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Research Challenges for Eco-Efficient and Circular Industrial Systems

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Abstract. The field of industrial sustainability is rapidly expanding with new concepts and frameworks emerging almost daily. At the same time, mature ones are being used in new applications and combined with new technologies and methodologies. While these developments are promising, the ambitions, scale, and speed of the change required to meet sustainability goals urgently need to increase. To accelerate industrial sustainability research and its impact, experts were invited to discuss research challenges in a webinar series focused on ten priority areas for eco-efficient and circular industrial systems. This paper presents the research challenges discussed to share sustainability practices, stimulate collaborations, and inspire change for more impactful applied research and knowledge transfer to industry.

Keywords: Circular economy, Eco-efficiency, Industrial sustainability, Research agenda, Collaborative research.

1 Background and Motivation

In response to the growing pressures to address environmental issues, such as climate change and the over-exploitation of natural resources, manufacturing organizations are formulating increasingly ambitious sustainability goals and strategies. National and international regulatory programs are also emerging every year, making environmental sustainability an imperative for companies' mid- and long-term survival. In addition, concepts such as eco-efficiency and circular economy have been developed and are now well-defined approaches to reduce the environmental impacts of industrial activities. However, they are not yet the norm and often contrasted to business-as-usual as they are still considered as add-ons (if at all). As a consequence, the current trajectory and delivered impacts are insufficient to meet sustainability goals by 2030 [1] or net-zero climate goals by 2050 [2]. This does not mean that the goals cannot be reached, but that new approaches, and possibly new paradigms, are necessary to succeed.

Looking at production systems through the sustainability lens, it is possible to translate eco-efficiency and circularity concepts into industrial actions. In 2022, a thematic research framework was proposed with ten priority areas [3]. To promote knowledge exchange on the topic of eco-efficient and circular industrial systems, a series of ten webinars was organized between December 2022 and December 2023 based on the ten priority areas and leading to the discussion presented in this paper: (1) Redefining success; (2) Highlighting trade-offs; (3) Empowering people; (4) Continuous improvement; (5) Disruptive or radical change; (6) Experimenting and learning from failure; (7) Data-driven solutions; (8) Technologies for sustainability; (9) Product and service design for value co-creation; and (10) Doing good through regenerative practices. One or two speakers were invited for each webinar based on their expertise within a given priority area. The webinar on product and service design for value co-creation was a larger event with four speakers. The interactions during and after the presentations engaged the webinar participants to discuss the challenges encountered when integrating sustainability into industrial practice within the context of a given priority area. This position paper presents these research challenges to stimulate further discussions in the international community on production management research, inviting both industry and academia to join the debate.

2 Research Challenges

2.1 Redefining success

Considering today's ecological and social issues, current definitions of *successful sustainable operations* must evolve. Building from sustainable development about "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [4], this new definition should promote a regenerative model as the ideal future industrial systems [5] to "put more back into society and the environment than they take out" [6] and compensate for the harm of past industrial systems (see Section 2.10 Doing good).

To succeed in the short- and long-term, a paradigm shift is needed to go beyond the triple bottom line (TBL) mindset, which remains useful for sustainability accountability, to a triple top line (TTL) mindset that aims to maximize the positive effects of industrial economic activities on the environment and society by design [7]. In this sense, TTL thinking moves sustainability accountability to the beginning of the design or re-design process of any industrial system, focusing on positive social and environmental impacts first while creating economic value [8]. A good example of a TTL business strategy is net positive manufacturing [6] or regenerative manufacturing [9], which not only tries to reduce the ecological footprint of any production system but also seeks to restore and rejuvenate its surrounding environmental and social systems.

As the research agenda for eco-efficient and circular industrial systems continues to evolve, such is the case of the metrics for *successful* sustainable operations. Sustainability indicators often focus on the negative effects of economic activities for risk minimization rather than benefit maximization [8] (see Section 2.2 Highlighting trade-offs). Consequently, current approaches to industrial sustainability may not be sufficient to save our planet and its people from future detrimental living and working conditions, thus neglecting *sustainability success* in the long-term. Therefore, future *successful* sustainable operations definitions must be built on the principles of biomimicry, circularity, life cycle management, net positive growth, resilience, and regeneration.

2.2 Highlighting trade-offs

While managers aspire to achieve win-win outcomes in sustainability practice, the reality often presents unavoidable win-lose scenarios, known as trade-offs. There are various kinds of trade-offs in sustainability practice. The most prevalent ones are the trade-offs between social, economic and environmental objectives; the dilemma of prioritizing short-term gains against long-term value; and the distribution of benefits among different stakeholders. Managing these trade-offs is crucial for companies to make holistic, evidence-based decisions. To navigate complex scenarios, scholars have explored strategies for managing trade-offs at both strategic and operational levels, proposing three criteria: impact, time and process/resources [10], and various prioritization logics for handling trade-offs, such as singular, flexible and holistic approaches [11].

Traditionally, sustainability trade-offs have been portrayed negatively, associating them with tensions, paradoxes, unintended consequences, or rebound effects. However, more recent studies have shown that, when properly managed, trade-offs can help companies reach their sustainability goals through a process of continuous improvement and continuous innovation [12] (see Section 2.4 Continuous improvement and 2.5 Disruptive or radical change). The evolving viewpoints also show that effectively navigating trade-offs is vital for eventually achieving a no-trade-off scenario.

Despite growing interest, research on sustainability trade-offs is still in its infancy. More theoretical research and practical methods are needed to help managers understand trade-offs and enhance decision making. For example, in system engineering, value-driven design emerged as an approach to strive for overall-best-value design rather than fulfilling requirements individually [13] and tradespace exploration as an approach to consider multiple design options to find the optimal one based on value [14].

Suggestions for further research include: (1) Develop dynamic trade-off models that could accurately capture the changing nature of trade-offs over time; (2) Explore the role of digital technologies in visualizing and managing sustainability trade-offs (see Section 2.8 Technology for sustainability); and (3) Longitudinal studies that track how trade-offs and their management evolve over time within organizations.

2.3 Empowering people

To commit to sustainability goals, organizations and their managers need to understand how to enhance employees' contribution to environmental activities in the workplace. For instance, rewarding green initiatives can motivate employees to continue such efforts [15] and establish sustainability as a meaningful goal. In many ways, employee motivation and empowerment are intertwined because empowerment can be defined as intrinsic motivation initiated through individual cognition about work tasks and through situational attributes (i.e., organizational structures and management practices) [16].

Empowered employees are pivotal when anchoring sustainability strategies [15, 17]. However, empowerment changes power dynamics and responsibility between employees and the organization. As employees have specialized knowledge and expertise, they often know more about the operations than their managers who thus must delegate part of the decision making. Seeking to empower employees to integrate eco-consciousness in manufacturing operations and product development requires reciprocal obligation and mutual commitment to sustainability between employees and management.

Organizational learning is a people-centric approach to establishing the conditions for empowerment [18]. In sustainability-oriented learning, it is a shift in mindset, knowledge, and values, which builds the skills needed for the future by raising awareness about knowledge gaps and prompting employee development [19]. Organizations can create or find existing (informal) networks of individuals with green competencies who are genuinely interested in sustainability. These networks can foster broader participation to solve sustainability issues beyond immediate work responsibility and form communities for collaborative learning and knowledge sharing. Empowerment through sustainability-oriented learning extends beyond the employees themselves, as they can positively influence internal and external stakeholders about eco-consciousness [20].

Despite the forward-looking nature of the sustainability discussion, research adheres closely to societal change and inter-organizational aspects, marginalizing the role of employees. Lately, intra-organizational focus has attracted more attention [19], however, mostly focused on certifications and technological advances. For organizations to manage their sustainability transition, power and authority should be allocated among employees (empowerment). Research efforts should focus less on why employees engage in sustainability, and more on how to engage employees in continuous enterprise-wide learning and hence how organizations can become more intentional about environmental sustainability, as this seems to be where the knowledge gaps are.

2.4 Continuous improvement

Continuous improvement is a well-known approach to production management and can be defined as "an organization-wide process of focused and sustained incremental innovation" [21]. New approaches for industrial sustainability can benefit and build from established production management systems, such as Lean or Six Sigma programs, to be embedded seamlessly into business as usual. In the age of digitalization and sustainable development, however, one might argue that such continuous improvement processes must extend beyond individual organizations and adopt an interorganizational perspective. For example, SDG17 states quite clearly that it will be partnerships that solve the goals, not individual efforts [1].

In a recent work exploring *Lean and the green economy* [22], lean thinking and practices—with continuous improvement and learning at the core—have an essential part to play in driving efforts towards sustainable development and eco-efficient operations. Three essential methods to move closer to a waste-free society are proposed: (1) *Hoshin Kanri* helps create consensus around the organization's critical challenges and break them down into bitesize pieces; (2) *A3 Management* presents managers with a structured process for solving problems encountered in pursuing the goals identified in the Hoshin Kanri process; and (3) *Toyota Kata* offers a means of realizing step-by-step improvement and learning through coaching.

In contrast to other industry trends such as digitalization and artificial intelligence, environmental sustainability received proportionally limited attention [23], underlining the importance of integrating more systematically environmental considerations in industrial production activities. Combing circular economy with lean-green strategies can improve the environmental and resource performance of manufacturing systems, leading to both environmental and economic benefits [24]. As such, focusing on continuous improvement initiatives for sustainable development using the three-step strategic deployment framework "Challenge, Problem, Kaizen" [22] can assist industrial production systems in moving closer to an eco-efficient and circular future, and provides researchers and practitioners with food for thought in addressing sustainability goals.

2.5 Disruptive or radical change

While the massive potential and cumulative effect of incremental change should not be ignored (see Section 2.4 Continuous improvement), there are circumstances when a more radical change to systems is required. In the 1990s, business process re-engineering was put forward as a radical approach to redesign and streamline operations and managerial processes to achieve a step change in cost, time and service quality [25]. A more incremental approach to business process improvement [26] was deemed more acceptable and was adopted in many companies. Both approaches shifted the focus from tasks to processes (as systems) to facilitate the analysis of problem situations at an appropriate level of detail for large-scale radical changes or small-scale incremental changes. An important management skill is to realize when it is time to stop improving the existing system, and instead design something new. This is well-known in the field of product development, but the application to industrial systems deserves more attention. This may be because eco-efficiency, circularity and other environmental concepts are relatively new and therefore lack general understanding and methodologies to guide their implementation in companies.

Transitioning to more eco-efficient and circular industrial systems requires business operations of all types to be re-examined. This is where researchers can support the transition with knowledge and guiding methodologies. Once the pressure for change has been established, business operations must be re-engineered to achieve business goals with reduced environmental effects. The solutions that are attempted might be either more gradual improvements against well-known performance measures with little business risk, or more radical changes to the systems concerned based on a vision of the future with risk being dependent on the vision being successful from a business point of view (see Section 2.1 Redefining success). To help industry operate in more eco-friendly ways, researchers must work with businesses to learn what problems they face, while developing useful new knowledge that can be applied in contexts of continuous improvement or radical change. For the more radical changes, businesses may need support in developing their vision of the future, assessing risks, and identifying those technologies that can be applied.

2.6 Experimenting and learning from failure

While learning from failure is widely accepted and encouraged in principle, it can be difficult to find reported cases of failed experiments within industry. In academia, this is due to publication bias or positive-outcome bias [27, 28]. Equally rigorous and capable researchers who understand why something did not happen are not rewarded like those who were lucky or in the right place at the right time. Although these problems are known, they remain the norm. There is a parallel with companies knowing about the need to change their practice, but they are not yet rewarded for better practice within a flawed system. These trends have perverse outcomes, delaying knowledge sharing in communities, and resulting in vast expenditure of time and resources to replicate null or negative results. This needs to be remedied by creating and nurturing a continuous and collaborative learning culture (see Section 2.3 Empowering people).

In addition, plans can be unrealistic given well-known cases of repeated failure. For example, Flyvbjerg and Gardner recently assessed over 16,000 projects, reporting that less than 50% of the projects were on time, less than 10% were on time and budget, and less than 1% were on time and budget while delivering the targeted benefits [29]. If this is business as usual, how can sustainability plans fare any differently? It may be acceptable for a product to reach the market late, but this cannot go unchallenged for activities with an existential mandate, such as industrial decarbonization.

Alongside technical progress, there are existing best practices which are not yet normalized in industry. These activities are already possible with no skills gaps or missing advances in hardware, software, legislation, market pull, or business models (see Section 2.4 Continuous improvement). However, the lessons learnt from implementing less harmful practices, even in the case of trials and failures to prevent the next projects from making the same mistakes, are not always shared within the company and are even less likely shared externally. This inability to effectively share existing best practices throughout industry is one of the largest barriers to rapid large-scale sustainability improvements [30].

Supporting industry to prioritize the change which is possible today through best practices shifts the discourse from barriers to enablers. This is a cultural approach to inexpensively accelerate the global sustainability transition, while saving money, within the limitations of current knowledge and practice. This approach is possible, and the benefits are large with a usually disproportionate return on investment. But academia and industry must deliberately and methodically set out to achieve this type of sharing of failure and success, as no one does it automatically, and is not yet well led by researchers or policymakers. There is room to learn from the challenges within research and policy to ease the first steps to experiment safely and learn from failures in sustainability projects, accelerate existing best practices, and use the benefits of early efficiency to subsidize the rest of the transition.

2.7 Data-driven solutions

Industrial digitalization increased data availability as sensors and wireless networks enabled machine tools and other assets to collect, store, share, and analyze data and to optimize processes, but opportunities to achieve sustainability goals are often overlooked [31] (see 2.8 Technology for sustainability). Many companies invest in digital technologies to take advantage of over-depreciation, thereby gain economic advantage, and collect data without a clear objective, merely following general trends and common practice. A sustainability-oriented mindset is rarely the driving force for such initiatives.

Digital solutions can measure performance in new ways and integrate environmental aspects [32]. For instance, intelligent energy management systems can precisely control real consumption, reducing operating costs while aligning with sustainability goals. The role and nature of data required to enable such data-driven solutions needs to be better understood: What data needs to be shared, at which level, and with whom? These questions are far from resolved and research must steer industrial developments in a sustainable direction.

Beyond the factory gates, data employed to design and operate manufacturing solutions can be integrated into more comprehensive platforms to improve traceability and transparency among the involved actors and to manage the performance of products throughout their life cycle. For instance, sensors embedded in smart products can monitor materials and components during production as well as products' structural and operational conditions during use to support sustainability-oriented performance [33]. Such sensing and communication capabilities are currently not fully exploited due to technical and economic reasons. Indeed, data is usually not standardized and collected with varied granularity and quality, therefore not easily interpretable by all stakeholders. This occurs because a gap exists between the necessary data for sustainability-oriented performances and companies' capabilities and priorities to collect and share this data. Furthermore, policy and incentives are necessary to accelerate the progress towards more standardized, high-quality sustainability data for systems-level impact.

Approaches to overcome this issue include combining digitalization with the upskilling of operators, managers, and data scientists in digital and green skills (see Section 2.3 Empowering people). Companies need to be aware that integrating data-driven solutions with a sustainable mindset can achieve competitive advantage. Therefore, the following research avenues are proposed: (1) Understand which data and formats are needed for specific industry and sustainable analytics objectives; (2) Investigate how to efficiently and safely share data and information in different supply networks; and (3) Identify specific green and digital skills for sustainable manufacturing and the manufacturing areas that most urgently need those skills.

2.8 Technology for sustainability

The digital transition (discussed in Section 2.7 Data-driven solutions) has strongly influenced manufacturing companies and their production systems. In particular, information systems (IS) are becoming a must-have to compete in the market. However, companies with low digital maturity are not able to reap the benefit from IS implementation due to the missing capabilities to exploit their characteristics effectively [34]. In addition, digital solutions are often oriented towards process optimization to reduce cost and time but miss the opportunities to exploit data and digital systems as enablers for circular strategies and sustainability-oriented performance optimization [35].

Indeed, advances in digital technologies can facilitate data collection, analysis and sharing both internally and externally to the company. Such data flows are instrumental to embrace circularity principles. However, possible negative externalities also need to be considered in this early stage of their digital-green transition to avoid drawbacks (see Section 2.2 Highlighting trade-offs). On the one hand, increased digitalization leads to increased impact from resource consumption and related emissions to produce and operate digital technologies themselves. On the other hand, these technologies can streamline processes, remove constraints and improve performance more holistically. From an environmental perspective, tailored assessments are needed to measure and balance the environmental impacts of such solutions [36]. From a social perspective, people need to be empowered with specific capabilities and green skills to use technologies for sustainability and circularity (see Section 2.3 Empowering people).

In addition to these evident and practical needs, further complexity is added due to the rapidly evolving regulatory requirements. For example, the digital product passport (DPP), first applied for batteries in Europe, has been extended to the fashion industry. These requirements are expected to apply to other sectors in the upcoming years and technological advances need to keep up. Therefore, we proposed three research streams to advance this topic: (1) Key technological requirements of IS in terms of data acquisition, visualization, sharing, writing, storing, etc. to automatically create the correct DPP with certified data; (2) Tailored assessment models to measure the environmental impacts of using such solutions; and (3) Competency models to ensure people are empowered to properly use these technologies.

2.9 Product and service design for value co-creation

The topic of product and service design for value co-creation was associated with a larger webinar with four speakers; therefore, this Section is broken down into two parts. First, key characteristics for designing such systems are presented. Then, ways to measure the sustainability performance of servitized systems are discussed.

Designing servitized and circular systems. Doing so requires industrial evidence and a holistic approach to integrate previously siloed perspectives that do not connect value chain and company-level thinking. Based on lessons learned from over 20 companies consolidated into six themes (see Fig. 1), future research should focus on how products and services can be co-designed for the following key success characteristics:

- **Company – Management:** Managing the transition towards servitization and circularity requires careful economic considerations, and particularly the need to achieve economies of scale and volume that justify new business offerings. Thus, there is a strong need to collaborate and find the right skills to define and measure data points to evaluate trade-offs. Moreover, it is necessary to identify which requirements and regulations open the door to new value-capture opportunities.
- **Company – Engineering:** The transition, and its success, toward servitization and circularity is highly dependent on the ability to embrace value and value co-creation in the design process. The physical product is the enabler of value, with early design choice impacting the abilities for value co-creation through all life cycle stages. Thus the design challenge expands from functional performance to a holistic view on value creation throughout the product-service systems (PSS) life [37]. Circular strategies hence require that engineers broaden their view of value creation where the source can be a product, a service, or combination of both.
- **Value chain:** From a value chain perspective, organizations must define common interests and initiatives that allow them to maximize the potential of digital technologies across actors that are geographically and culturally diverse. In this context, historical relationships become more relevant, as many companies across value chains struggle with data sharing and networking that enable platform thinking [38].
- **External stakeholders:** Creating success in servitized business models requires receptiveness and openness from the markets towards new offering structures. In several cases, it has been expressed that mismatching expectations can hinder progress in this field. Additionally, companies need to educate their stakeholders and involve them in brainstorming processes to create functional ecosystems [39].
- **Digital technologies:** Data is a valuable and critical success factor. However, the large amount of data stresses the importance of good data collection strategies and data management [40]. Exploring data-value links requires more expertise and digital competences to identify how data and digital technologies can support the value creation in different life cycle stages. A cornerstone for this is to understand how data can be transformed into knowledge. Finally, data democracy and data safety have to be addressed to enable data sharing among stakeholders.

The success of servitization for circular economy cannot be achieved through one theme only but relies on the integration between multiple themes, connecting to many sections (especially Section 2.7 Data-driven solutions and Section 2.8 Technology for sustainability).

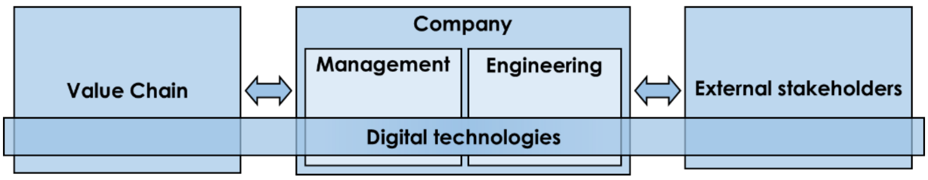

Fig. 1. Research themes and key characteristics for designing servitized and circular systems.

Measuring the sustainability of servitized systems. Turning to measuring the performance of servitized systems, additional research challenges arise. Although PSS business models combining products and services were defined as promoting sustainability and circularity [41], they may result in rebound effects [42] (see Section 2.2 Highlighting trade-offs). These effects are influenced by the customer, often in unpredictable ways. Therefore, it is challenging to assess the environmental impact of servitized systems, especially in the long term. Moreover, customers may exhibit varying degrees of sensitivity to environmental sustainability when selecting a business solution. It follows that assessing the environmental performance of PSS can be instrumental in raising customer awareness of both the solution's explicit impact and implicit consequences of their long-term behavior.

A well-established method for assessing the environmental impacts of PSS is life cycle assessment (LCA) [43], enabling a more holistic view of the solution's sustainability performance. This is essential when servitizing the business since the delivery process shifts from a single point in time to the entire life cycle. However, researchers have also highlighted limitations and challenges of LCA, such as high efforts in collecting data and ensuring high data quality, interpretating the results deriving from different impact categories, uncertainties of the results depending on the assumptions and scenarios tested, and the lack of integration with the economic and social dimensions.

Based on the above-mentioned advantages and disadvantages of the LCA method, some key principles should be taken into account to build a standard for facilitating the transition towards eco-efficient and circular business operations: (1) Considering the life cycle perspective, in particular the distribution, use and end-of-life phases; (2) Using a common language that can be understood by non-expert in sustainability-related topics; (3) Integrating the economic perspective; and (4) Highlighting the product ownership, since it can drive responsible consumption.

Based on these considerations, new research avenues are emerging to explore the use of dynamic supporting tools, such as simulation. To adhere to the aforementioned principles, these tools should denote the stochastic behaviors of PSS offering as a single entity throughout the life cycle which makes it possible to obtain a more accurate indication of its sustainability impacts. Key parameters include maintenance, energy, materials consumption, transport, the number of uses, product substitution and lifetime, and user behavior. The tools should concentrate on already in-use sustainability indicators while looking simultaneously at environmental and economic sustainability, for example, CO_2-eq emissions and ownership/use costs. Moreover, they should be user-friendly enough to allow even non-expert users to modify settings and test scenarios.

2.10 Doing good

As society approaches (and has already crossed) multiple planetary boundaries [44], it puts into question the search for a sustainable industrial system. Traditionally that has implied an industrial system that does not harm people or the planet (see Section 2.1 Redefining success). The European Commission has recently issued six environmental objectives as part of the Taxonomy Regulation for sustainable activities which include 'do no significant harm' (DNSH) principle: climate change mitigation; climate change adaption; sustainable use and protection of water and marine resources; transition to a circular economy; pollution prevention and control; and protection and restoration of biodiversity and ecosystems.

Given the wider conditions and damage already done, the principle of zero harm may no longer be ambitious enough. The concept of industrial sustainability calls for a paradigm shift in how manufacturing works, where industry systematically improves the health of people and the planet and becomes a regenerative system. This switch from 'doing less harm' to 'doing only good' is fundamental and implies zero negative emissions and pollution (not 'net zero'). This precautionary approach [45, 46] was first advocated in marine preservation policies, and later in forestry and agriculture [47], but has yet to be adopted in other industries.

Considering a sufficiently long timescale, it is possible to envision scenarios where manufacturing can be a health-generating system—when the air, water, materials, and people leaving every factory are healthier than when they enter [5, 6, 9]. Such a vision of regenerative manufacturing may be considered science fiction because it seems remote from today's reality, or even impossible to achieve within the time available before climate change or other global threats compromise our ability to realize such scenarios.

What can industry and researchers do to support such a shift and create pathways for this vision to become possible? Firstly, researchers must become more ambitious about the change expected of the industry and think ahead to generate the foundational knowledge to solve the problems that the industry will face in 2028 and beyond. Industry is also expected to become more willing to change processes, materials, and material flow cycles, and be prepared for, and even lead, this discussion (see Section 2.5 Disruptive or radical change).

As this is a system-level problem, expertise from many disciplines is needed, integrating material science, process engineering, supply chain and operations management, business development, policy, finance, etc. Research on 'less harmful' processes and materials must stop so time and resources can be focused on net positive outcomes; for example, stop research supporting process development to reduce the toxicity within some bounded financial reality (based on today's thinking) and start finding alternative materials and processes that are intrinsically benign, and hence will never be banned. While such a proposal is controversial given the status quo, opening the debate can generate much-needed new ideas. With such a large-scale shift, the list of interesting, demanding, and important research questions is vast. Therefore, industry and researchers are encouraged to join the discussion and formulate starter questions together.

3 Concluding Remarks

This paper presented various perspectives on current research challenges in the field of industrial sustainability, centered around previously established ten priority areas [3]. A summary of key challenges discussed in this paper is provided in Table 1. These challenges emerged from a series of webinars on research for eco-efficient and circular industrial systems. Despite the rapid increase in literature on topics related to sustainable manufacturing, circular economy, servitization, and digitalization, the necessary changes to achieve sustainable development goals are not happening at the scale and speed needed to meet global targets. To accelerate this process and increase the sustained impact, it is essential to coordinate research and development efforts globally.

Table 1. Research recommendations to address the challenges discussed in this paper.

Challenges	Research recommendations
Redefining success	• Define successful sustainable operations with positive aspirations for social, environmental, and economic benefits for all stakeholders • Measure sustainability performance with new metrics for the top triple line
Highlighting trade-offs	• Capture the changing nature of trade-offs with dynamic models • Use digital technologies to visualize and manage trade-offs • Track how trade-offs and their management evolve over time
Empowering people	• Identify knowledge gaps and encourage employee development • Focus on how to engage employees in continuous, collaborative learning
Continuous improvement	• Extend continuous improvement beyond individual organizations and adopt an interorganizational learning perspective • Combine circularity and sustainability with lean-green strategies • Investigate the links between the firm's critical challenges, its operational problems, and its improvement efforts through learning and coaching
Disruptive change	• Develop guiding methodologies to adopt an appropriate level for problem analysis (small-scale incremental changes or large-scale radical changes)
Experimenting and learning from failure	• Ease the first steps to experiment safely and learn from failed projects • Create a learning culture to accelerate existing best practices, and use the benefits of early efficiency to subsidize the rest of the transition
Data-driven solutions	• Understand the data needed for sustainable analytics objectives • Investigate how to share data efficiently and safely in supply networks • Identify green-digital skills and the areas needing them the most urgently
Technology for sustainability	• Define information systems requirements to handle data automatically • Tailor environmental assessment models to integrate with information systems and new technologies, such as DPP • Develop competency models so people can use these technologies
Product and service design for value co-creation	• Focus on how products and services can be co-designed using the proposed key success characteristics (see Fig. 1) • Develop dynamic tools adopting a life cycle perspective and assessing environmental and economic sustainability simultaneously
Doing good	• Set up ambitious goals to envision industry as health-generating systems

As a collective of researchers (i.e., the authors of this paper), our viewpoints aimed to be ambitious, even provocative at times, to open the discussion with the wider community of researchers and practitioners about directions and priorities to ensure that efforts are placed in areas where they will matter the most. However, we have almost certainly missed important topics and alternative perspectives on the issues raised. Therefore, we invite responses to the research challenges presented in this paper to continue the debate about how to best tackle the seemingly unsurmountable sustainability problems we face as a society at large.

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