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A Holistic approach to corporate sustainability assessment: Incorporating sustainable development goals into sustainable manufacturing performance evaluation

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ABSTRACT

Corporate Sustainability Assessment (CSA) in manufacturing is a framing of tools that guide the organization toward sustainable practices and indicate how the same organization contributes to a global Sustainable Development (SD). In addition to the discussion about shortcomings of existing CSA practices, the need to incorporate UN Sustainable Development Goals (SDGs) into reporting has been advocated by the sustainability society. This paper proposes a new CSA method for manufacturing companies in which (1) sustainability is seen as a process of directed change, (2) assessment tool is designed by modeling manufacturing company using systems representation, and (3) assessment of Corporate Sustainability (CS) is context-based and linked to SDGs. The proposed CSA method takes a holistic view on Sustainable Manufacturing (SM) and CS.

1. Introduction

The manufacturing sector is an important actor in achieving SD. Its role in creating jobs, improving social welfare, and reducing environmental impact has led to increased attention to research in the field of SM. The interest in the academic community escalated after United Nations set 17 Sustainable Development Goals (SDGs) and 193 countries agreed upon them in 2015. Responsible Consumption and Production, as one of the goals, is considered as an overarching sustainable development priority. United Nations and Global Reporting Initiative strongly prescribe businesses to report on their contribution to and impact on the SDGs [1]. Therefore, organizations worldwide have begun to discuss a means to assess their impact against the 17 goals.

CSA as a decision support tool that directs decision-makers toward SD has been on agenda of research for some decades already. However, the current generation of CSA does not yet sufficiently address SDGs, and the scientific community is still inconclusive about some of its shortcomings and challenges, including (1) CSA methods fail to address system performance [2], and (2) CSA methods in manufacturing include an uncomprehensive and unsystematic list of indictors [3]. These and other shortcomings affect the ability of CSA to provide a holistic view on the sustainability performance of a company and identify the associated improvement potential.

The underlying reasons for the existing challenges and shortcomings of CSA in manufacturing are due to the use of the so-called reductionist approach and the lack of a comprehensive description of the SM concept due to the diversity of sustainability discourses. SD is a complex and multi-dimensional concept with no ‘correct’ interpretation. Therefore, a variety of sustainability discourses has emerged over the years. Each one represents a specific view of what sustainability or SD is, according to different worldviews and values. Pope et al. [4] distinguish four discourses: (1) the first discourse views SD as a pragmatic integration of development and environmental goals; (2) the second discourse emphasizes the idea of limitations on human activities; (3) the third discourse views SD as a process of directed change; (4) the fourth discourse defines the goal of SD by the concepts of resilience and justice. Most of the existing CSA methods are based on the discourse of a pragmatic integration of development and environmental goals, and sustainability is typically represented as a so-called triple bottom line or composite indicators. This is an example of a traditional reductionist approach to a complex concept of SD and the development of sustainability assessment (SA). This approach has been subjected to criticism, and systems approach has been suggested as a means to address current shortcomings of SA practices, including CSA [5]. Furthermore, the need for a new paradigm to the development of SA methods and tools has already been argued by researchers [6].

Although there are many types of SA methods and tools in manufacturing—ones that consider both the application domain (product,

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process, work-cell, company, supply chain) and dimension (environmental, social, economic, or any combinations of them)—this work is limited to the integrated assessment at company level, i.e. CSA. This paper elaborates on the idea to overcome some of the existing challenges and shortcomings of CSA in manufacturing and to incorporate SDGs into the assessment. Therefore, the research question of this article is defined as "What design of CSA method can overcome existing shortcomings and challenges, and enable manufacturing companies to report on their contribution to SDGs?" For this purpose, we choose to develop CSA method grounded on the discourse that underpins sustainability as a process of directed change or transition, according to the classification suggested by Pope et al. [4]. We propose a CSA method, i.e. architecture and application guidelines, based on systems thinking and complexity theory. This approach is based on the research [7,8] which proposes a complexity-based definition of SM.

The reminder of the paper is structured as follows. First, the theoretical background for the CSA in manufacturing is provided, outlining some of the shortcomings and challenges of existing CSA methods. Second, the discourse that sees sustainability as a process of a directed change or transition is presented. Third, we define the requirements for CSA methods in the context of *transition discourse*. Fourth, a new method is proposed and a case study is presented to illustrate the application of the method. Finally, quality of the method is evaluated against (1) the defined set of desirable characteristics the method should incorporate, and (2) observed shortcomings of existing methods, before closing the article with conclusions and future work.

2. Theoretical background

2.1. Sustainability assessment

SA is mostly defined as a decision support tool that directs decision-making toward sustainability [9]. The term SA is commonly 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 company. According to the categorization framework proposed by Morrison-Saunders et al. [10], sustainability assessment tools can be placed within three dimensions: (1) underpinning sustainability discourses, (2) representations of sustainability within the assessment process, and (3) the decision-making context. The purposes of SA are defined by Waas et al. [11] as information generation for decision-making; structuring complexity; operationalization and forum for participation, debate and deliberation; and social learning. Also, Moldavska and Welo [5] formulate the purpose of SA as "to support decision makers, facilitating the identification of actions that they should undertake in the attempt to contribute to sustainable development." They also specified that SA should provide information about issues in the company that require improvements.

Due to the plurality of sustainability assessment, i.e., a plurality of theoretical perspectives on sustainability assessment, and a plurality of stakeholders with multiple perspectives [12], "no single, definitive and globally agreed sustainability assessment process is likely to emerge beyond some basic steps" [13]. However, according to Marsden et al. [14], an incomplete definition of SA leads to the inability of current methods to capture the full range of concerns. Since the concept of SD is central to SA, pluralism of SD has led to a diversity of definitions of SA [15–19] and approaches to assessment, see, e.g., [4,5,15,19–22]. The variety of viewpoints on what SA is and how to perform it has resulted in a vast number of sustainability assessment tools.

2.2. Sustainability assessment in manufacturing

The number of the SA tools and approaches used to develop SA tools in manufacturing is growing every year [4,15,20–25]. In manufacturing, SA tools focus either on the specific aspect of the company (e.g., product, process, work-cell), the whole company (i.e., corporate sustainability assessment), or the whole industry (e.g., wine industry, automotive industry). Moreover, each of these tools can evaluate either one dimension (e.g., environmental assessment), two (e.g., socio-economic assessment), or all dimensions. The literature on SA in manufacturing demonstrates a myriad of approaches which researchers use, including the use of multi-criteria approach, see e.g., [26], fuzzy-logic methods, e.g., [27,28], a value stream mapping, e.g., [29–37], an AHP, e.g., [38], resilience approach, e.g., [39]. CSA as a type of SA is focused on the environmental, social, and economic considerations at a company level [40].

One branch of the literature on SA in manufacturing covers indicator frameworks and indices for assessment, including Global Reporting Initiative, OECD Core indicators, NIST Sustainable Manufacturing Indicators Repository, Composite Sustainable Development Index, Sustainable Manufacturing Index, Dow Jones Sustainability Indexes, see, e.g., [27,41–46]. These frameworks vary in application domains (i.e., product, process, company, etc.) and address different sustainability issues (i.e., environmental, social, and economic). Researchers who analyzed the frameworks concluded that most of these indicators tend to focus on external reporting while lacking internally useable information for decision-makers [47]. Also, some frameworks are too general in nature [27] and might be too fuzzy for practical application [48].

Another branch of literature focuses on the SA methods and tools, i.e., description of both elements for assessment sustainability themes or indicators, and an algorithm to handle them. This branch includes among others well-known SA tools such as LCA, LCC, and material flow analysis. Analysis of 55 assessment tools concludes that most of these tools miss a holistic approach to sustainability [49]. Analysis of another seventeen assessment tools indicates that, although these tools are widely used and solve many of the assigned tasks, most of them address just one or two sustainability aspects [50]. Some examples of SA tools for different domains in manufacturing could be found in [51–55]. Researchers argue that the majority of available assessment tools focuses on environmental aspects [26]. However, more holistic approaches to sustainability assessment in manufacturing are being developed. For example, Rödger et al. [56] in their work describe the framework that might enable sustainability-oriented decision-making alongside with the assessment method which embraces the planetary boundaries concept and incorporates performance indicators at several organizational levels. Similarly, Sproedt et al. [57] proposed simulation-based decision support for eco-efficiency, by integrating discrete-event simulation and system analysis and modeling, supporting the identification of appropriate improvement measures.

Recognizing integrated consideration of the social, economic, and environmental issues as a basic requirement of the pursuit of sustainability, significant efforts have been made to develop integrated SA addressing three aspects of sustainability. Several examples of integrated SA for a product, process, technology, work-cell, industry, plant, or company are presented in [26,29–3338,39,47,58–67]. Despite the progress in the field, variety of shortcomings, challenges, and research gaps have been documented in the literature (Exhibit 1). Exhibit 1 is sorted according to a publication year.

2.3. Corporate sustainability assessment in manufacturing

In the scientific and professional literature, CSA (or denoted SA at company level), as a branch of sustainability assessment, has been embraced as an instrument to evaluate organizational performance to assist decision-makers in determining which actions should or should not be taken in an attempt to contribute to sustainable development. Donovan et al. [81] define CSA as "a planning tool for the private sector on how to identify, assess and manage the impacts of their business operations across environmental, social and economic issues." Schneider and Meins [82] define it as "an approach to measure the

Exhibit 1
Summary of the shortcomings, challenges, and research gaps in manufacturing sustainability assessment.

- None of the existing indicator schemes is adequate for the purpose of providing all essential information about a system and its rate of change [68].
- The aggregation of indicators may hide serious deficits in some parts of the assessed system [68].
- Most indicator frameworks are still under development and no framework is applicable as a whole to evaluate sustainable production [41].
- Limited consensus exists on a reasonable taxonomy of sustainability metrics [69].
- Very few examples of effective assessment processes can be found in the literature [15].
- Determination of weights of indicators may not always be straightforward and accurate, reflecting opinion of decision-makers and may therefore suffer from a high degree of subjectivity [42].
- There is still no useful method for integrated sustainability assessment on the company level available [42].
- There is a lack of a comprehensive framework of sustainability criteria for sustainability assessment of manufacturing companies [42].
- Normalization and weighting of indicators are the source of subjectivity and reveal a high degree of arbitrariness, scientific rules for aggregation are often not taken into account [70].
- Most of the existing tools miss a holistic approach on sustainability [49].
- Some of the existing frameworks for indicators are aimed at external reporting, rather than providing valuable information for internal decision makers [47].
- SA tools can be too technical and complicated for manufacturing companies [29,43,49].
- Three spheres of sustainability have not received equal attention during sustainability assessment, and how to measure the social dimension remains a major problem in recent research [71].
- Comparison and aggregation of indicators can be difficult because different types of indicators use different reference units (work cycle, yearly production volume, days, product, etc.) [29].
- There is still a lack of comprehensive assessment models and tools covering all the three aspects of sustainability in a holistic approach [50,72] [73].
- The lack of a clear framework for measures and metrics at strategic, tactical, and operational levels in sustainable business development [74].
- It is difficult “to identify current measurable indicators that point to sustainability” since sustainability is associated with the future while indicators measure the present [75].
- Different assessment tools can present different sustainability performance due to the choice sustainability issues covered [76].
- Contradictory strategies for how to improve sustainability performance can be established due to the compositions and interpretations of the indicators [46].
- Most available assessment tools focus on environmental aspects of manufacturing system sustainability [26].
- The existence of many indicator sets has created confusion when a manufacturing company attempts to select a suitable tool [46].
- Sustainability assessment tools may appear too theoretical and abstract [27,48].
- Manufacturing companies have had difficulty identifying assessment tools that are relevant to their desires to assess and improve the sustainability of their plants [77].
- There is a lack of easily applicable tools that assess the status of sustainability based on key performance indicators and that derive priorities for systematic improvement [66].
- While theory moves toward constructivist approach, the practitioners in SA still utilize technical-rationalist models, and suggest that it is caused by a resistance to change of practitioners and challenges created by inevitable complex systems [78].
- A traditional sustainability assessment based upon linear cause-and-effect thinking is inadequate [79].
- A comprehensive assessment that spans over all pillars of sustainability, fully connected in terms of the covered themes and techniques used, and forward-looking does not exist at present [79].
- Sustainability indicators, which are calculated by gauging, comparing, correlating these quantities during a specified period of time, are blind to the dynamics of the manufacturing processes in that period of time [80].
- SA has to deal with different sources of complexity, i.e. different assessment levels (product, process, company, etc.), different sustainability dimensions (social, economic, and environmental), different perspectives, and different time references [80].

contribution of firms to sustainable development,” focusing on contribution rather than impact. Sometimes, CSA is argued to be a replacement for financial performance as the sole measure of corporate success [83]. Maas et al. [84] define two main purposes of CSA; i.e., to improve organizational performance, and to inform stakeholders about company’s impact. Profound research on the development of CSA for different types of organizations—e.g., SMEs, large companies, manufacturing, and public—has been carried out in broad terms. The literature demonstrates that researchers and practitioners have already gained valuable insights into CSA [27,41–4446,51–55]. A variety of methods exists in the literature, e.g., [2,82,85,86], including several ones for manufacturing companies, e.g., [40,87,88].

There is no standard approach to develop CSA. The corporate sustainability field is still evolving and different approaches to define and theorize corporate sustainability exist, whereas a standardized method to measure it remains to be proposed [40]. Montiel and Delgado-Ceballos [40] analyzed two approaches to CSA used by researchers: (1) a use of scales and instruments to quantify the level of corporate sustainability already created by external organizations, e.g., the Dow Jones Sustainability Index, the Ethibel Sustainability Index; (2) a development of own constructs and scales to measure the three dimensions of corporate sustainability. Researchers that choose the second approach are often driven by the challenges and shortcomings of existing assessments. For each new CSA method and tool, two decisions should be made: what issues to integrate in the assessment, and how to integrate the chosen issues. These two decisions correspond to two dimensions of the categorization framework proposed by Morrison-Saunders et al. [10], underpinning sustainability discourses and representations of sustainability within the assessment respectively. The shortcomings of existing CSA methods and tools in manufacturing are presented below in relation to each decision and are summarized in Exhibit 2 .

2.3.1. What to integrate?

One of the shortcomings of the existing CSA methods is that most of them do not distinguish between the extent of implementation of sustainability-related practices and actual sustainability performance of the organization [83]. This is discussed by Ihlen and Roper [89], who argue that steps toward sustainability should not be presented as

Exhibit 2
Summary of the observed shortcomings of CSA methods.

- The inability of some CSA to capture the complexity of SM—relationships between sustainability issues and interlinkages between elements of the company—due to a widely used reductionist approach to CSA [97].
- CSA tend to mix sustainability performance of a company and sustainability-oriented practices (most of them do not distinguish between the extent of implementation of sustainability-related practices and actual sustainability performance of the organization) [83];
- The inability of many CSAs to provide a practical approach for the companies to identify improvements and possible sustainability-oriented practices [92,93];
- CSA fails to address system performance [2];
- The use of a set of unrelated indicators, since an assessment of separate entities without considering relationships between them neglects the dynamics of the company [80];
- Companies measure what is measurable rather than what is necessary concerning the SM, due to the challenge to address simultaneously organizational context and SM phenomenon (context-based & Global SD) [90];
- Use of incomprehensive and unsystematic lists of indicators for CSA in manufacturing [3].

actually having reached sustainability. Ihlen and Roper analyzed sustainability reports published by 30 of the world's largest corporations and identified that organizations present attempts to operationalize sustainability (e.g., environmental management system, design for X, sustainability strategy) as an indicator of sustainability performance. Thus, there is a risk that organizations possessing sustainability-oriented practices can be claimed to be sustainable ones. This shortcoming is caused by the lack of a clear and unified definition of corporate sustainability, or in case of manufacturing, definition of sustainable manufacturing.

The second shortcoming is the use of incomprehensive lists of indicators for CSA in manufacturing. Hallstedt [3] argues that the reason is that the sustainability criteria used today may be chosen because they are common or well-known, e.g., reducing GHG emissions. Thus, such an approach fails to provide a complete picture of SM. Another shortcoming is an often experienced situation when organizations measure what is measurable rather than what is important concerning the given subject or phenomenon. In the context of CSA in manufacturing, SM is a given subject or phenomenon. Therefore, Hák et al. [90] argue for indicators related to SDGs in the hope to overcome this shortcoming. These two shortcomings are caused by the challenge to address simultaneously organizational context and SM phenomenon. The use of a standard set of sustainability indicators can be ineffective and either overlook some important aspects associated with unsustainable practices or focus on irrelevant ones. On the other side, the use of completely different sets of indicators by each particular organization can lead to measuring what matters most to an individual organization while missing the full picture of SM.

The lack of the operational definition of SM and its criteria are barriers to an effective CSA in manufacturing and an underlying cause of the shortcomings presented above. An analysis of 89 definitions of SM done by Moldavska and Welo [91] shows that (1) there is a wide deviation from the core understanding of SM concept, i.e., the number of issues associated with SM, (2) there is inconsistency in the understanding of issues associated with the concept, and (3) there is a mix of performance-related features and sustainability-oriented instruments in the definitions of SM. The authors see the variety of definitions as a barrier to further development of the industry. Acceptance of many definitions and interpretations of the concept can lean the concept towards the perceptions of the one who defines it. In other words, some actions that do not lead to sustainability might be hidden behind some interpretations or definitions of SM.

2.3.2. How to integrate?

One of the shortcomings related to how CSA methods integrate sustainability into assessment is an observed inability of many methods to provide a practical approach for the companies to identify improvements and possible sustainability-oriented practices. Despeisse et al. [92] 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 [93] 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 [94] 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 companies' needs. One of the reasons can be the focus of CSA methods on the reporting, rather than internal decision support. Even though SA is generally understood as a support to decision-making toward SD, the results of assessment produced by some CSA tools might be difficult to use as informative input to decision-making. Another possible reason is the application of a paradigm of rational and objective knowledge to CSA. Sustainability is not an exact science, meaning it is difficult to describe sustainability by using accurate quantitative expressions, quantifiable measurements, or precise predictions, which are the common characteristics of exact sciences. However, CSA methods often utilize paradigms of rational and objective knowledge. Some of the methods aim to identify whether an organization is sustainable, or identify the level of sustainability by using methods as analytical hierarchy process, multi-criteria decision-making, or similar [26,38,42,43,59]. These methods handle complex problems and provide the result using exact numbers. However, in the context of sustainability, it can be almost impossible to define and assign exact numbers to whether ‘x’ amount of wastewater is worth more or less than ‘y’ amount of lost investments, for example.

Another shortcoming of CSA methods is the use of a set of unrelated indicators since an assessment of separate entities without considering relationships between them neglects the dynamics of the company [80]. Neglecting organizational dynamics can affect the trustworthiness of the assessment result and lead to unintended consequences of the decision made based on the result of CSA, e.g., sub-optimization. The inability of some CSAs to capture the complexity of SM—relationships between sustainability issues and interlinkages between elements of the organization—is due to a widely used so-called reductionist approach to CSA. The need to shift a view of the world from reductionism to complexity has already been stressed by different researchers, see, e.g., [95]. This idea was supported by Halog and Manik [96] arguing that SD is a complex phenomenon that cannot be fully covered by the reductionist-oriented tools. Researchers advocate for a holistic CSA approach [2], ensuring that CSA indicates ‘system performance’ instead of an aggregation of a number of unrelated individual indicators. Practitioners in systems thinking and complexity science stress the crucial role of studying the relationships between elements of the system in order to understand the dynamics and behavior of the system.

3. CSA based on the transition discourse

3.1. Sustainability as a process of directed change or transition

To overcome the shortcomings and challenges discussed in Section 2, we advocate for the utilization of a discourse of ‘directed change or transition’ as a means to develop CSA method that is capable of supporting decision-making toward SD based on a comprehensive and systematic assessment of the company. Sustainability as a process of directed change has been discussed within the fields of transition theory and transformational view [4]. Three metaphors can describe this discourse, including transformation, sustainability transition, and reformist-radical change continuum [22]. This discourse is based on the critics of ‘business as usual’. Its strength is the ability of the SD concept to change in response to knowledge generation. Nabavi et al. [98] state that SD is a pathway that must be continuously constructed based on our values and knowledge about the systems.

According to the *transformative approach* to sustainability, the root of the problems in the environment and society is in the fundamental characteristics of the society and its interrelations with the environment. To avoid a crisis, therefore, radical changes are necessary. This calls for a transformation of the society and human relations with the environment [99]. This is supported by Kemp [100], who states that SD is a redirection of development and a never-ending process of progressive social change that evolves multiple transitions or system innovations. SD requires radical changes in the functional system and governance, needs and wants, cultures and practices. Transition theory is proposed as one of the relevant approaches to better understand and support the societal adaptation to sustainability.

Transitions can be represented as transformation processes in which socio-technical systems change in a fundamental way over a generation [101], or as a radical, structural change achieved in incremental steps [102]. Radical changes are important because incremental development can lead to lock-ins and sub-optimization. It is thus important to prevent lock-in of unsustainable technologies and practices, while introducing social and technical innovations. In this connection, van Eijnatten [103] defines a successful transformative change as a transition from “old thinking, old doing” to “new thinking, new doing”.

A transition is a result of changes or developments in different domains such as culture, ecology, economy, technology, institutions, or belief systems—ones that reinforce each other [101]. Changes in one system might affect the interrelated systems and cause unwanted effects. Thus, cooperation and interrelationships between systems and actors play a key role in the transformation [102]. It can be argued that transformation is a result of actions in different systems and at different levels of one system. Therefore, a transformation process must deal with complex interactions within the system as well as between the systems. These interactions are usually characterized by different reinforcement and feedback mechanisms.

Rotmans [6] argues that the symptoms of unsustainability reflect deep problems that are rooted in the societal structures and institutions. These problems are the result of different system failures, institutional (dominance of institutions that block innovation), social (worn-in behavior and habits that hamper change in behavior), and ecological (dominance of species or ecosystems that threaten biodiversity). Rotmans argues for a new form of planning that aims at sustainable innovation rather than optimization—one that takes complexity and uncertainty as a starting point, using experimenting and learning as a guiding principle. According to Rotmans and Loorbach [104], in order to combat system failures one has to restructure a system; i.e., transition. Different approaches to foster SD have emerged based on social theory, new forms of governance and the so-called complex systems approach. One of these is *transition management*, which has been propounded as a measure to achieve SD [100].

Achieving a better understanding of the dynamics of complex systems provides an opportunity to successfully influence such systems. The transition takes place within multiple domains and at different scales. Therefore, it is important for decision-makers to understand the cumulative effect of actions to sustain the whole system by maintaining the harmony between sub-systems. In other words, an action in one sub-system can have a significant impact on other parts of the system.

Limited research has been conducted in the field of SA when considered in the context of sustainability as a process of transition—and not as an integration of development and environmental goals [4]. Hence, the characteristics of CSA which underpins SD as a process of transition have not yet been sufficiently addressed. In the next section, we will address these characteristics as a contribution to bridging some of the identified knowledge gaps.

3.2. Characteristics of CSA supporting the transition discourse

In the previous section, the need for seeing sustainability as a process of transition or directed change to overcome the observed shortcomings of existing assessment methods was discussed. In order to support decision-makers within this discourse, CSA must be different from those arising from other discourses such as the ones considering SD as integration, limits, or justice and resilience [4].

Rotmans [6] criticizes the current paradigm that underlies SA since previous attempts to develop adequate tools had more or less failed. A prevailing approach is rooted in *neo-classical economics*, using the rational actor paradigm and equilibrium approximations to describe the behavior of actors. However, the neo-classical approach cannot address the complexity of SD since non-linear dynamics cannot be described in terms of equilibrium, efficient resource allocation, or price-driven actor behavior. Furthermore, Rotmans argues that new methods and tools are needed for SA. These should provide modeling capabilities that can semi-quantitatively (i.e. relative analysis instead of an absolute one) assess multiple dimensions of sustainability.

There are several shortcomings associated with CSA developed based on the current paradigm. Firstly, seeing sustainability as an end state led the measurement industry to assess a state of the system against the fixed threshold [98]. Second, “the most often used indicator lists are deficient with respect to the accurate (parsimonious and

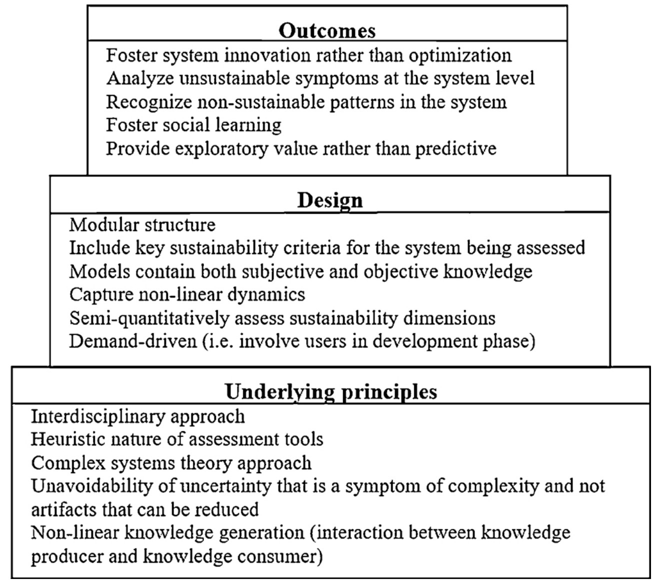

Fig. 1. Characteristics of CSA within the transition discourse.

sufficient) representation of the system and its problems”, since they fail to consider all dimensions of sustainability. Neither do they address the interdependency with other systems and interlinkages between the indicators [21]. These shortcomings could potentially be more effectively addressed by a new generation of CSA. In the context of the transition discourse, the focus is on guidance and navigation, instead of governance and measuring the state of the system. Hence, both process and dynamic targets within the scope of general sustainability goals should be addressed [98]. It could also be argued that CSA supporting decision-making toward sustainability transition should be built on a complex systems representation, rather than on an integrated system description by means of indicators lists. Future CSA methods have to better comprise the understanding of system dynamics and interrelationships between different systems [23].

Every evaluation is made based on some set of criteria for decision-making. Therefore, for the purpose of CSA, “a coherent set of explicitly identified and consistently applied criteria” is required [105]. This is supported by Kemp et al. [100], arguing that even if there exists dissent about appropriate solutions, it might be possible to define key parameters for future sustainable systems. Based on the works of Rotmans [6] and Haxeltine et al. [106], the characteristics of CSA methods to support decision-makers within the transition discourse were developed and presented in Fig. 1. The pyramid shape structure presents three types of characteristics: ones for underlying principles for CSA; ones for a design of the assessment method; and finally ones for outcomes of the assessment.

4. Holistic CSA method

4.1. CSA architecture

The new CSA method (a CSA architecture and an application guideline) was developed in order to overcome the shortcoming of existing CSA methods discussed in Section 2.3 and satisfy the requirements to the characteristics of CSA within the transition discourse (see Fig. 1). A CSA architecture was developed using a complexity-based model of SM presented in [7,8]. Moldavska and Martinsen [8] define SM as *a complex behavioral pattern to which any manufacturing company should tend to evolve.* This behavioral pattern is defined by the criteria for SM such as to improve operational effectiveness, improve professional knowledge and competence of employees, increase the wealth of the society, and reduce discrimination. An organization can be seen as

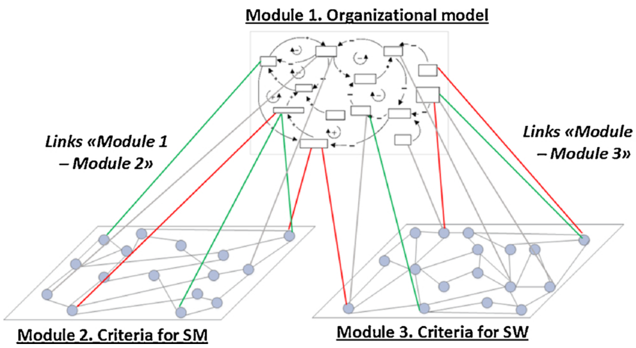

Fig. 2. Conceptual architecture of corporate sustainability assessment.

one that contributes to SM if it is continuously changing and its change is defined by the criteria for SM. The proposed definition can assist the developers of CSA in manufacturing by providing a comprehensive list of criteria that can guide the selection of sustainability indicators for different types of companies. Such an approach proposes a combination of a science-led process for defining criteria for SM and a business-led process for developing sustainability indicators. The criteria for SM are a base for indicator development ensuring a context-based assessment which measures what is important concerning the SM phenomenon.

An architecture of CSA that is able to address characteristics of the assessment within the transition discourse (see Fig. 1) and overcome the observed shortcomings of CSA methods (Exhibit 2) is presented in Fig. 2.

4.1.1. Module 1. Organizational model

The first module denoted Module 1 in Fig. 2, including the system representation of the entire manufacturing company, is designed to enable a context-based assessment. Since each company is different and there is no 'one-size-fits-all', this module should be developed for each particular company. A holistic representation of manufacturing organization should include technical and human elements and their interactions. In addition, material, information, energy, data, and knowledge flows should be presented. Since the knowledge of an individual is too limited to identify a consistent set of elements of the system, a participatory approach is suggested as the appropriate procedure to build the model of the company. System mapping can be obtained through participatory modeling with different employees, e.g., one from each functional unit of the company. A combination of different mental models can contribute to a more holistic and adequate representation of the system. Videira et al. [23] discuss the need for the integrating participatory model building with system dynamics to support CSA. Participation of employees in organizational modeling can help create a shared view of the company, enabling non-linear knowledge generation and including subjective knowledge in the model. Moreover, it ensures participation of potential users in the development stage of the CSA. Different tools can be used to develop organizational model that represents causalities and interrelationships between elements of the company.

4.1.2. Module 2 and module 3. Sustainability criteria

From the early beginning of sustainability assessment research, scientists argued for the use of systems approaches to structure the search for sustainability indicators [68]. However, this recommendation has rarely been followed by the developers of CSA methods. Therefore, to address this shortcoming, we argue that sustainability criteria should be the basis for indicators development, ensuring a more harmonized and systematic approach to assessment. This approach, i.e., to define sustainability through the criteria, is similar to the one proposed by Pope et al. [15], who suggested that sustainability can be represented within SA by means of sustainability criteria. Unified criteria can therefore be a common ground for developers of CSA, whereas the choice of indicators will depend on the specific company context. Sustainability criteria provide a framework for managing a system such as a manufacturing company, while indicators are the measure of performance and are used to infer the status of a criterion [107].

Module 2 and Module 3 in Fig. 2, include criteria for sustainable manufacturing and sustainable world (SW). A set of criteria for SM has been developed by Moldavska and Martinsen as a part of the definition of SM [8]. 76 criteria have been proposed based on content analysis of SM definitions and a literature review (Appendix A). A comprehensive list can provide a complete picture of sustainability as compared to a selective use of common or most known criteria. Criteria for SW are developed based on the SDGs [108] and are presented in Appendix B. Moreover, work on SDGs as a network has been published [109], arguing that relationships between goals are important for a transition to SD. Thus, there are several opportunities to present criteria for SW as a network in the future, as presented in Fig. 2. Moreover, Module 2 and 3 provide the flexibility to change as the general understanding of SD and SM evolves. This implies that SD within the adopted discourse (transition or directed change) can change over time.

Moldavska and Welo [5] suggested that the manufacturing company should be considered as a sub-system of the large system (i.e. world) that contributes to global sustainability, rather than focusing only on its own performance. However, for a practical reason, we present the criteria for SM and SW as separate modules. Therefore, some of the criteria in Module 2 can be similar to criteria in Module 3, particularly to criteria developed from the Goal 12 'Responsible Consumption and Production' (from SDGs). The purpose of the module 'Criteria for SW' is to enable assessment that indicates how a company contributes to SD of the larger system; i.e., the world.

4.1.3. Links between modules

Module 1 and 2, and Module 1 and 3 are linked by indicators. For each criterion in Module 2 and Module 3, sustainability indicators are developed and connected to the elements of the organizational model. Therefore, indicators are linking organizational model and sustainability criteria, forming the 'Criterion—Indicator—Element of organizational model' numerous links. Each indicator may have three main states: (1) green – indicating the positive contribution of an organization to SM and SW; (2) red – indicating the negative contribution an organization to SM and SW; and (3) grey – when data are not collected.

4.2. Application guideline

Application guideline provides the step by step instruction for the development of CSA tool, by customizing the CSA architecture to an individual company.

4.2.1. Stage 1. Develop organizational model

A model of the company is to be developed, representing dynamics and complexity. Involvement of employees is strongly recommended. Approaches as agent-based modelling, social network analysis, and system dynamics (both qualitative and quantitative) can be considered for modelling. The overall goal is to leverage the ability to identify places of interventions in the company.

4.2.2. Stage 2. Choose relevant sustainability criteria

A holistic set of sustainability criteria should be chosen from the proposed list (Appendix A, B). This list can be modified as the research community's understanding and conceptualization of SD and SM emerge. The choice of criteria has to be done by the specialist in sustainability and can be done either without company's participation or with limited participation. The company should not influence the choice too much since the list should include issues relevant for SD rather than what is more desirable or comfortable for the company, avoiding leaning from the sustainability concept in the direction of what the company wants.

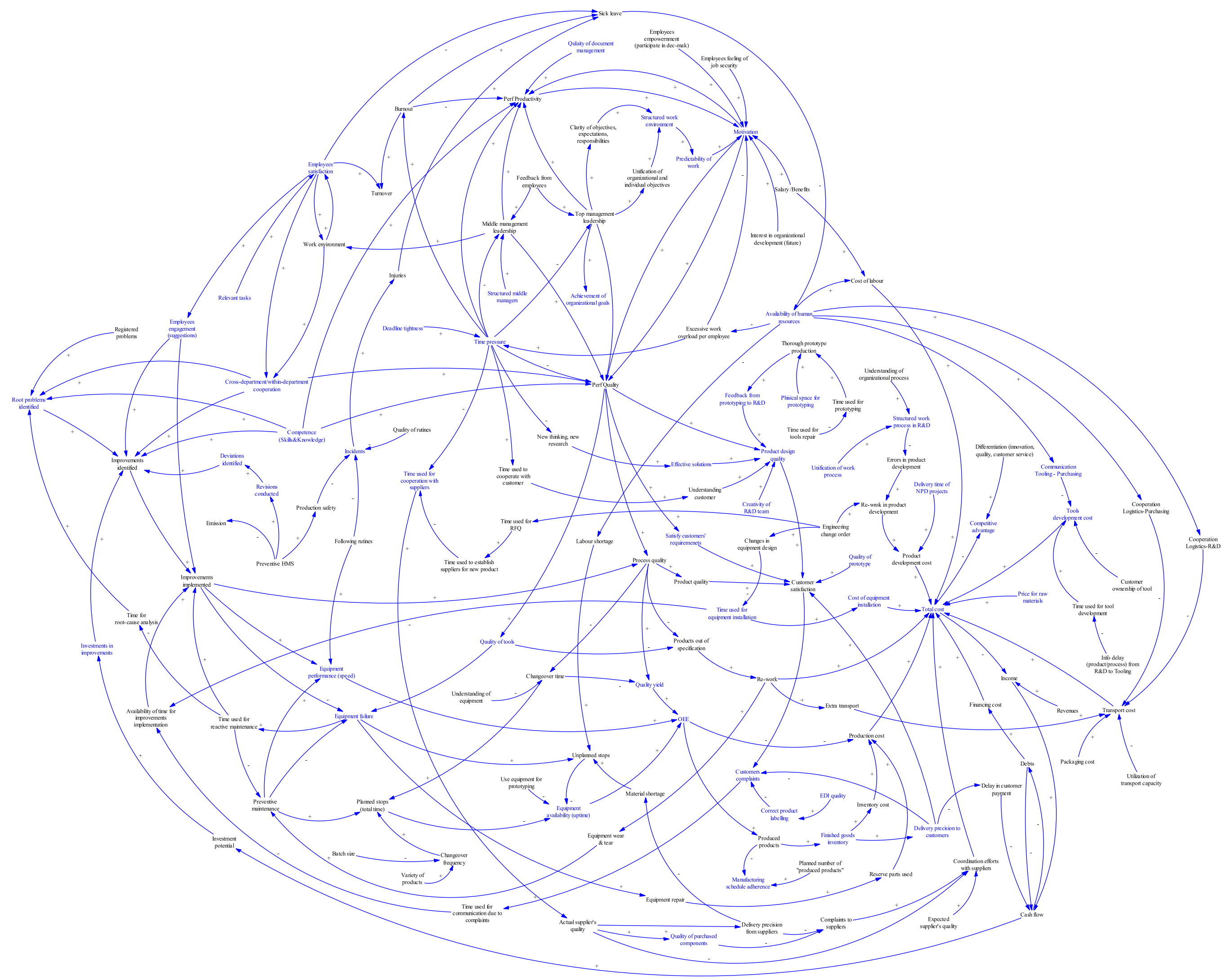

Fig. 3. Module 1. Organizational model of the case company.

4.2.3. Stage 3. Develop indicator(s)

Indicator(s) should be developed for each criterion, ensuring a mix of lagging and leading indicators. This ensures that both actual performance and actions toward sustainability are tracked. Lagging indicators will reveal performance patterns, while leading indicators can be used to track whether measures toward sustainability do change the performance of the company. The development should be guided by the list of criteria and avoid data driveness, i.e., when indicators are chosen based on what data are already available. Moreover, depending on the company's experience with sustainability assessment and formal measurement systems, employees' participation in indicators development can create a stronger feeling of ownership, which in turn will increase the acceptance of the resulting indicator list.

4.2.4. Stage 4. Identify desire direction for indicators

For each indicator, a desired direction of changes should be defined, i.e., 'increase' (for 'Total tax paid per year' indicator) or 'decrease' (for 'Hazardous chemicals used in production' indicator). For some of the indicators, the desired value can be identified, for example, for indicator 'Total number of safety incidents'.

4.2.5. Stage 5. Link criteria and organizational model

Identify corresponding variable(s) from the organizational model for each indicator, whenever possible. If there is no corresponding variable, then either leave the indicator without it or add relevant variable(s) to the organizational model.

4.3. Application of the new method

4.3.1. Case description

The CSA method was used to develop a CSA tool for a case company. Here it is important to emphasize that the purpose was not to assess sustainability performance of the case company, but to develop an assessment tool for it. The case company is a Norwegian automotive supplier, with 45 million euro turnover and 169 employees. First, an interview with the contact person was conducted, focusing on the background information about the company, including the revision of the documentation as strategy, products portfolio, yearly plans, indicators, metrics, code of conduct, IT systems. Second, a plant tour was conducted to observe and see the organization at work. Then, semi-structured interviews were conducted with different managers (Tooling, Plant manager, R&D, Industrialization, Production, Maintenance, HMS, Quality, Logistics, Purchasing, and Prototyping). On average, each interview lasted for 1.5 h. Interviews were conducted with the goal to collect mental models of managers to develop organizational model (Module 1).

The multiple semi-structured interviews were chosen as a suitable approach to collect the mental models of the managers. During the interviews, the focus was on the participants' ways to construct the meaning about the same phenomenon; i.e., the structure and behaviour of the company. The choice of individual interviews instead of a group interviews was motivated from the need to interact with the interviewees, to reduce the randomness of topics, increase the willingness to attend and talk openly about their views on how the company operates. All managers were ensured and agreed with anonymization in order to suppress their identity. The main focus was on how managers perceive/view the company: (1) what managers sees as the most important issues (e.g., for economy manager it can be cost, and for maintenance manager – motivation of his workers and availability of reserved parts), and what influences these issues and what these issues can influence; (2) what can describe the performance of his/her business unit (e.g., delivery time for logistics manager, safety incidents for quality manager); (3) what problems and challenges the department has. These three questions were used to guide the conversation, while maintaining flexibility to permit inquiry about new topics that emerged during the course of the conversation. The obtained data were further used to build the organizational model.

The mental models of the managers are important because managers in SMEs are the ones with the greater knowledge about the company and their decisions and actions define performance of the company, i.e., systems behaviour. Interviewing representatives from different departments allows addressing different interviewees' views and opinions based on his/her experience. Moreover, it ensures giving consideration to the whole organization instead of the view of a single employee.

4.3.2. Stage 1. Developing organizational model

Different approaches can be utilized to build an organizational model, including discrete event modeling, agent-based modeling, social network analysis, and system dynamics (both qualitative and quantitative) [110–116]. Although all approaches essentially can be used for creating an organizational model for CSA, we advocate for the qualitative system dynamics modeling since several aspects of manufacturing may be difficult to express in mathematical equations. Qualitative modeling using causal loop diagrams does not require mathematical formalism and can represent causal relationships within the company by visualizing mental models and capturing the dynamics implicitly contained in the interviewees' answers. Such an approach—i.e., building CLDs based on data from interviews—has previously proven to be effective in capturing and integrating mental models [117]. Therefore, organizational model (Module 1) for a case company was built using the causal loop diagram, and is presented in Fig. 3.

The purpose of an 'organizational model' is to customize the tool to the context of the company, i.e., type of functions and departments, B2B/B2C, make-to-order/make-to-stock, type of problems and challenges, work environment, organization of work, etc. Customization ensures that the result of the assessment is useful for identifying improvement opportunities by decision-makers in the company. Since a company contains many decision-makers with their multiple realities, an organizational model based on mental models of different managers ensures incorporation of knowledge and insights from different viewpoints. An integration of different mental models can contribute to a more holistic and adequate representation of the company. When the company is modeled as a part of the CSA, the purpose is not to create a perfect model in order to accurately and deterministically predict future behavior. Instead, the goal is to develop an accurate representation of mental models, one that is shared by decision-makers, in order to support decision-making process with 'what-if' type of questions.

For the development of organizational models, two alternatives were considered, (1) participatory modeling with different employees, e.g., at least one from each business function, or (2) development of a model based on the data from a set of one-to-one interviews with different employees. The former can provide a learning process and facilitate discussions around the elements and interconnections in the model. However, this approach may also prevent participants from being completely open about their opinions. The latter is beneficial in terms of openness of the participants which is central for the success to represent the company adequately. One of the possible shortcomings of this approach, however, is that the development of the model happens without employees' participation, thus hindering organizational learning and changing mental models. Another shortcoming is related to the influence of the actual setting on the interviewee. For example, the interviewee's implicit knowledge, the current situation in the company, and a time limit might influence thoroughness of the answers. This shortcoming can be resolved by the verification of the organizational model by either employees or specialists.

In this study, the organizational model was built iteratively based on the data from one-to-one interviews with different employees. First, one interview was analysed and variables and links with positive and negative polarity were drawn. Then, the next interview transcript was read, and variables and links were added to the previous diagram, thus building the model interview by interview. Since the organizational model was built based on the data from interviews, it represents how the structure and behavior of the company are seen by different managers. To enrich the model and verify the quality, focused group discussions were performed with five specialists in organizational management and operational management within the manufacturing. The specialists were selected based on their extensive experience in industry and academia.

Fig. 3 presents the complete organizational model for the case company, where variables in blue color are issues named by managers as what matters most to them, challenges they have, or what they think can describe performance of their business function. Although a myriad of variables and relationships could be depicted when conceptualizing the socio-technical system, the resulted model is considered to be relevant as a basis to discuss performance of the company since it is built based on the mental models of the managers who are the ones making decisions in these SMEs. The model describes the company as a system in terms of significant variables and relationships, defined by managers.

4.3.3. Stages 2-4. Selecting relevant criteria and developing indicators

First, relevant criteria were selected from the list of criteria for SW. The company did not influence the choice of the criteria, since the list should include issues relevant for SD rather than what is more desirable or comfortable for the company, thereby avoiding leaning from the sustainability concept in the direction of what the company wants. All criteria for SM were chosen. This resulted in 74 criteria for SW and 75 criteria for SM. Second, indicator(s) were developed for each criterion, and the desired direction for each indicator was chosen. An example of such an approach, i.e., minimization or maximization as a preferable value, has previously been used in measuring corporate sustainability [118]. During the development of indicators, the mix of leading and lagging [119], absolute and relative, and qualitative and quantitative indicators, was insured wherever possible.

4.3.4. Stage 5. Linking organizational model and sustainability criteria by indicators

The possibility to link criteria to the variables of the organizational model depends on the variables in the organizational model. For each indicator developed for sustainability criteria, a corresponding variable from the organizational model was identified. For example, for the indicator 'Total number of safety incidents', the corresponding variable is 'Incidents'. In the case when no corresponding variables are available for an indicator, the indicator was left without a variable. Table 1 shows an excerpt from the two tables: 'Criteria for SM — Indicators — Desired direction — Elements of organizational model', 'Criteria for SW — Indicators — Desired direction — Elements of organizational model' (links between Modules 1 and 2, and Modules 1 and 3).

Table 1
Modules 2 and 3, and links. Excerpt from the list of criteria, indicators, and corresponding elements of organizational model.

Criteria	Indicators	Desired direction	Element of organizational model
Sustainable World			
2.1. Reduce extreme poverty	Minimal wage for workers per year.	↑	Salary/Benefits.
	Total tax paid per year.	↑	Revenue.
	Range of benefits for workers.	↑	Salary/Benefits.
	Supplier price/Market price.	↑	Price for raw materials.
2.4. Reduce exposure and vulnerability to climate-related extreme events	Risk management related to climate-related events.	Y/N	
	Investments in resilience to environmental hazards and resource scarcity, NOK.	↑	Investment potential.
2.27. Reduce deaths and illness from hazardous chemical	Hazardous chemicals used in production.	↓	
	Hazardous chemicals in product.	↓	
2.28. Reduce deaths and illness from air, water, and soil pollution and contamination	Total air emissions (GHGs, ODS, NOx, SOx, POP, VOC, HAP, PM).	↓	Emission.
	Water quality within the company.	↑	
	Total water discharge by quality and destination.	↓	
	Total weight of waste by type and disposal method.	↓	
Sustainable Manufacturing			
1.3. Improve safety of technologies	Total number of safety incidents.	0	Incidents.
1.4. Reduce pollution to air during the whole LC of the product/service	Total air emissions (GHGs, ODS, NOx, SOx, POP, VOC, HAP, PM) during material extrusion.	↓	
	Total air emissions (GHGs, ODS, NOx, SOx, POP, VOC, HAP, PM) at the suppliers.	↓	
	Total air emissions (GHGs, ODS, NOx, SOx, POP, VOC, HAP, PM) during the production.	↓	Emission.
	Total air emissions (GHGs, ODS, NOx, SOx, POP, VOC, HAP, PM) during the distribution.	↓	
	Total air emissions (GHGs, ODS, NOx, SOx, POP, VOC, HAP, PM) during the use.	↓	
1.5. Improve customers satisfaction	Customer satisfaction.	↑	Customer satisfaction.
1.12. Ensure competitiveness of the product	Cost of product compared to similar products.	↓	
	Quality of product compared to competitors.	↑	Product quality.
1.13. Ensure competitiveness of the organization	Organizational income.	↑	Income.
	Organizational image.	↑	
	Technological advancement.	↑	
1.27. Improve quality of the process	Yield for process.	↑	Yield.
1.29. Improve reliability of the product	Failure rate of product in use.	↓	
1.34. Improve safety of processes	Hours of safety training per employee.	↑	
	Safety incidents per process.	0	Incidents.

4.4. Linking CSA architecture and CSA tool

Since the CSA architecture was developed based on the complexity-based model of SM, Fig. 4 illustrates the transition from the model of SM (top block) to CSA architecture (middle block), and, finally, to CSA tool for the case company (bottom block). The model of SM represents a ‘sustainable’ company as ‘a system that contributes to the sustainability of the larger system while maintains its own sustainability’, i.e., company should tend to contribute to the global sustainability, i.e., world (A1), as well as maintain its own sustainability (A2) [8]. Manufacturing company is a sub-system with its own sustainability values (A2) – SM, and global sustainability values (A1) – SW. A1 and A2 can be seen as complex behavioural patterns to which company is attracted. Behavioural pattern A1 is defined by sustainability criteria for the global system (sustainable world), whereas A2 is defined by sustainability criteria for manufacturing. Thus, a company can be seen as sustainable if it is continuously changing and this change is defined by the criteria for SW (A1) and SM (A2).

4.5. Guideline to apply CSA tool

Once the CSA tool is developed, sustainability performance of the company can be assessed and improvements can be identified by following the guideline.

4.5.1. Stage 1. Data collection

Establish the frequency of data collection for each indicator and continuously collect data. The frequency can be different for different indicators.

4.5.2. Stage 2. Data analysis

The data should be regularly reviewed. Each indicator is assessed against the desired direction and color coding is used. Compare whether changes in an indicator’s value matches the desired direction of change. If yes, then choose green color for the indicator (follow desired direction), otherwise choose red color (does not follow desired direction). If data are not available for a specific indicator, then choose grey (information is lacking).

4.5.3. Stage 3. Analyze red colored indicators

For an indicator colored in red, find corresponding variable(s) in the organizational model. Study and discuss variables that influence the corresponding variable. During the analysis and discussion, the variables in the model can be changed or added, and new links can be created. Linking indicators to variables in the organizational model is what creates the arena for discussion on how to improve organizational performance, including optimization and innovation.

Elements of the model should be continuously discussed and analyzed by the decision-makers during the root cause analysis of sustainability performance and identification of actions and potential improvements toward SD. At this stage, possible actions to improve the value of the indicator should be identified. Also, the list of indicators is dynamic and can be updated. Stages 1, 2, and 3 should be continuously repeated.

To guide decision-makers in identification of actions or sustainable manufacturing practices, a model ‘Domains—Performance—Instruments’ is proposed (Fig. 5). Once the assessment is conducted and links (indicators) between Module 1 and 2, and 1 and 3 are identified as red, green, or grey (see Fig. 2), the organization can identify instruments to improve

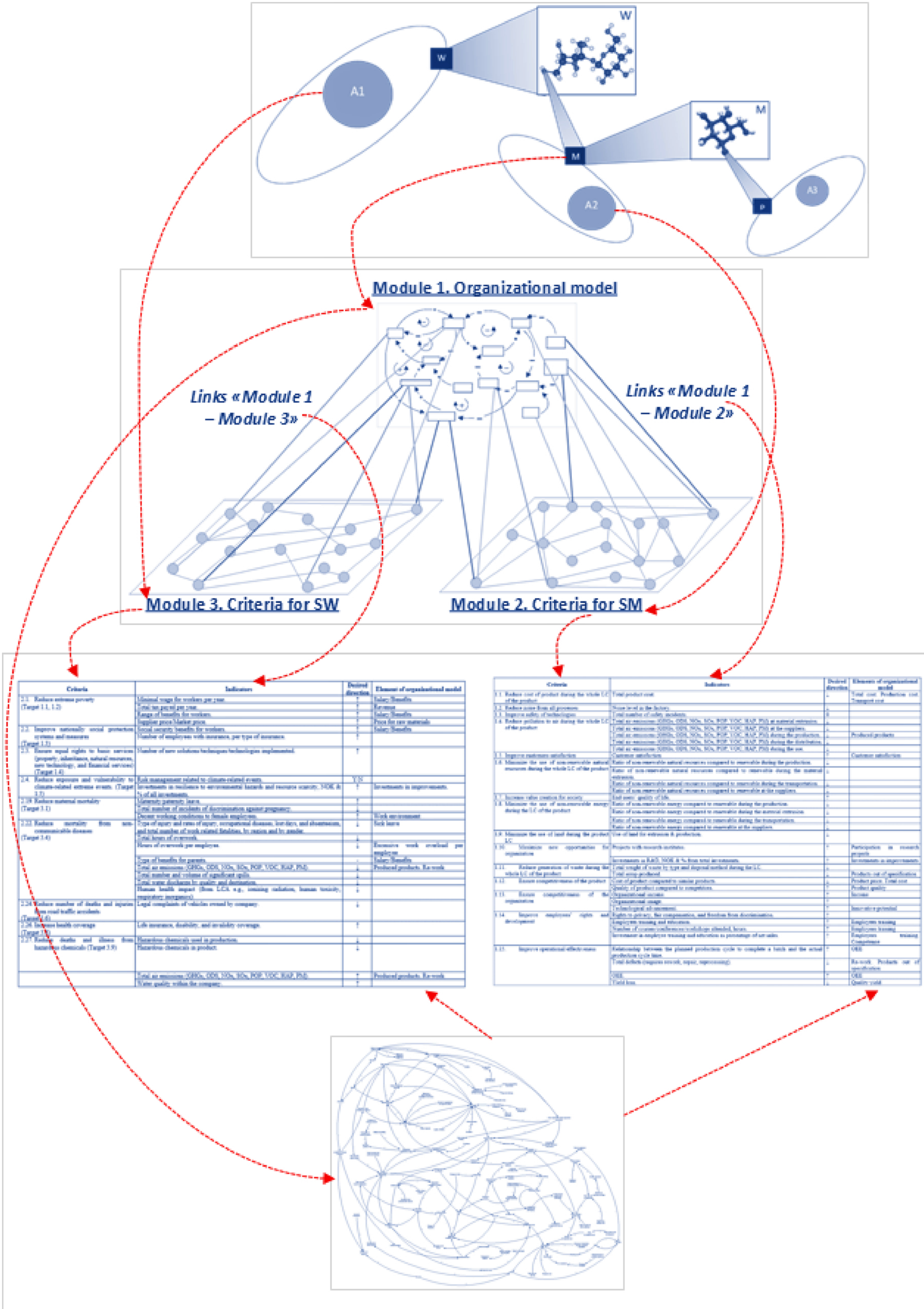

Fig. 4. Linking the model of SM, CSA architecture, and CSA tool.

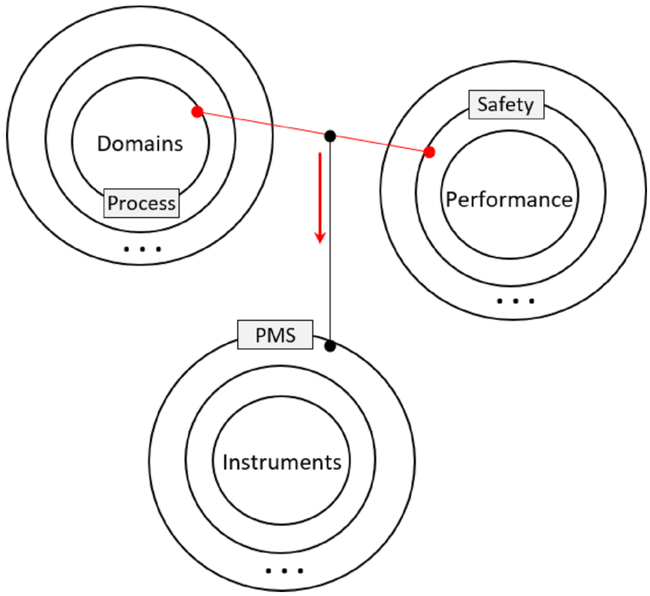

Fig. 5. Model 'Domains—Performance—Instruments' to identify practices for SM.

the performance of a particular domain. For example, if the assessment identified that for criteria 'Improve safety of processes', indicator 'Safety incidents per process' is red (see Table 1), then domain 'process' and performance 'safety' in Fig. 5 are connected. Next, following the line down (red arrow in Fig. 5) to the module 'Instruments', existing instruments or practices can be identified, e.g., process safety management (PMS). The use of this model will require the database of the practices for sustainable manufacturing. A wide range of sustainable manufacturing practices has already been described in the literature, see, e.g., [120,121], in addition to attempts made to develop a library with sustainable manufacturing practices [122]. The proposed model can be used to identify possible tools, methods, or practices to improve sustainability performance of a company.

5. Verification of the CSA method

The new CSA method (CSA architecture and the application guideline) is a result of the design and development research. The quality of the method is evaluated against the previously defined set of desirable properties the method should satisfy. After the CSA method was tested, i.e., used to develop CSA tool for a case company, a feasibility evaluation of method was performed as part of the verification phase. In this paper, we evaluate the capability of the new method to (1) satisfy the required characteristics of CSA within the transition discourse (Figs. 1 and 2) overcome some of the observed shortcomings of existing CSA methods and tools presented in Exhibit 2 . The later, was done to demonstrate the added value provided by the new CSA method, comparing to the state of the art. The method of inclusion or consideration in the new CSA is described for each aspect in Table 2.

The proposed method conceptualizes sustainability through the criteria, which are then used to develop sustainability indicators. The use of a holistic set of criteria as a base for indicators development ensures that CSA measures what is relevant for sustainable development instead of what is measurable. The architecture enables a context-based assessment of the company while covering the span of issues associated with sustainability. Moreover, it aims to support a holistic representation of the company, providing potential to serve as a management tool for guidance toward more sustainable capabilities and practices in manufacturing companies. The architecture of CSA—specifically the links between the model of the company and criteria for both SM and SW—enables a transition to sustainability instead of maintaining the status quo of current practices and organizational culture. Therefore, it can support the sustainability discourse, in which sustainability is seen as a process of a directed change or transition [4]." Sustainability transition implies among others a shift in dominant practices. Thus, practices such as LCA, DfE, recycling, etc., which are commonly used as sustainability indicators, should not be the primary focus of the assessment tool. Instead, criteria of SM should be explicitly presented and accounted for.

If the goal is system innovation instead of a system optimization, as discussed above, changes are required at the system level rather than within sub-systems. In order to apply changes on the system level, the assessment must also cover the system perspective. If holistic improvements or changes are expected—as in the case of sustainability transition—an SA that focuses only on parts of the organization, or on a single sustainability domain, will in best case be incomplete. No part of the system can be changed without triggering changes across the whole organization. According to Bérard [123], in the case of complex systems, changes might not lead to the intended result if the design fails to take into account key feedback loops. Thus, systems representation should be an integral part of the CSA.

A too narrow system scope can jeopardize decision-making, failing to address interdependencies within the system, which in turn may mislead decision-makers. Even though a full integral representation of social-cultural-economic-technological-environmental systems is impossible [6], a more holistic approach to the representation of the organization should be chosen with the focus on the analysis of interactions and feedback loops between the components of the manufacturing system. This can enable the identification of non-sustainable patterns that have to be changed during the sustainability transition.

6. Concluding remarks and future work

The main research question of this paper was "What design of CSA method can overcome existing shortcomings and challenges, and enable manufacturing companies to report on their contribution to SDGs?" The list of the shortcomings of the current CSA methods was our motivation for a development of a new CSA method. The use of a reductionist approach and the lack of a comprehensive definition of SM are one of the main reasons for the existing shortcomings and challenges of CSA. Thus, as a means to address the underlying problems, we built CSA method upon the sustainability discourse of a 'transition or directed change'. This led us to the use of a systems view on CSA, complexity-based definition of SM, and criteria-based development of indicators.

The main contribution of this paper is the CSA method for manufacturing companies that adresses shortcomings of the existing CSA methods, and incorporates SDGs into assessment of an individual company. We presented the architecture of CSA, the guidelines to develop a CSA tool, and the guideline to assess the sustaianbility perfrmance of the company using the CSA tool. To summarize, the key characteristics of the new CSA method are:

- SM is defined through the model of SM, using complexity theory;
- the model of SM is a frame for CSA architecture;
- CSA architecture has a modular structure: Module 1 – dynamic organizational model, developed for each company, Module 2 – sustainability criteria for manufacturing, Module 3 – sustainability criteria for world;
- the organizational model is developed based on mental models of managers, using qualitative system dynamics;
- criteria for SW are developed from SDGs;
- criteria for SM are developed based on the current state of the art;
- criteria are flexible, satisfying adaptability requirement and dynamism principle of sustainable development;
- criteria-based indicators development, integrating scientific-led development of criteria and business-led development of indicators;
- indicators are not aggregated;
- for each indicator, the desired direction is defined;

Table 2
Evaluation of CSA method against the requirements to the characteristics of SA within the transition discourse and observed shortcomings of existing CSA methods.

1. Requirements to the characteristics of CSA within the transition discourse:	Method of inclusion or consideration in the design of CSA:
Outcomes:	
Foster system innovation rather than optimization	Since the organizational model is linked to the list of criteria, which 'pulls' a company toward sustainable development instead of only optimizing the usual issues, presented in organizational model. The tool focuses on both innovation and optimization.
Analyze unsustainable symptoms at the system level	Company as a system is modeled and linked to global SD.
Recognize non-sustainable patterns in the system	Through indicators linked to both the company and criteria.
Foster social learning	Changing mental models by discussing indicators in relation to the organizational model.
Provide exploratory value rather than predictive	Through the choice to not aggregate the indicators and allowing the exploration of the reasons for any undesirable indicator value.
Design:	
Modular structure	Three modules: two include sustainability criteria and one – organizational model.
Include key sustainability criteria for the system being assessed	Sustainability criteria for SM and SW are included.
Models contain both subjective and objective knowledge	Subjective knowledge is included by means of managers' mental models as a base for an organizational model, objective – by the analytical approach to defining SM and sustainability criteria.
Capture non-linear dynamics	Non-linear dynamics of a company is captured by CLDs in Module 1.
Semi-quantitatively assess sustainability dimensions	Desired direction for indicators is chosen instead of desired values.
Demand-driven (i.e., involve users in development phase)	Managers who make decisions are involved in organizational modeling. Also employees should be consulted regarding the indicators development when possible.
Underlying principles:	
Interdisciplinary approach	Addressed by using criteria from SDGs (which were developed by an interdisciplinary team) and participation of managers from all functions for organizational modeling.
Heuristic nature of assessment tools	The result aims to gain more insight into and achieve a better understanding of the problem areas (red indicators), rather than provide a deterministic value of company's sustainability performance.
Complex systems theory approach	SM is defined using the complexity theory. CSA is developed using the systems approach.
Unavoidability of uncertainty that is a symptom of complexity and not artifacts that can be reduced	The aim of the proposed CSA is not to avoid uncertainty of the dynamic interconnections in a company, but to model it to a possible extent for a continuous discussion.
Non-linear knowledge generation (interaction between knowledge producer and knowledge consumer)	Development of organizational model and choice of relevant criteria for a company is done by interaction between specialist (sustainability researcher/professional) and users (managers).
2. Shortcomings of existing CSA methods:	
CSA fails to address system performance;	Manufacturing company is modeled as a part of global socio-ecological system using dynamic modeling and holistic set of sustainability criteria.
Use of incomprehensive and unsystematic lists of indicators for CSA in manufacturing;	Indicators are developed for each criterion for SM and SW. Thus, the resulting list of indicator is systematic and comprehensive.
CSA tend to mix sustainability performance of company and sustainability-oriented practices (most of them do not distinguish between the extent of implementation of sustainability-related practices and actual sustainability performance of the organization);	The purpose of CSA is to evaluate the contribution, for each criterion indicators of actual performance and sustainability-oriented practices are included (leading and lagging), but not aggregated into an index.
Organizations measure what is measurable rather than what is important concerning the SM, due to the challenge to address simultaneously organizational context and SM phenomenon (context-based & Global SD);	What to measure is defined by the comprehensive list of criteria, selected by the specialists. The context is addressed by developing an organizational model for each company and choosing relevant criteria systematically, partly involving the company.
The inability of many CSAs to provide a practical approach for the companies to identify improvements and possible sustainability-oriented practices;	Improvements can be identified by analyzing the organizational elements linked to the indicators that should be improved (red).
The use of a set of unrelated indicators, since an assessment of separate entities without considering relationships between them neglects the dynamics of the company;	Indicators are linked to the elements of an organizational model, which are connected by cause-effect relationships.
The inability of some CSA to capture the complexity of SM—relationships between sustainability issues and interlinkages between elements of the organization—due to a widely used reductionist approach to CSA.	Complexity of a manufacturing company and sustainable development is addressed by separating them into two blocks: organizational model and sustainability criteria (SM/ SW). Organizational model focuses on the interlinkages between elements of the company. Assigning the variables from the organizational model to indicators captures relationships between sustainability issues.

- indicators are links between criteria and organizational model.

The proposed approach to CSA can enable companies, which do not yet have established a sustainability strategy, to define potential interventions towards sustainability. The use of CSA for identification of areas of concern or potential improvements can allow the company to formulate a sustainability strategy and identify goals and targets. Assessment as a prerequisite for a sustainability strategy formulation was already discussed in the literature [124]. We argue for CSA being a first step taken by manufacturing companies to pursue SD—in contrast to a more widely used approach that follows the path of a strategy formulation, goals and targets identification, and a progress assessment. Singh et al. [27] demonstrated how the use of CSA can be used for development of the strategy, by identifying weak areas of performance which require appropriate strategy to enhance the overall sustainability. A holistic CSA as a basis for strategy development can safeguard companies from leaning the concept of SM towards their perceptions, interpretations, and definitions of the concept and thus prevent them from taking actions that do not contribute to sustainability or lead to sub-optimization.

Due to the space limit, this paper includes the result of only one case study. The more extensive validation of the proposed CSA method by means of an in-depth, multiple case study will be presented in the next research paper. Moreover, future work will focus on study of the interconnections between the criteria for sustainable manufacturing and between the criteria for sustainable world.

Appendix A. Criteria for SM

Reduce cost of product during the whole LC of the product/service	Improve professional knowledge and competence of employees
Reduce noise from all processes	Improve safety of systems
Improve safety of technologies	Ensure compatible salary
Reduce pollution to air during the whole LC of the product/service	Reduce pollution to soil during the whole LC of the product/service
Improve customers satisfaction	Improve employees satisfaction
Minimize the use of non-renewable natural resources during the whole LC of the product/service	Minimize the use of toxic materials during the whole LC of the product/service
Increase value creation for society	Increase employee involvement and empowerment
Minimize the use of non-renewable energy during the whole LC of the product/service	Provide democratic processes and accountable governance structures
Minimize the use of land during the whole LC of the product/service	Minimize the use of water during the whole LC of the product/service
Maximize new opportunities for organization	Increasing the wealth of the society
Reduce generation of waste during the whole LC of the product/service	Improve the quality of life (employees, customers, and society)
Ensure competitiveness of the product/service	Decrease in the frequency of environmental accidents
Ensure competitiveness of the organization	Provide equitable opportunities for all employees
Improve employees' rights and development	Ensure fairness on employee wages and benefits
Improve operational effectiveness	Ensure organizational survival
Improve operational efficiency	Encourage workplace diversity
Ensure social equity	Ensure acceptable working hours
Increase functionality of the product	Improve company reputation
Protect personal health during the whole LC of the product/service	Maximize effectiveness of product/service over the whole LC
Increase innovation (through innovative techniques/ methods/ technologies/ practices/ products/ services	Reduce pollution to water during the whole LC of the product/service
Improve information security and cybersecurity	Ensure conformance to laws and regulations
Enhance learning of employees	Ensure fair competition
Improve conditions of work and social protection for employees	Increase productivity of employees
Increase organizational productivity	Improve occupational health and safety
Increase organizational profitability	Ensure freedom of association and collective bargaining
Improve quality of the product/service	Reduce discrimination
Improve quality of the process	Improve restoration of natural habitats
Improve quality of systems	Increase employment creation
Improve reliability of the product/service	Improve well-being of local communities
Improve reliability of processes	Ensure human rights for employees
Improve reliability of technologies	Improve work-life balance for employees
Improve reliability of systems	Respect indigenous rights
Improve safety of the product/service	Responsible political involvement
Improve safety of processes	Increase social investment
Ensure fairness on employee wages and benefits	Increase supplier support and collaboration
Reduce employee turnover	Ensure customers' rights
Protect biodiversity	Increase stakeholder engagement
No bribery and corruption	Threat suppliers fairly

Appendix B. Criteria for SW

Reduce extreme poverty	Improve global financial markets/institutions
Improve nationally social protection systems and measures	Increase proportion of members from developing countries in global international institutions
Ensure equal rights to basic services (property, inheritance, natural resources, new technology, and financial services)	Improve migration policies
Reduce exposure and vulnerability to climate-related extreme events.	Improve mobility of people
Reduce exposure and vulnerability to economic/environmental/social shocks and disasters	Improve imports treatment for developing countries
Reduce poverty (below the national poverty line)	Increase resource flows for development to developing countries
Contribute to poverty reduction programmes	Reduce remittance costs
Ensure access to safe, nutritious and sufficient food	Reduce slums
Reduce malnutrition	Increase access to safe, adequate and affordable housing
Increase agricultural productivity	Increase access to safe, adequate and affordable transport
Increase incomes of small-scale food producers	Improve road safety
Ensure sustainable food production systems	Expand public transportation
Increase implementation of resilient agricultural practices	Increase participation of civil society in urban planning/management
Strength capacity for adaptation to climate change and extreme events	Preserve world's cultural and natural heritage
Increase genetic diversity (plants, animals)	Reduce number of deaths and affected by disasters
Increase agricultural productive capacity	Reduce economic loss caused by disasters
Reduce trade restrictions in world agricultural markets	Reduce urban solid waste
Ensure proper functioning of food commodity markets	Reduce air pollution
Reduce maternal mortality	Increase amount and accessibility of green spaces
Reduce neonatal mortality	Increase cooperation between urban, peri-urban and rural area
Reduce the epidemics of communicable diseases	Increase implementation of integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters
Reduce mortality from non-communicable diseases	Increase financial and technical support for building sustainable and resilient buildings
Reduce use of narcotic drugs and alcohol	Implement SCP national action plans
Reduce number of deaths and injuries from road traffic accidents	Reduce the use of natural resources
Increase access to sexual and reproductive health-care services	Reduce food waste and food losses

Increase health coverage	Reduce releases to air/water/soil of chemicals and all wastes throughout their life cycle
Reduce deaths and illness from hazardous chemical	Reduce waste generation
Reduce deaths and illness from air, water, and soil pollution and contamination	Publication of sustainability reports
Strength the implementation of tobacco control	Increase the use of sustainable public procurement practices
Increase R&D of vaccines and medicines	Promote education about sustainable development
Increase financing/training/development/retention of health workforce	Support developing countries in scientific and technological capacity
Strength the capacity for early warning, risk reduction and management of health risks	Implementation of tools to monitor SD impact for sustainable tourism
Ensure free, equitable and quality primary and secondary education for all girls and boys	Reduce the use of fossil-fuel
Ensure access to quality early childhood development, care and pre-primary education	Increase resilience and adaptive capacity to natural disasters
Ensure equal access to affordable and quality technical, vocational and tertiary education	Increase adaptation to climate change
Increase the number of youth and adults with relevant skills for development/decent jobs/entrepreneurship	Foster climate resilience
Eliminate genders disparities in education	Reduce GHG emission
Ensure access to education/training for vulnerable	Improve education on climate change mitigation/adaptation
Ensure literary and numeracy for youth and adults	Increase number of CC mitigation actions
Improve knowledge and skills to promote SD	Increase support for developing countries for CC-related planning and management
Upgrade/build education facilities	Reduce marine pollution
Expand scholarships for developing countries	Improve marine and coastal ecosystems
Increase the supply of qualified teachers in developing countries	Minimize ocean acidification
Reduce discrimination against all women/girls	Reduce overfishing
Eliminate violence against women	Reduce destructive fishing practices
Eliminate harmful practices for women	Increase protected coastal and marine areas
Recognize unpaid domestic work and care	Reduce illegal, unreported and unregulated fishing
Ensure equal opportunities for women for leadership	Improve sustainable management of fisheries, aquaculture and tourism
Ensure access to sexual and reproductive health and rights	Increase research and transfer marine technology (increase scientific knowledge)
Ensure legal rights to land ownership for women	Increase access for small-scale artisanal fishers to marine resources
Provide rights to economic resources to women	Implement legal frameworks for conservation and sustainable use of oceans
Increase the use of technology to empower women	Increase conservation and restoration of freshwater ecosystems
Promote gender equality	Increase conservation and restoration of terrestrial ecosystems
Increase access to safe and affordable drinking water	Decrease deforestation
Increase sanitation and hygiene	Increase afforestation
Improve water quality	Improve mountain ecosystems
Increase water-use efficiency	Reduce degradation of natural habitats
Reduce water scarcity	Reduce loss of biodiversity
Improve water resources management	Increase equal sharing of genetic resources
Protect and restore water-related ecosystems	Decrease illegal trafficking of species
Help developing countries with water- and sanitation-related activities and programmes	Reduce an impact of invasive alien species on land and water ecosystems
Increase partnership of local communities in improving water and sanitation management	Integrate ecosystem and biodiversity values into national planning
Provide access to affordable and reliable energy services	Increase financial resources to conserve and sustainable use of ecosystems and biodiversity
Increase the use of renewable energy	Increase financial resources to sustainable forest management
Improve energy efficiency	Reduce trafficking of protected species
Increase access to clean energy research and technology	Reduce violence and deaths rates related to violence
Increase investments in energy infrastructure	Reduce abuse, exploitation, trafficking and violence against children
Increase investments in clean energy technology	Promote the rule of law
Sustain economic growth	Reduce illicit financial and arms flows
Increase economic productivity	Reduce corruption and bribery
Ensure technological upgrading and innovation	Improving public institutions
Increase decent job creation	Improve decision-making at all levels (responsive, inclusive, participatory, representative)
Ensure creativity and innovation	Increase a participation developing countries in the institutions of global governance
Improve resource efficiency in consumption	Increase legal identity for all
Provide decent work for people with disabilities	Improve public access to information
Provide employment to young people	Protect fundamental freedoms
Minimize forced labor	Increase independent national human rights institutions
Minimize child labor	Reduce discrimination and harassment
Improve safe and secure working environment	Increase domestic capacity for tax and other revenue collection
Promote sustainable tourism (creates jobs, promote local culture and products)	Increase financial assistance to developing countries
Increase access to banking, insurance and financial services	Help developing countries to reduce dept
Increase Aid for Trade support for developing countries	Increase investments in least developed countries
Increase youth employment	Increase international cooperation on science, technology and innovation
Improve infrastructure	Increase international knowledge sharing on science, technology and innovation
Increase industry's share of employment and gross domestic product	Increase the use of ICT and other technologies in least developed countries
Increase the access of small-scale enterprises to financial services	Increase support of effective and targeted capacity-building in developing countries to implement SDGs
Increase resource-use efficiency	Improve multilateral trading system (universal, rules-based, open, non-discriminatory and equitable)
Increase scientific research	Increase the export of developing countries
Increase resilience of infrastructure	Increase duty-free and quota-free market access for least developed countries
Support domestic technology development	Increase microeconomic stability
Increase research and innovation in developing countries	Enhance policy coherence for SD
Increase access to ICT and Internet	Respect internal (country) policy and leadership for poverty eradication and SD
Increase income of the bottom 40% of population	Improve global partnership for SD
Reduce proportion of people below 50% of median income	Improve public, public-private and civil society partnership
Reduce inequalities and discrimination	Increase capacity-building support for increasing data availability for SD
Adopt policies to decrease inequality	Improve measurement of progress on sustainable development

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