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Brief Overview of Collaborative Approaches in Sustainable Manufacturing

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Abstract. The manufacturing sector is experiencing a profound transformation as reflected in the Industry 4.0 movement, combined with the growing societal concerns for sustainability. This trend has led to the notion of sustainable manufacturing. On the other hand, the increasing interconnectivity among organisations, people, and physical systems, supported by recent developments in communication technologies, points to the important role that collaborative networks have in the ongoing digital transformation processes. As such, this paper analyses the synergies between sustainable manufacturing and collaborative networks. More specifically, the goal is to analyse how the responsibility for the various facets of sustainability can be distributed among the multiple entities involved in manufacturing. This study is based on both literature survey and our experience in various research projects in the area and is organised according to the typical six dimensions of Industry 4.0. The work is complemented with a brief summary of proposed indicators to measure sustainability under this networked manufacturing perspective.

Keywords: Collaborative networks, Sustainability, Sustainable manufacturing, Industry 4.0, Digital transformation, Sustainability indicators.

1 Introduction

The manufacturing sector has experienced considerable evolution in the last decade as reflected in the Industry 4.0 and digital transformation "movement". The convergence of multiple new technologies and the political support to this "industrial revolution" led to the emergence of new organisational and managerial forms, new processes, extended notion of product-service, and new business models.

In parallel, the manufacturing world also faces the challenge of coping with a growing societal claim for sustainability. This is reflected, for instance, in the UN Agenda 2030 [1], which establishes 17 goals for sustainable development. Manufacturing has a crucial role in this context, as addressed in the various sub-items of Goal 9, "Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation". But other (indirect) links to manufacturing

can also be found in other goals of the Agenda, e.g., "double the global rate of improvement in energy efficiency", "achieve higher levels of economic productivity through diversification, technological upgrading and innovation", "promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalisation and growth of micro-, small- and medium-sized enterprises", etc. As such, in recent years the term "sustainable manufacturing" [2] is becoming more relevant.

As identified in [3], there is a great potential for mutual beneficial synergies between the fields of collaborative networks and sustainability science. This was one of the earliest works arguing that sustainability requires a wide collaboration among multiple stakeholders, not being possible to achieve by individual entities. On the other hand, collaborative networks have also been pointed out as a core enabler for Industry 4.0 and digital transformation [4, 5]. Given this context, this work is guided by the following general research question: *What is the role of collaborative networks in sustainable manufacturing?* More specifically, we are interested in analysing how the responsibility for the various facets of sustainability can be distributed among the multiple entities involved in networked manufacturing systems.

As this research is ongoing work, this paper mainly tries to identify and categorise relevant examples and trends to help understand the synergies among these three areas: collaborative networks, manufacturing, and sustainability.

2 Base Concepts and Research Method

In this section, some base concepts are briefly revisited in order to provide a context for the following discussion.

The notion of sustainability is typically analysed under three perspectives: environmental, economic, and social [3]. Such a notion involves considerable complexity, not only because of this multi-dimensional nature, but also because it calls for a difficult balance among objectives that are often conflicting and involving multiple stakeholders. When it comes to manufacturing, various related terms are often used, including sustainable manufacturing, industrial symbiosis, and circular economy.

Sustainable manufacturing has emerged in recent years as the "*integration of processes and systems capable to produce high quality products and services using less and more sustainable resources (energy and materials), being safer for employees, customers and communities surrounding, and being able to mitigate environmental and social impacts throughout its whole life cycle*" [6]. A similar definition is provided in [i], which further refers the need to be "economically sound".

Industrial symbiosis can be seen as one specific implementation of sustainable manufacturing representing a "*process by which the wastes or by-products of an industry or industrial process become the raw materials for another*" [7]. This notion implies a collective endeavour through which a group of separate industries form a kind of collaborative business ecosystem to exchange materials, energy, water and by-products [8]. It implies moving from a linear model of "take-make-dispose" to a circular model in which waste is valorised as a resource.

Circular economy is a more general concept, which focuses on "*higher resource utilisation by recollecting and reusing components of products after their use is over*" [9]. In other words, it "*enables the reintegration of materials into production processes through their reuse, recycling, and recovery*" [10]. From a traditional point of view, while circular economy focuses on the entire economy, sustainable manufacturing appears focused solely on the manufacturing phase [11]. However, when we take the Industry 4.0 view, and the notion of extended smart product and the need of considering the whole life cycle of the product, the notions of sustainable manufacturing and circular economy get a bigger overlapping.

The effective materialisation of all the above notions implies some form of collaboration among multiple stakeholders, and thus, the role of collaborative networks in support of sustainable manufacturing deserves attention. In fact, the common notion of **collaborative network** as "*composed of a variety of entities – organisations people and even smart machines – which are largely autonomous, geographically distributed, and heterogeneous in terms of their operating environment, culture, social capital and goals... that collaborate to (better) achieve common or compatible goals*" [12] provides a comprehensive view of the interactions and inter-dependencies among the multiple entities involved in a manufacturing system. The notion of community or business ecosystem, as implicit in Virtual organisation Breeding Environments, helps to build a better perception of co-responsibility of all involved actors regarding the sustainability challenges [3].

In this work, as a preliminary stage to understand the synergies among sustainability, manufacturing, and collaborative networks, we adopted a mixed method, combining a systematic mapping study based on literature with case studies / acquired experiences from various research projects. On the other hand, the study of such synergies is also expected to contribute to a better understanding of the next generation of collaborative networks. In fact, a business ecosystem or any other form of a collaborative network not only involves collaboration but rather a complex and dynamic mix of collaboration and competition. In such business communities, there is some form of "survival instinct" and shared vision that can lead members to align their commitments and to find mutually supportive roles. By further expanding these ideas, we hope to acquire new insights on better organisational and governance principles that will likely contribute to more sustainable business ecosystems.

3 A Collaborative Networks View of Manufacturing Systems

Various recent works have presented collaborative networks as one of the core enablers for Industry 4.0 and the ongoing digital transformation process [4, 5, 13, 14]. In fact, considering the typical dimensions of the current industrial revolution, including both the manufacturing system and product/service perspectives, it becomes clear that we need to deal with, at all levels, networks involving multiple actors, being them organisations, people, smart machines, and smart systems, with varying degrees of autonomy and heterogeneity. The highlights of such a trend are illustrated in Fig. 1, which go far beyond the traditional view of networks applied to value chains and

rather influence all dimensions of Industry 4.0.

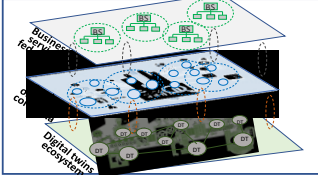
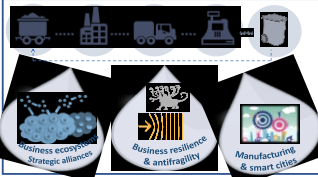


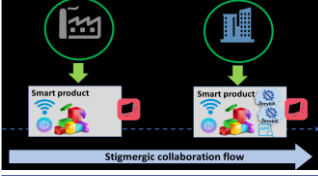
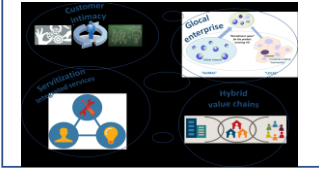
Manufacturing system perspective	Vertical integration or networking of smart production systems		<ul style="list-style-type: none"> Increasing smartness of devices and sub-subsystems -> leading to multi-layered networked ecosystem of smart entities and digital twins Emphasis on collaboration, not on control
	Horizontal integration through global value chain networks		<ul style="list-style-type: none"> Collaboration along the value chain Collaborative logistics networks Collaboration in circular economy and industrial symbiosis (notion of green virtual enterprise)
	Acceleration of manufacturing		<ul style="list-style-type: none"> Involvement of new actors (representing exponential technologies) Nomadic collaboration New interaction forms (VR/AR) Collaboration M-M, H-M
Product/Service perspective	Through-engineering across the entire value chain (end-to-end engineering)		<ul style="list-style-type: none"> Internal (multi-department) and external collaboration (co-design, co-innovation, open innovation) Multi-stakeholder collaboration along product life-cycle
	Smart products & Digitalization of products and services		<ul style="list-style-type: none"> Stigmergic collaboration in development of smart products Collaboration in traceability / product history Collaboration in added-value services Digital twins of smart products
	New business models and customer engagement		<ul style="list-style-type: none"> Collaboration with customers (customer intimacy) Hybrid value chains re-enforcing sustainability Implementation of <i>glocal</i> enterprise Servitization / service-enhanced products

Fig. 1 – Dimensions of Industry 4.0 and role of Collaborative Networks

This view of a manufacturing system as composed of multiple networks of autonomous or partially autonomous entities implies a distribution of responsibilities among these entities. As such, also the issue of sustainability needs to be analysed under a collaborative networks perspective in the sense that multiple entities/sub-systems are co-responsible for the sustainability level of the manufacturing system.

The role of CNs in sustainability has been addressed in relation to the horizontal integration dimension, namely in terms of circular economy and industrial symbiosis, or in relation to new business models, such as some cases of hybrid value chains [10,

8]. However, the issue has been less studied in the case of the other dimensions, which justifies an effort to analyse existing trends and relevant examples in order to characterise research gaps.

4 Trends and Examples

The latest developments associated with Industry 4.0 have focused on developing solutions aimed at introducing more sustainable manufacturing practices, not only from the point of view of costs and profit but also considering the other two pillars of sustainability, related to social and environmental aspects. Although this trend towards more sustainable ecosystems can be noticed, an assessment is not usually made of how the collaboration aspects are directly or indirectly related to improving these complex ecosystems. These distributed and complex systems imply constant communication between the players to optimise the systems, whether from an economic, social and/or environmental points of view.

The association of the collaborative perspective with these systems is usually not much explicit in the manufacturing literature, besides the obvious case of the horizontal dimension. However, in many studies, it is possible to identify that collaboration is an essential aspect in the design and operation of these complex environments. For example, it is possible to find shopfloors' implementation where machines collaborate with each other and/or with the operators. Another case widely observed in the literature is the optimisation of distributed manufacturing systems where different factories, suppliers, and transportation systems work together to optimise themselves as a whole. Products are also beginning to emerge with new features such as connectivity to the cloud that allows data extraction from products and changing their functionality remotely by manufacturers. This aspect also contributes to the product design being done collaboratively between the company's different departments, including the customer and the product itself in this process. This new reality is becoming clear with the introduction of new emerging technologies such as Additive Manufacturing, Artificial Intelligence or Cyber-Physical Systems that will force companies to apply new business models.

A summary of studies focusing on developing sustainable manufacturing systems in which collaborative aspects are presented is shown in Table 1. This table covers the infrastructure perspective and presents examples aiming to increase the sustainability of manufacturing systems through collaboration.

Similar to Table 1, Table 2 presents the elements of collaboration and added value regarding sustainability that are found in studies related to the dimensions of End-to-End Engineering, Smart Products, and the creation of new business models.

Table 1 – Examples of sustainability aspects in the manufacturing infrastructure dimensions.

	Economic	Social	Environmental
Vertical Integration	<ul style="list-style-type: none"> • Collaboration between machines to reduce costs and increase productivity. [15, 16]. • Increase productivity using human-robot collaboration [17, 18]. • Share factories to increase efficiency [19]. 	<ul style="list-style-type: none"> • Human-robot collaboration (Improve working conditions, reduce health problems) [17, 18, 20, 21, 22]. 	<ul style="list-style-type: none"> • Implementation of shared factories to reduce energy and natural resources consumption [19]. • Human robot collaboration in order to improve recycling process, reducing waste [21, 22].
Horizontal Integration	<ul style="list-style-type: none"> • Collaborative resource allocation. [16, 23]. • Increase efficiency sharing spaces and machines [24]. • Shared logistics for cost reduction [25]. • Collaborative strategies for pickup and delivery network of eco-packages through resource sharing [26]. • Contributions of environmental collaboration to firm performance [27]. 	<ul style="list-style-type: none"> • Auction-based logistics for social welfare [25]. • Collaborative platforms to ensure human rights protection, patient confidentiality and welfare. [23]. • Role of green supply chain to improve brands and customer value [28]. • Sustainable collaborative governance of supply chains [29]. 	<ul style="list-style-type: none"> • Reduce resources' waste sharing spaces and machines [24]. • Reduce carbon footprint and energy consumption through trustable collaborative supply chain [23, 30, 31]. • Various methods to select suppliers for sustainable supply chains using the 3 dimensions of sustainability [32, 33, 34].
Acceleration of Manufacturing	<ul style="list-style-type: none"> • CPS systems for allowing interoperability among factory resources [15]. • Digital Twins to design products by different teams and in different stages [35]. • Digital Twins to optimise shared resources' allocation [24]. • Self-organised approaches to optimise network of resources [19]. • Blockchain to increase trustability among suppliers [23]. 	<ul style="list-style-type: none"> • Additive manufacturing and 3D printing as part of circular production and consumption. [36, 37]. • Digital Twins to increase the collaboration between human and robots [17]. • Blockchain to ensure social aspects in a collaborative distributed ecosystem [23]. 	<ul style="list-style-type: none"> • Distributed manufacturing of 3D printed products to reduce energy and material consumption [38]. • Overall reduction of energy and material consumption using Digital Twins [24, 30]. • Blockchain technology to allow a trustable waste and resources consumption reduction in collaborative supply chains [23].

Table 2 – Examples of sustainability aspects in the product/service dimensions.

	Economic	Social	Environmental
End-to-End Engineering	<ul style="list-style-type: none"> • Co-creation and user innovation [37, 39, 40]. • Shorten design cycles and reduce costs using the data collected from products and customers. [35, 41]. 	<ul style="list-style-type: none"> • (Re)design products according to customer needs and desires based on product data [39]. • Guarantee product quality through remote product analysis during execution [42]. • Value co-creation network [40]. 	<ul style="list-style-type: none"> • Utilisation of the collected data from the product to design more ecofriendly transport conditions [43].
Smart products / Digitalisation	<ul style="list-style-type: none"> • Product data extraction to (re)design better products [39]. • Extract and analyse products' data along the supply chain to reduce costs [39]. • Symbiosis network [40]. 	<ul style="list-style-type: none"> • Extract data to assess product quality and execution [42]. • Extract and analyse data from the product to reduce delivering time [39]. 	<ul style="list-style-type: none"> • Constant assessment of products' conditions during transportation [43]. • Extract and analyse products' data along the supply chain to reduce environmental impact [39]. • Smart products contribution to circular economy [44].
New Business Models	<ul style="list-style-type: none"> • Sharing economy to increase competitiveness [19, 24]. • Application of industrial symbiosis [31, 45]. 	<ul style="list-style-type: none"> • Increase customer involvement [36, 37]. • Stigmergic Mass customization, co-creation, co-design [46]. • Hybrid value chains and social innovation [47, 48]. 	<ul style="list-style-type: none"> • Circular economy-based model [21, 36]. • Distributed manufacturing model [38, 49]. • Sharing economy to reduce wastes and consumptions [19, 24]. • Application of industrial symbiosis [31, 45]. • Global business sustainability [50].

It is possible to verify by the results summarised in Table 1 and Table 2 that some work has already been done in order to develop more sustainable systems using as a base the combination of practices of Industry 4.0 and collaborative networks. In most of the studied works, the collaboration aspects are not usually highlighted; nevertheless, the synergy between sustainable manufacturing and collaborative networks can be inferred. For instance, a research project in sustainable manufacturing in which our research centre participated is illustrated in Fig.2, where it is possible to identify the role of collaborative aspects at different levels.

From the analysed examples, as summarised in the tables above, it is possible to verify that the collaborative aspects are already present in various cases of applying the Industry 4.0 concepts to achieve sustainability. It can also be noticed that these aspects appear more frequently in terms of the vertical and horizontal integration dimensions. Another interesting point is that emerging technologies, included under the acceleration of manufacturing, are particularly relevant in the efficient application of the collaborative aspects. However, it is important to underline that the combination of manufacturing, sustainability and collaborative networks are not always explicitly presented in the studied literature, but it is possible to infer their importance, as summarised in Table 1 and Table 2.

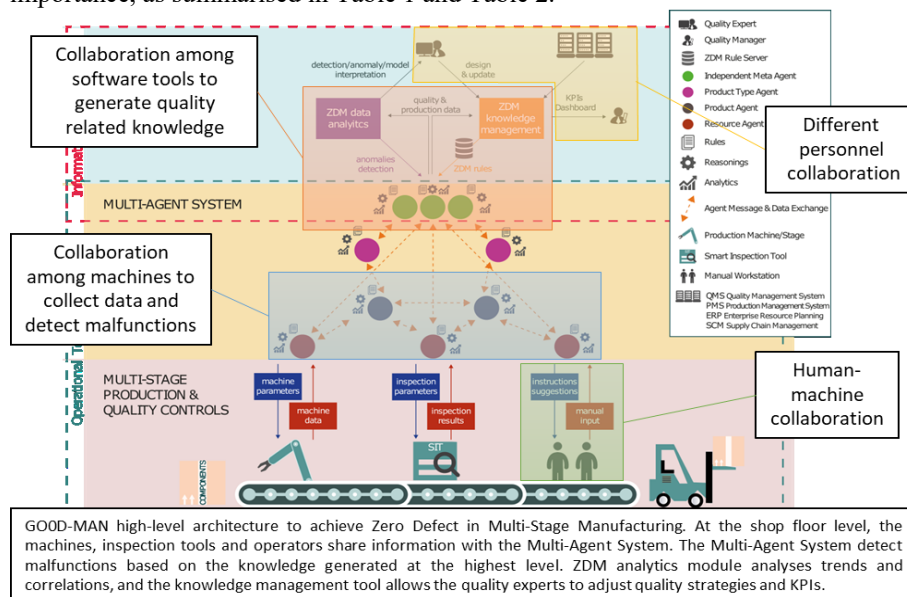


Fig. 2 – GOODMAN High-Level Architecture and Collaborative Aspects (adapted from [51])

5 Measuring Sustainability

Although it is widely agreed that sustainability is one of the main concerns for manufacturing, to be more effective, sustainability must be measured and proper sustainability-related performance indicators established. As summarised in Table 3

and Table 4, some examples of efforts on measuring sustainability under a collaborative perspective and addressing the economic, social, and environmental concerns can already be found in the literature.

The examples in Table 3, addressing the manufacturing infrastructure perspective, propose mainly metrics and indicators to evaluate sustainability performance, borrowed from traditional manufacturing and supply chains. Concerning the collaboration perspective, some attempts can be found, underlining the importance of collaboration between the various players towards better sustainability.

Table 3 – Examples of sustainability metrics/indicators in the manufacturing infrastructure dimensions.

	Economic	Social	Environmental
Vertical Integration	<ul style="list-style-type: none"> • Metrics for evaluation of manufacturing sustainability performance at the production line level [52]. • Framework to map and analyse the interconnections between technical and economic performance metrics at the operation [53]. 	<ul style="list-style-type: none"> • Metrics for evaluation of manufacturing sustainability performance at the production line/plant level [52]. • Framework to map and analyse the interconnections between technical and social performance metrics at the operation [53]. 	<ul style="list-style-type: none"> • Metrics for evaluation of manufacturing sustainability performance at the production line/plant level [52]. • Framework to map and analyse the interconnections between technical and environmental performance metrics at the operation [53].
Horizontal Integration	<ul style="list-style-type: none"> • Dashboard of KPIs of a Virtual Factory processes [54]. • Framework to develop metrics for evaluating system effectiveness to improve sustainability [55]. • Proposal for a sustainability index to show performance at manufacturer and supply chain level [56]. • Measurement of sustainability performance in products and processes for manufacturing companies [57]. 	<ul style="list-style-type: none"> • Framework to develop metrics for evaluating system effectiveness to improve sustainability [55]. • Proposal for a sustainability index to show performance at manufacturer and supply chain level [56]. • Social responsibility metrics to evaluate and select sustainable suppliers [32]. • Measurement of sustainability performance in products and processes for manufacturing companies [57]. • Sustainability performance indicators for an Industry 4.0 virtual learning environment [58]. 	<ul style="list-style-type: none"> • Dashboard of KPIs of a Virtual Factory processes [54]. • Framework to develop metrics for evaluating system effectiveness to improve sustainability [55]. • Proposal for a sustainability index to show performance at manufacturer and supply chain level [56]. • Environmental metrics to evaluate & select sustainable suppliers [32]. • Measurement of sustainability performance in products and processes for manufacturing companies [57]. • Sustainability performance indicators for an Industry 4.0 virtual learning environment [58]. • Model for the assessment of the performance of a supply chain, based the perspectives used in the balanced scorecard e[59]
Acceleration of Manufacturing	<ul style="list-style-type: none"> • Indicators/practices to optimise economic returns [60]. • Metrics to evaluate the influence of Industry 4.0 on sustainable manufacturing [11]. • Study to integrate the sustainable smart manufacturing performance by incorporating sustainable manufacturing measures [61]. • Metrics framework for assessing sustainability benefits in cyber manufacturing systems [62]. 	<ul style="list-style-type: none"> • Indicators/practices to optimise social returns [60]. • Measures for talent attractiveness in SMEs to achieve social sustainability in the cities of the future [63]. • Metrics to evaluate the influence of Industry 4.0 on sustainable manufacturing [11]. • Study to integrate the sustainable smart manufacturing performance by incorporating sustainable manufacturing measures [61]. • Metrics framework for assessing sustainability benefits in cyber manufacturing systems [62]. 	<ul style="list-style-type: none"> • Indicators/practices to optimise environmental returns [60]. • Metrics to evaluate the influence of Industry 4.0 on sustainable manufacturing [11]. • Study to integrate the sustainable smart manufacturing performance by incorporating sustainable manufacturing measures [61]. • Metrics framework for assessing sustainability benefits in cyber manufacturing systems [62].

Table 4 presents examples related to sustainability metrics and indicators focused on smart products, digitalisation and new business models. Under this perspective, the identified attempts are preliminary approaches to measurement models, identification

of benefits, and insights on the influence of these products and services on sustainable performance. At this level, the collaboration that is more worth highlighting is between human-machine.

Table 4 – Examples of sustainability metrics/indicators in the product/service dimensions.

	Economic	Social	Environmental
End-to-End Engineering	<ul style="list-style-type: none"> • Preliminary approach towards a measurement model for value co-creation in service design [64]. 	<ul style="list-style-type: none"> • Identification of benefits for customers from co-creation [65]. 	
Smart products / Digitalisation	<ul style="list-style-type: none"> • Smart targets to smart energy systems transition with economic impact [66]. 	<ul style="list-style-type: none"> • Smart targets to smart energy systems transition with social impact [66]. 	<ul style="list-style-type: none"> • Smart targets to smart energy systems transition with environmental impact [66].
New Business Models	<ul style="list-style-type: none"> • Insights that servitisation and lean bundles have complementarity effects on sustainable performance [67]. • Index to assess the sustainability and the circularity of manufacturing companies [10]. • Framework based on concepts of circular economy to assess sustainability performance of manufacturing companies [60]. • Quantitative framework for Industry 4.0 enabled circular economy [68]. 	<ul style="list-style-type: none"> • Index to assess the sustainability and the circularity of manufacturing companies [10]. • Framework based on concepts of circular economy to assess sustainability performance of manufacturing companies [60]. 	<ul style="list-style-type: none"> • Insights that servitisation and lean bundles have complementarity effects on sustainable performance [67]. • Index to assess the sustainability and the circularity of manufacturing companies [10]. • Framework based on concepts of circular economy to assess the sustainability performance of manufacturing companies [60]. • Quantitative framework for Industry 4.0 enabled circular economy [68].

This study only presents some examples and not an exhaustive list of cases. Nevertheless, and despite some valuable attempts, there is still a lack of concrete performance indicators to assess the benefits of collaboration towards a better manufacturing sustainability performance.

6 Conclusions

Sustainability is a major challenge for modern manufacturing systems. Although the manufacturing sector has received a renewed attention in the last years, as reflected in the multiplication of initiatives around Industry 4.0 and digital transformation, making such systems more sustainable remains a crucial challenge.

On the other hand, as manufacturing systems become increasingly smart, autonomous, and interconnected, reflecting a kind of distributed intelligence, the issues of sustainability need to be analysed under a distributed and collaborative perspective. To this aim, the synergies between collaborative networks and sustainable manufacturing need to be further explored.

This study reveals a good number of steps in this direction, both at the manufacturing infrastructure level and at the product/service/business model level.

However, the collaboration aspects among all the entities present in these ecosystems are still not usually considered and analysed. But it is clear that despite the identified positive examples, there is a need to substantially pursue the exploitation of synergies among the areas of sustainability, manufacturing, and collaborative networks and develop corresponding assessment methodologies and indicators.

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