This is a post-peer-review, pre-copyedit version of an article published in IFIP Advances in Information and Communication Technology book series. The final authenticated version is available online at: http://dx.doi.org/DOI: 10.1007/978-3-031-16411-8_44

Thematic Research Framework for Eco-efficient and Circular Industrial Systems

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Abstract. Global sustainability challenges are increasingly constraining and driving industrial development. Eco-efficiency and circular economy are powerful concepts providing guiding principles to achieve superior environmental performance. However, they are not systematically integrated into the design, planning, development, management and improvement of industrial systems, potentially resulting in increased environmental impacts and other unintended consequences. This paper presents a thematic research framework based on workshops with manufacturers and researchers in the field of production engineering and management. The framework aims to establish a stronger foundation to advance research and technological development for eco-efficient and circular industrial systems, embracing environmental sustainability as core operating principles.

Keywords: Circular economy, Eco-efficiency, Green manufacturing, Sustainable production, Research framework.

1 Introduction

Addressing global and systemic environmental issues (e.g., climate change, accumulation or persistent pollutants, natural capital depletion) has been recognised as an imperative for decades to ensure a healthy future for our society and our planet. Industry is a key driver for sustainability transitions, especially since it has been a driving force for social and economic development, yet at a high environmental cost. Coordinated and systematic efforts are needed to accelerate actions if we are to mitigate and avoid the worst of the unintended consequences of industrial developments in the past centuries.

The United Nations created the Sustainable Development Goals (SDGs) in 2015 to establish an international agenda to assist such globally coordinated efforts. While the SDGs are high-level, many companies have translated them into ambitious strategic goals and started to develop roadmaps to achieve them. Eco-efficiency and circular economy are powerful approaches to executing these strategies and roadmaps. Eco-efficiency is achieved "by the delivery of competitively priced goods and services that satisfy human needs and bring quality-of-life, while progressively reducing ecological impacts and resource intensity throughout the lifecycle to a level at least in line with the earth's estimated carrying capacity" [1]. Its guiding principles are: reduce material and energy intensity, reduce toxic dispersion (waste and pollution), enhance recyclability, maximise the sustainable use of renewable resources, extend product durability, and increase service intensity. These principles align with the circular economy principles as advocated by the Ellen MacArthur Foundation: eliminate waste and pollution, circulate products and materials at their highest value, and regenerate nature [2].

To support research in a more sustainable direction, the purpose of this paper is two-fold: (1) to provide priority areas and examples of research questions to advance production engineering and management research toward environmental sustainability; and (2) to propose a framework capturing different research themes to tackle environmental challenges meaningfully and realistically in industrial development.

2 Methods

A thematic analysis was used to identify common topics and patterns in production research towards eco-efficiency and circular industrial systems. The structure of the thematic research framework was developed based on a systematic review of the last ten years of research contributions from the International Federation for Information Processing Working Group 5.7 (IFIP WG5.7) on Advances in Production Management Systems (APMS) through its dedicated annual conference[1] [3]. Three workshops (Table 1) were used to collect experts' inputs about research needs (challenges and opportunities) to transition to more eco-efficiency and circular industrial systems. The outputs from the workshops were analysed and clustered around similar research needs to create the initial priority areas. The thematic research framework was then iteratively refined by the authors and consolidated with research questions to reach a consensus about research priorities for more sustainable production systems.

Table 1. Workshop dates, topics, and number of participants.

Date	Workshop, No. of participants
29 April 2021	TRUST project[2], workshop on "Why is eco-efficiency so rare?", 21 participants from academia and industry

[1] www.ifipwg57.org and www.apms-conference.org

[2] European project: Twinning foR indUstrial SustainabiliTy (TRUST)

12 October 2021	Swedish Manufacturing R&D, Cluster on Production Management, workshop on "Sustainable production through eco-efficiency and circularity", 37 participants from academia and industry
23 March 2022	IFIP WG5.7, workshop for the Special Interest Group on Eco-efficient and Circular Industrial Systems, 20 participants from academia

3 Results

This section summarises the results of the workshops with references to relevant work. For each priority area, we propose some research questions to guide future research and to track the impact of the research agenda on the community over time. The thematic framework is then presented to encourage researchers in the field of production research to (re)frame their contribution toward environmental sustainability.

3.1 Priority Areas and Research Questions

I. Redefining success. Defining success metrics and strategic goals for organisations is a complex undertaking. This translates directly to the sustainability arena. When performance and success are defined with a narrow definition, it may limit the factors included in the design, planning, development, and management of manufacturing, service, and logistics operations. In the context of this thematic research framework, successful operations are considered *sustainable operations* [4] that follow eco-efficiency and circular principles. Moreover, the requirement to adopt a longer-time perspective can act as a barrier in many industries. Therefore, companies must deal with rebound effects [5] and the dilemma to balance short-term impact and long-term effectiveness [6] along their journey towards sustainable operations, accounting for the short-term successes that will make possible the long-term ones. Currently, decisions are often too short-sighted to deliver the desired sustainability benefits as they exceed the typical time horizon expected by some of the stakeholders (e.g., standard timeframe for return on investment). This requires a careful reframing of the purpose of industrial development to tackle environmental problems directly and prevent unintended consequences by design, and not as an afterthought (as predominantly done today); i.e., avoidance and direct reduction of detrimental impacts as part of industrial systems design (greenfield) and redesign (brownfield) requirements. If the technical and managerial solutions proposed do not contribute directly to sustainability, then we should question whether they are suitable options. If a "solution" creates more problems than it solves, then it should be redesigned or not be developed.

RQ1.1: What are the environmental sustainability implications of manufacturing, service, and logistics operations improvements in the short and long term for individual organisations and industry as a whole?

RQ1.2: How can these environmental implications be measured and integrated into the definition of sustainable industrial performance and therefore success?

II. Highlight trade-offs for holistic, evidence-based decisions. Beware of common sense and intuitive responses to *green options.* For example, circular and service-based solutions may only result in environmental benefits under specific conditions. Much of the data and evidence depends on the boundaries and characteristics of their providing system—a major hurdle in making scenarios truly comparable for objective decision making. The current gold standard is to adopt a holistic and lifecycle perspective as much as possible. For example, resource efficiency strategies are vulnerable to rebound effects when they lead to additional resource use via behavioural and systemic responses [5]. If some negative impacts are unavoidable within current systems, they should be acknowledged and used as a learning opportunity to update the behavioural dynamics of the system modelled for future scenario simulations and assessments. These insights can help identify countermeasures to these unavoidable negative effects in the short term while developing options to eliminate them in the long term as the system moves towards a more sustainable state. Having the right measures and metrics available is the first step to making trade-offs visible, detecting and anticipating rebound effects, and understanding the underlying issues to solve present problems in the near future.

RQ2.1: What needs to be considered to enable holistic decision making from a lifecycle perspective for environmental sustainability?

RQ2.2: What are key variables to consider and appropriate simplifications to reduce complexity in decision-making processes for environmental sustainability?

III. Empowering people. For stakeholders, predominantly producers and consumers, to buy into the sustainability practices, they need to have sufficient control and the intrinsic motivation to do good. Given this assumption, understanding and putting sustainability principles into practice can better be achieved by empowering individuals throughout their organisation and personal life so their ideas can become actions. Hence, bottom-up initiatives can be more impactful than top-down approaches from the executive board. Achieving buy-in and the intrinsic desire to improve the current situation will avoid the 'it is not my job' attitude when it comes to proposing and promoting sustainable production and consumption practices and behaviours [7,8]. While motivation and ideology may vary, (almost) everybody agrees that we need to conserve resources, avoid waste, and mitigate climate change. However, too few are ready and allowed to act within their current role (outside of their job description). To overcome this hurdle in the short term, creating incentives (e.g., gamify sustainable practices and behaviours) to involve all the stakeholders both internally and externally. This is particularly important for circular value chains in which producers, consumers; service providers (for maintenance, repair, remanufacturing, etc.) need to work together for product useful life extension and material recovery.

RQ3.1: What are the barriers preventing people from engaging directly (e.g., job description) and indirectly (e.g., motivation) in sustainable practices and behaviours?

RQ3.2: What are appropriate incentives to empower different stakeholders to transition towards environmentally sustainable practices and behaviours?

RQ3.3: How can employers and employees be actively involved in the transition towards environmentally sustainable operations?

IV. Continuous improvement. A core aspect of industrial engineering is the continuous assessment and improvement of existing processes. Companies need to understand their current state and/or maturity, and the readiness level of their value chains when it comes to environmental sustainability, then identify what sustainability practices are already in place and why those were selected, e.g., lean, green, and circular manufacturing practices [9]. We should envision, design, and develop solutions building from where we are today through retrofits, upgrades, improvements, etc. Whenever possible, barriers to *change* should be removed or lowered significantly to increase buy-in from the stakeholders involved. Moreover, understanding that *change* takes time, it is important to create an environment to stimulate a learning curve and build momentum. No matter how small the incremental improvements are (short-term wins), they serve a purpose as long as they move us in the right direction (long-term gains). A roadmap and a strategic communication plan should inform stakeholders in an approachable way about the pathways and concrete benefits of continuous improvements towards sustainable operations at an individual organisation and value chain levels.

RQ4.1: How can manufacturing companies assess their current performance and identify potential for improvements towards environmental sustainability?

RQ4.2: What are the practices already in place to support environmentally sustainable activities? What improvements can be made to these practices/activities?

V. Disruptive change. While continuous improvement is the dominant approach in most manufacturing environments, disruptive change can overcome hurdles that are tough to tackle in current systems. Regrouping and starting from a brand-new solution can enable leaps forward (e.g., replacing outdated machines with eco-efficient ones). Although it might slow down development, sustainability must be considered in the early planning stage to avoid falling back into the traditional 'first we build the system and then we make it sustainable'. In such a scenario, the system developed is initially unsustainable and achieving sustainability goals will take longer compared to considering it as an equal requirement integrated during the design and development stage. Getting it right on the first try is usually easier in the long run even if harder in the short term. This requires merging core business values with sustainability objectives in the overall Key Performance Indicators (KPIs) landscape and not viewing sustainability as an add-on or a stand-alone element to avoid conflict. Hence, all future industrial systems shall be 'Design for Sustainability' by default for the redesign of existing products, services, and systems, and the development of new ones [10], following an engineering approach that emphasizes the well-being of people and the environment as the outcome.

RQ5.1: How can sustainability be integrated and elevated as a core design principle for all products, services, and systems from their conception (and not as an add-on)?

VI. Dare to fail and share. In entrepreneurship, the 'fail fast' paradigm is considered an appropriate strategy towards success. As part of continuous improvement from a sustainability perspective, we need to embrace this design thinking mindset and methodology. Thus, we need to encourage and dare to experiment, fail, learn, and share both successes and failures. *Falsification* applied to qualitative research is a powerful way to advance our continuous improvement and innovation methods. Positive outcome bias in publishing results may prevent valuable lessons learnt to transfer to the rest of the research community. From a sustainability perspective, we are all working towards a common goal which is a significant pivot from our competitive driven mindset to a *coopetitive* one where 'competition' and 'cooperation' can go hand-to-hand since we all operate on one planet and a global market. *Coopetition* in the industrial ecosystem is the only sustainable way to face the challenges ahead in a volatile, uncertain, complex, and ambiguous environment. The triple bottom line of people, planet, and profit is under pressure to succeed before the time runs out for many organisations and value chains in face of new and stronger environmental regulations. Therefore, sharing the best environmental sustainability practices between organisations and value chains is the fastest track to sustainable industrial development [11].

RQ6.1: What are the best practices, tools, methods, and frameworks that ease the implementation of environmental solutions towards sustainable operations?

RQ6.2: What are the pitfalls that hinder the implementation of environmental solutions towards sustainable operations?

RQ6.3: How can falsification help to speed up the development of more effective, robust, and feasible environmental solutions, lowering the barriers to implementation and success in achieving sustainable operations?

VII. Data-driven solutions. Digital transformation and smart manufacturing are inherently *data-driven.* Transparency, traceability, availability, accessibility, quality, usability, and standardisation of information and information models within and outside organisations (their value chains) are recurring challenges still unsolved today. This expands to sustainability KPIs, practices, and insights development. The objective is to have the right information (what) in the right format (how) for the right people (who) at the right time (when) for decision-making or action-taking on the shop floor and across value chains. This is even more challenging for environmental measures that require additional and costly infrastructure for data collection, processing, storage, and analysis solutions with potential outcomes that might be detrimental to the bottom line at first sight [12]. In addition, companies are often faced with the conundrum of having too much data but not in the right quality or state, or not the right data for environmental performance management and sustainability metrics. A lot of the data available are stored without the necessary context and represent data swamps that are hardly usable for informed decision making. The missing contextualization is partly traceable to a skills shortage, lack of awareness of the context for sustainability-related metrics among operators and data scientists, lack of standards to increase usability for different stakeholders, and a perceived lack of incentives to share data among stakeholders, within and outside the organisation. Moving forward, we need to create and use standards to facilitate collaboration (data integration, sharing, and usage) to achieve not only sustainable operations at individual organisations' level but also at the value chain level [13]. Using industry commons to design both products and processes in a sustainable manner (e.g., Design for Circularity) is essential for industrial development.

RQ7.1: What data/information needs to be shared, at which level of granularity, and amongst which stakeholder(s) to facilitate efficient, sustainable operations?

RQ7.2: How to ensure information systems interoperability and avoid misinterpretation of data/information using standards for improved decision making?

RQ7.3: How to facilitate communication and information exchange beyond organisational boundaries for more efficient, sustainable value chain operations?

VIII. Use technology to become the ideal partner for sustainability. Take full advantage of the sustainability opportunities and new capabilities unlocked by the recent advances in operational and information technologies and systems, which companies are already investing in [12]; e.g., industrial digitalization, automation, and additive manufacturing. Digitalization has the potential to improve efficiency and the organisation's bottom line both directly and indirectly, but it would also lead to exacerbated ecological harm of industrialisation [13]. Technology development, selection and implementation should focus on sustainability as a primary goal (not secondary behind cost, quality, productivity, etc.). Direct gains include resource efficiency and pollution reduction. Indirect gains include the ability to manage sustainability-related data within companies and across value chains to coordinate sustainability efforts. The mechanisms through which technologies generate either negative or positive impacts should be characterised to ensure that additional impacts from producing, exploiting, and disposing of digital technologies are amortized [13].

RQ8.1: What are the environmental sustainability implications (positive and negative) when developing, selecting, and implementing advanced technologies?

RQ8.2: How can these implications be measured and integrated into technology development, selection, and implementation to ensure positive outcomes?

IX. Customer-oriented value definition for products and services design. Customers' choices (i.e., the voice of the customer) are fundamental for promoting sustainable business operations. Therefore, organisations' product and service portfolios must be sustainably improved by relying on what customers are willing to pay for. Customer orientation addresses the needs of the market by educating the consumer and promoting a sustainable consumption mindset (i.e., a healthier and more responsible consumption behaviour). Involving customers in the path towards circular and sustainable business models can be a competitive advantage since their consumption habits and attitudes are fundamental for sustainable consumer behaviours, which are based on four principles that encompass (i) selecting environmentally friendly products and services; (ii) minimising the range of consumption; (iii) maximising functionality and product life; and (iv) segregating waste to ease recycling or reuse [8] in the circular and sharing economies. Furthermore, taking customer requirements and needs as continuous improvement or innovation opportunities for sustainable business development.

RQ9.1: How to involve customers in the co-design of products and services to meet their needs in a more eco-efficient way?

RQ9.2: How to involve customers in extending the life of their products and increasing value co-creation during their usage phase?

RQ9.3: What type of product and service design standards facilitate the transition towards environmentally sustainable and circular business operations?

X. Doing good. Can incremental improvements of non-sustainable processes eventually lead to sustainability? For example, time, efforts, and investment spent on improving a coal-fired power plant may seem necessary to reduce its environmental burden, but it may also distract from shifting to renewable energy systems. Sustainable alternatives should be the focus of industrial improvements to phase out as soon as possible non-sustainable activities and start new sustainable, environmentally positive ones [15]. However, regenerative sustainability is still rarely considered when planning, building and managing industrial systems. The traditional view that we are separate and independent from nature contributed to the disconnection of our human systems and the ecosystem services they rely on. Companies can move from doing *less bad* to doing *more good* and go beyond *zero impact* by understanding the mechanisms governing the well-functioning of the surrounding natural ecosystems and accounting for local renewal and assimilation rates [16]. Cumulating incremental and radical green improvements, production and consumption levels could pass the threshold for our society to operate within the planetary boundaries. First, specific vulnerabilities in damaged local ecosystems can be targeted to stop or remove the *bad* already done (passive regeneration and restoration). Then, more active measures can be adopted through bio-inspired innovations and technological developments to tackle the remaining negative impacts.

RQ10.1: How can companies operate within natural ecosystems' limits, accounting for their renewal and assimilation ability (eco-efficient and circular practices)?

RQ10.2: What are the mechanisms through which companies can contribute positively to ecosystems' health (regenerative and restorative practices)?

3.2 Thematic Research Framework

The thematic research framework (see Fig. 1) connects the priority areas to six dominant research themes or fields identified through a thematic analysis of the last ten years of APMS conference proceedings. Each theme captures a cluster of related topics:

1. **Operations management**—scheduling, production planning and control, lean and green, asset management, maintenance, quality management, risk management, etc.
2. **Business development**—strategic planning, organizational change, organizational learning, dynamic capabilities, innovative business models, servitization, etc.
3. **Value chain management**—product lifecycle, manufacturing strategy, green supply chains, industrial symbiosis, collaborative networks, transparency, etc.
4. **Technological development**—process and product design, novel applications of manufacturing technologies, ICT, automation, Industry 4.0, etc.
5. **Human factors**—health and safety, operator support, skills and knowledge, engineering education, professional training, continuous and life-long learning, etc.
6. **Performance management**—novel indicators, multi-criteria decision making, modelling and simulation, optimisation, machine learning, big data analytics, etc.

Some of these research themes already connect strongly to the priority areas. For example, the field of business development is challenging the definition of success and value (priority area I); e.g., corporate social responsibility, service-based business models, and sharing economy. A growing number of fields are taking advantage of data-driven solutions (priority area VII) with operations management and performance management leading the way. Research on human factors is developing better support systems to assist, inform and educate people to work more efficiently and safely, empowering them to make better decisions (priority area III); e.g., new and renewed occupational health and safety standards, modern worker assistance systems with augmented and collaborative technologies. Much can be learnt from the field of operations management regarding tools and methods for continuous improvement (priority area IV); e.g., lean-green and zero-defect paradigms to improve resource efficiency. However, regenerative sustainability (priority area X) is still rarely adopted in industrial research.

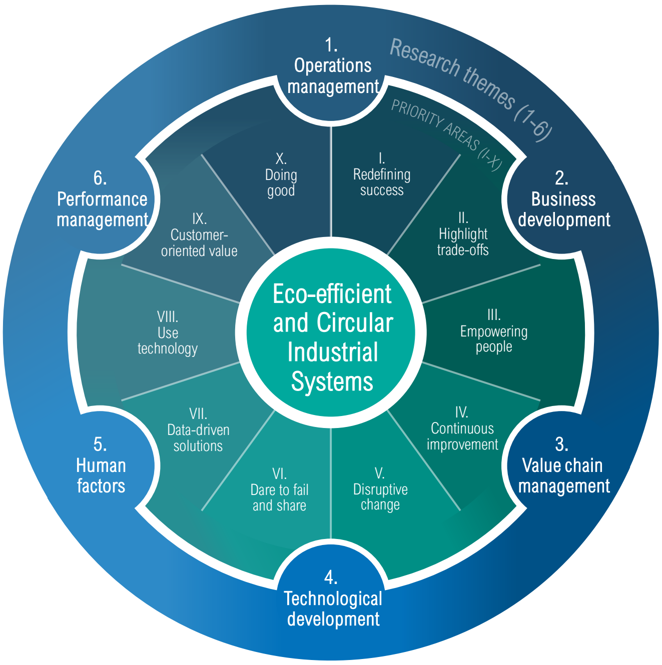

Fig. 1. Thematic Research Framework for Eco-efficient and Circular Industrial Systems.

Each research theme requires a different approach to tackle environmental sustainability meaningfully and realistically. The priority areas can be used to reframe the practical problems addressed and reflect on the conditions causing them. Then the proposed research questions can be used to prompt and guide the formulation of more specific research questions and research frameworks by individual researchers in their field. Ultimately, it is the responsibility of each researcher to scope and focus their contribution to move in the right direction (towards operating within the planetary boundaries).

4 Conclusions

This paper aims to stimulate discussions and encourage us all to address environmental sustainability more systematically and effectively in production engineering and management research. A thematic research framework for eco-efficient and circular industrial systems is presented to take advantage of the ongoing efforts on dominant research themes. With a clearer understanding of the research needs in the field of industrial sustainability, priority areas and research questions are proposed to guide ongoing and future research with a strong focus on environmental challenges to tackle them meaningfully in further industrial development. All stakeholders, from producers to consumers, need to embrace eco-efficiency and circular economy principles as the standard mode of operation for industry (production) and society (consumption), building on each other's knowledge and actions, enabling mutual learning, and eventually accelerating the much-needed sustainability transition.

Finally, the thematic research framework presents the priority areas along with six dominant themes to guide further research and technological development towards sustainable industrial solutions in the factory, supply chain, and industry as a whole level.

Acknowledgements. With thanks to the workshop participants, the European Research Council (grant no. 810764), the Swedish Manufacturing R&D, and the IFIP WG5.7.

References

1. World Business Council for Sustainable Development: Eco-efficient Leadership for Improved Economic and Environmental Performance (1996)
2. Ellen MacArthur Foundation, http://ellenmacarthurfoundation.org, last accessed 2022/04/10
3. Despeisse, M., Acerbi, F.: Toward Eco-efficient and Circular Industrial Systems: Ten Years of Advances in Production Management Systems and a Thematic Framework. Production & Manufacturing Research 10(1), pp. 354-382 (2022)
4. Houman Andersen, P.: Sustainable Operations Management (SOM) Strategy and Management: An Introduction to Part I. In: de Boer, L., Houman Andersen, P. (eds) Operations Management and Sustainability. Palgrave Macmillan, Cham (2018)
5. Vivanco, D. F., Sala, S., McDowall, W.: Roadmap to Rebound: How to Address Rebound Effects from Resource Efficiency Policy. Sustainability 10(6), 2009 (2018)
6. Didonet, S.R., Fearne, A., Simmons G.: Determining the Presence of a Long-term/Short-term Dilemma for SMEs when Adopting Strategic Orientation to Improve Performance. International Small Business Journal 38(2), 90-110 (2020)
7. Alayón, C., Säfsten, K., Johansson, G.: Conceptual Sustainable Production Principles in Practice. Journal of Cleaner Production 141, 693-701 (2017)
8. Janikowski, R.: Imperative of a Sustainable Consumer: Principles of a Sustainable Consumption. In: U. Pretterhofer (ed.), Strategies of a Sustainable Policy, pp. 29-32. IFF/IFZ, Graz Austria (2000)
9. Powell, D.J., Romero, D., Gaiardelli, P.: New and Renewed Manufacturing Paradigms for Sustainable Production. Sustainability 14(3), 1279 (2022)
10. United Nations Environment Programme: Design for Sustainability: A Step-by-Step Approach (2009)
11. Moore, S. A.: The Effect of Knowledge Sharing on the Environmental Performance of Proactive Environmental Organisations. PhD thesis, Southern Cross University (2010)
12. Wuest, T., Romero, D., Khan, M.A., Mittal, S.: The Triple Bottom Line of Smart Manufacturing Technologies: An Economic, Environmental, and Social Perspective. H.D. Kurz et al. (eds.), The Routledge Handbook of Smart Technologies, Routledge, pp. 310-330 (2022)
13. Acerbi, F., Sassanelli, C., Terzi, S., Taisch, M.: A Systematic Literature Review on Data and Information Required for Circular Manufacturing Strategies Adoption. Sustainability 13(4), 2047 (2021)

14. Kunkel, S., Tyfield, D.: Digitalisation, Sustainable Industrialisation and Digital Rebound – Asking the Right Questions for a Strategic Research Agenda. Energy Research & Social Science 82, 102295 (2021)
15. Rubio-Mozos, E., García-Muiña, F.E., Fuentes-Moraleda, L.: Rethinking 21st-Century Businesses: An Approach to Fourth Sector SMEs in their Transition to a Sustainable Model Committed to SDGs. Sustainability 11(20), 5569 (2019)
16. Morseletto, P.: Restorative and Regenerative: Exploring the Concepts in the Circular Economy. Journal of Industrial Ecology 24, 763-773 (2020)