behavior of a complex system, “the path that a system has taken in the past and will take into the future is the result of a set of feedbacks that have been acting (positive and negative), and have not been acting (missing or forbidden), along with their intensity and scale.” If a decision is made based on the assessment that overlooked some feedbacks, it may lead to inappropriate decisions, i.e. “if economic indicators provide us no feedback regarding matters crucial to human health and well-being, these will continue to be undermined by misguided policies” [42].

Information flow is one of the powerful feedback mechanisms that can be addressed during the assessment; “if you make information go to places it did not go before, it may well cause people to behave differently” [45].

3.4. Delays

Besides the feedbacks, a dynamic behavior of the complex system is additionally defined by delays i.e. differences in time between actions and its consequences [39]. Inability to address delays during the assessment of manufacturing organization may affect a validity of the conclusions regarding the cause and effect of actions.

3.5. Self-organization

Stable self-organization is a product of trade-offs made between sub-systems; to achieve a stable self-organization, a sub-optimization should be avoided [47]. In order to enhance stability and sustainability of the system, self-organization becomes a crucial characteristic of the system. Self-organization concept can be viewed as an enabler of flexible and resilient manufacturing that moves from a fixed and centralized structure to distributed one—a network. Through the integration of learning and autonomy, a dynamic self-configuration, self-optimization, and self-healing can be achieved [47].

3.6. Holism and emergence

Complex behavior of the system emerges from the interactions among the system’s elements, which by themselves do not lead to such behavior. The concept of holism is called a vertical emergence when “microlevel behavior can lead to macrolevel behavior that cannot be easily (if at all) derived from the microlevel from which it emerged” [48]. Applying this to sustainable manufacturing, the behavior of the organization should be studied though the behavior of micro levels.

3.7. Conflict

A conflict is an inherent part of any sustainable manufacturing due to conflicts between sustainability criteria, among stakeholders, between sustainability and innovation, between the nature and humankind, etc. In contrast to a reductionist view that tends to avoid conflicts, complexity theory sees a conflict as a key concept that gives a rise to creative processes. An example of the analysis of sustainable manufacturing using the idea of conflict was presented by

Dassisti [49]. The author studied sustainable manufacturing through the prism of game theory and provided an approach to deal with a conflict between two players, a humankind and the Earth. Therefore, a sustainability issue in manufacturing can be viewed as an 'optimization game' where the objective is to search solutions where both, the Earth and the humankind, thrive.

3.8. Included middle

While traditional approach search for a sustainable product, project, action, organization, etc. in contrast to unsustainable one, the idea of included middle indicates that a decision, judgment, or phenomenon can be viewed in dual terms, i.e. a decision can be both sacrificial and beneficial [47]. Decades of practices and studies in a sustainable product, organization, practice, etc. demonstrates the inability to identify absolute sustainable option. The idea of included middle can advocate the pluralism of sustainable development, the view that has been discussed by researchers already [50, 51].

3.9. Leverage points

Leverage points are parts of the complex system where small changes can cause a transformation of the whole system. One of the evaluation and decision criteria for sustainability assessment is "to seek for leverage points to obtain maximum net gains" [52]. Hjorth and Bagheri [45] stated that causal loop diagrams can be useful to find the leverage points in a system. Also Rickerby [53] states that life cycle assessment can be used to identify environmental leverage points.

3.10. Attractor

An attractor is defined as "a set of values in the phase space to which a system migrates over time" [54], where the phase space is an abstract space that represents a system's behavior that has as many dimensions as the variables of the system.

One example of the attractor is Lorenz attractor in a 3D phase space, see Fig.1.

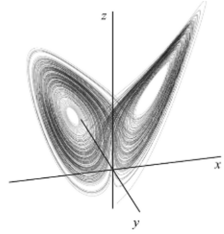

Fig. 1. Lorenz attractor [55].

4. Complexity-based model of sustainable manufacturing

Modeling of a complex system helps to understand the behavior of a system and relationships between system's components. Zhen et al. [56] stressed the importance of the model creation as a way to minimize the complexity of reality. However, Efthymiou et al. [57] who studied manufacturing modeling, concluded that although traditional modeling approaches have been used extensively, they do not describe the dynamic behavior of the organization. Babiceanu [58] stressed the need for a new modeling approach that addresses complex structural and operational characteristics of an organization. The author argued that we should borrow already studied concepts such as complexity, fractals, emergence, self-organization, adaptation, and evolution, to analyze organizational systems. Thus, taking into account all complexity theory's ideas that have been presented in Section 3, a model of sustainable manufacturing has been developed (Fig. 2). The model serves as a definition of sustainable manufacturing and as an architectural frame for sustainability assessment tool.

According to Nooteboom [34], who utilized a complexity theory's ideas, "a system has a sustainable development if that development enables it to maintain its wholeness as an integral system, whilst also maintaining its role as part of a larger system on which it depends". A manufacturing organization should be then considered as a sub-system that contributes to global sustainability rather than focusing only on its own performance. Furthermore, if to consider sustainability as an

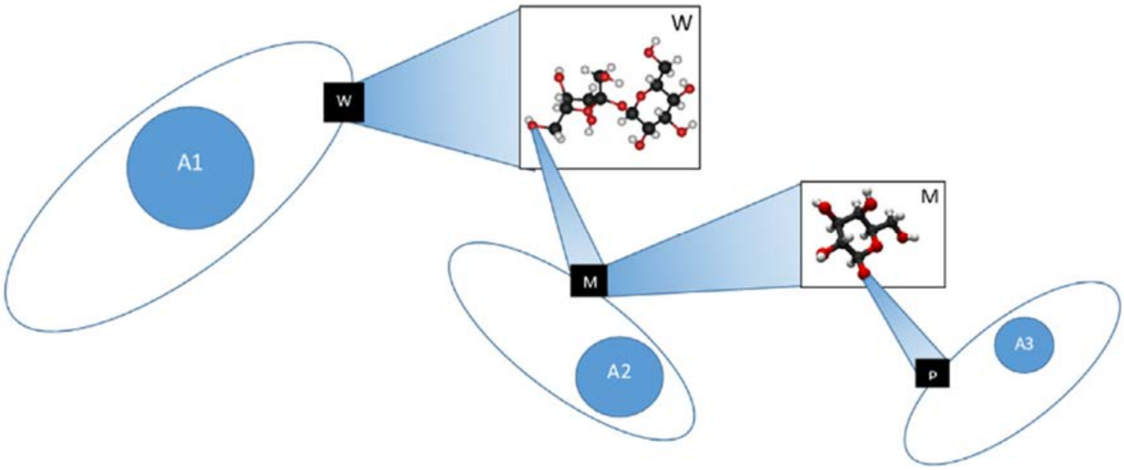

Fig. 2. Complexity-based model of sustainable manufacturing.

attractor, then sustainable manufacturing can be defined as 'a system that contributes to the sustainability of the large system while maintains its own sustainability.' Thus, A1 on Fig.2 is an attractor, i.e. sustainability, for the world (W) that is a complex system with various elements, which behavior is defined by myriads of relationships, feedbacks, and delays. For simplification, the orbit is presented as a circle (see Fig.2) while in reality it is an N-dimensions phase space.

Sustainable manufacturing organization (M) is one of the elements of the world system (W) and has its own attractor (A2), i.e. sustainability. Manufacturing organization tends to maintain its own sustainability (A2), as well as contribute to the sustainability (A1) of the world. The manufacturing organization, it turn, is also a complex system consisting of different interconnected elements and sub-systems. One of the sub-systems is a production department (P), which has its own set of sustainability values (A3), and which contributes to the sustainability of the larger system, i.e. manufacturing organization.

Such representation of the sustainable manufacturing ensures the integration of self-organization idea. Considering sustainable manufacturing as a part of the large system with its own set of sustainability values (A1), as well considering relationships within the organization may help to avoid a sub-optimization.

Moreover, the relationship between attractor A2 and manufacturing organization (M) can be presented through the system of functions, where each function is defined by equation (1). Each value of the attractor is defined by the elements of manufacturing organization.

$$A2\_valN = f_N(M_{el1}, M_{el2}, \dots, M_{elM}) \quad (1)$$

Where

- $M_{el1}, \dots, M_{elM}$ are the elements of the manufacturing system (M), e.g. produced goods, a number of employees, orders, and sales.
- $A2_{val1}, \dots, A2\_valN$ are the values which define the attractor A2, e.g. emission, employee's satisfaction, and profit.
- f_N is a function that describes the relationships between elements of manufacturing organization and values of the attractor.

The system of functions that defines relationships between attractor's values and elements of manufacturing organization allows identification of leverage points in the manufacturing organization.

5. Model-based sustainability assessment

Sustainability assessment based on the proposed model of sustainable manufacturing can ensure that dynamism of manufacturing organization is addressed through the relationships between elements of an organization, feedbacks, and delays. Furthermore, identification of relationships between attractor's values and manufacturing elements can enable simulation of different scenarios or potential improvements. By changing the value of one element of the manufacturing (M), the effect on other elements and, thus, on the values of attractor will be visible. A simulation based on the link between attractor's values and manufacturing elements demonstrates the idea of included middle—one action can be both beneficial (e.g. improve one attractor's value) and sacrificial (e.g. sacrifice another attractor's value). Despite changes in each value, the system still can tend to evolve toward its attractor.

A sustainability assessment tool based on the complexity-based model of sustainable manufacturing proposed here can be placed into the characterization framework of Morrison-Saunders *et. al.* [30] in the following way:

(1) underpinning sustainability discourses – *a process of directed change or transition*;

(2) representations of sustainability within the assessment process – *systems representation*;

(3) the decision-making context – depends on the level of details in the model.

6. Conclusion

The transition of a manufacturing organization to sustainable one is currently constraint by the lack of a practical definition of sustainable manufacturing, shortcomings of existing sustainability assessments to analyze sufficiently current conditions of the organization, and the uncertainty of the effect of actions proposed by decision makers based on the result of a sustainability assessment.

The use of complexity theory's ideas to study sustainable manufacturing may help to overcome the shortcoming of the current approaches to analyze and reach sustainable manufacturing. In order to benefit from the complexity theory's ideas during the transition to sustainable manufacturing, a complexity-based model of sustainable manufacturing has been developed. The model represents the complexity-based definition of a sustainable manufacturing that may enable a practical use of this concept. A model of sustainable manufacturing can help to reduce the complexity of sustainability and manufacturing issues, thus, it can serve sustainability assessments.

As a base for sustainability assessment, the proposed complexity-based model of the sustainable manufacturing can ensure that current conditions of a manufacturing organization will be assessed sufficiently, and the complexity of the organization will be addressed. Moreover, such model may facilitate an identification and testing of the actions toward sustainable manufacturing. A model-based sustainability assessment can enable a comprehensive and systematic assessment and a systematic identification of improvement areas, thus, enhance the transition to sustainable manufacturing. The model of sustainable manufacturing can provide a better visualization of different aspects of sustainability and manufacturing, and enable a comprehensive assessment of sustainability performance. The main idea of the sustainability assessment based on the sustainable manufacturing model is to analyze a "system performance" instead of a number of aggregated individual indicators.

Future work

Future work on the development of the complexity-based model of a sustainable manufacturing will include the identification of elements of the model and values of the attractor, as well as identification of relationships between the elements, and between the manufacturing's elements and attractor's values.

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