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Kristina Säfsten, Ulrika Harlin, Kerstin Johansen, Lisa Larsson, Anna Öhrwall Rönnbäck

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Resilient and sustainable production systems: towards a research agenda

Kristina Säfsten*

Department of Product Development, Production and Design,
School of Engineering,
Jönköping University, Sweden
Email: kristina.safsten@ju.se
*Corresponding author

Ulrika Harlin

Department Methodology, Textiles and Medical Technology,
Division Materials and Production,
RISE Research Institutes of Sweden, Sweden
and
HELIX Competence Centre,
Linköping University, Sweden

Kerstin Johansen

Department of Product Development, Production and Design,
School of Engineering,
Jönköping University, Sweden

Lisa Larsson and Anna Öhrwall Rönnbäck

Department of Social Sciences, Technology and Arts,
Luleå University of Technology, Sweden

Abstract: It is widely recognised that manufacturing companies need to pay attention to sustainability aspects to be competitive. However, there is still no clarity on how to combine requirements for sustainability and profitability to achieve long-term competitive manufacturing. Furthermore, there is a need for knowledge on how to develop resilient and sustainable production systems. This paper aims to explore the state-of-the art and state-of-practice associated with the development of resilient and sustainable production systems, with a focus on challenges and enablers. To achieve this, a narrative literature review was carried out, combined with results from knowledge creation workshops with five manufacturing companies striving towards resilient and sustainable production systems.

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Biographical notes: Kristina Säfsten is a Professor in Production Systems at School of Engineering, Jönköping University, Sweden. She holds a PhD in Assembly Technology from Linköping University, Sweden. Her research focuses on integrated development of products and production systems, sustainable production, knowledge integration and boundary crossing. Her publications include books on development and operation of production systems and research methodology for engineers. Her scholarly papers have appeared in for example *Journal of Manufacturing Technology Management*, *International Journal of Production Economics*, *Research-Technology Management*, *Journal of Cleaner Production* and *Sustainability*.

Ulrika Harlin is an Industrial Researcher at RISE Research Institutes of Sweden and affiliated to Linköping University. She holds a Licentiate of Engineering in holds a Licentiate of Engineering in Production System Development and Human Factors Engineering from Chalmers University of Technology. Her research focuses on integration of human and organisational aspects in change processes, transitions, and design phases of production systems. Her scholarly papers have been published in for example *Journal of Manufacturing Technology Management*, *Small Business Economics*, *Management Learning*, *European Journal of Workplace Innovation*, *Batteries* and *Journal of Cleaner Production*.

Kerstin Johansen is a Professor in Integrated Product and Production Development at the School of Engineering, Jönköping University, Sweden. She holds a PhD in Assembly Technology from Linköping University, Sweden. Her research focuses on human-robot collaboration, emerging technologies related to Industry4.0, flexible production, industrialisation and sustainable production in a circular economy. Her scholarly papers have appeared in *Robotics and Computer Integrated Manufacturing*, *Production Engineering*, *Journal of Manufacturing Technology Management*, *International Journal of Sustainable Engineering* and *Sustainability*.

Lisa Larsson is an Associate Senior Lecturer at the Division of Humans and Technology, Luleå University of Technology, Sweden. She holds a PhD in Product Innovation from Luleå University of Technology. Her research sits at the intersection of production management and innovation management, focusing on production innovation and its role in sustainable development in manufacturing firms.

Anna Öhrwall Rönnbäck is a Chaired Professor in Product Innovation at the Division of Humans and Technology, Luleå University of Technology, Sweden. She holds a PhD in Industrial Engineering and Management from Linköping University, Sweden. Her research focuses on sustainable business development, innovation management, and integrated product and production development. Her publications include books on innovation management and scholarly papers published in *Journal of Engineering Design*, *International Journal of Innovation Management*, *International Journal of Production Research* and *Sustainability*.

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1 Introduction

A decade ago, a forecast identified sustainability as an emerging megatrend, similar to IT and quality (Lubin and Esty, 2010). Today, sustainability is a vital part of the industrial strategy, including the twin transition to a green and digital economy formulated by the European Commission. An associated initiative is the European Green Deal, striving towards a climate neutral Europe by 2050 (European Commission, 2019) (i.e., the EU's growth strategy) which aims to develop a prosperous and fair society with a resource-efficient, modern and competitive economy. As a response from the manufacturing industry, sustainable production systems have emerged as a concept, with an overarching purpose-driven mission to accelerate change, making the world a better place for future generations, with goals to preserve resources and in parallel contribute to economic growth and human welfare (Bosma et al., 2020; Johansson et al., 2019). To enable the endeavour towards the development of sustainable production systems, industrial organisations need increased knowledge of barriers and enablers to realise solutions that contribute in this direction (Alayón et al., 2022).

Manufacturing is the backbone of Europe; in addition to the ability to sustainably manufacture products, there is a need for production systems to manage unexpected and expected conditions in a resilient way. The ManuFUTURE 2030 vision has recently been expanded to include sustainability dimensions and also focus on adaptive and resilient manufacturing ecosystems, whereas the previous focus was purely on competitiveness (ManuFUTURE, 2019). The need to pay significant attention to resilience and sustainability, in addition to profitability, has been put forward by the European Commission; Industry 5.0 is regarded as a successor and complement to the technological focus in Industry 4.0. Industry 5.0 specifically recognises the 'power of industry to achieve societal goals beyond jobs and growth, to become a resilient provider of prosperity, by making production respect the boundaries of our planet and placing the well-being of the industrial worker at the centre of the production process' (Breque et al., 2021).

Based on these challenges and forecasts, manufacturing industries need an agenda that includes sustainability and resilience perspectives, where production innovations and new competence are essential elements. It is assumed in the literature that there is no trade-off between profitability and sustainability; however, the awareness on how to proceed in practice varies, and there exists a knowledge gap about how to combine requirements on profitability and sustainability to achieve competitive manufacturing (Machado et al., 2017). It is well known that it is beneficial to regard requirements during the development phases of production system (Bellgran and Säfsten, 2010). As development of production systems is often carried out as part of new product development projects, considering aspects related to sustainability and resilience, together with profitability, in early design phases would be beneficial. However, the inclusion of aspects related to production system development in current product development processes is limited (Guðlaugsson et al., 2017; Henriksson and Detterfelt, 2018). In general, there is a lack of a systematic approach and long-term thinking regarding the development of the production system, and production innovations are often of an ad hoc character (Larsson, 2020; Stoffels et al., 2021). Furthermore, the increased complexity of fast-moving environments, in which a multitude of influencing factors need to be considered in parallel during the development of production systems, is an emerging challenge. So far, there is limited research on how to develop resilient and sustainable production systems that contribute to manufacturing company's competitiveness and profitability.

Thus, the aim of this paper is to outline a research agenda with a focus on the development of resilient and sustainable production systems. To achieve this, the concepts of resilience and sustainability must be understood in the context of production systems. In addition, enablers and barriers related to the development of resilient and sustainable production systems must be identified. The foundation for the suggested research agenda was the state-of-practice and state-of-the-art related to the development of resilient and sustainable production systems. A narrative literature review was combined with empirical studies within companies striving towards resilient and sustainable production systems.

2 Research methods

In this chapter, the research methods and data collection techniques are introduced. An interactive research approach is applied, and a developed workshop typology is presented. Furthermore, an analysis framework is introduced.

2.1 Narrative literature review

The state-of-the art description was developed with a narrative review as a foundation, which is suitable when a research agenda is aimed at (Jesson et al., 2011; Rhoades, 2011). The results of a narrative literature review show gaps in current knowledge and deficiencies in current studies that need further elaboration (Dekkers et al., 2021). To obtain an overview of current research related to the development of sustainable and resilient production systems, different sources were combined, such as scholarly journals, conference proceedings, books, as well as strategy documents and research agendas from the EU. An initial systematic search in Scopus gave unsatisfactory results. The search string 'sustain* AND resilien* AND development AND ('production system' OR 'manufacturing system')' resulted in 249 hits in Scopus. Limiting the search to English, engineering-related topics and publication types as specified above, 44 papers remained, of which a few were relevant. One challenge was that few papers on production system development (or, similarly, manufacturing) included aspects related to both sustainability and resilience. Another challenge was that few papers specifically addressed the development of production systems (or manufacturing), but rather focused on the resulting production system capabilities. A more successful approach to identifying relevant literature was to address themes related to the overall topic, in line with the logic for a narrative review (Dekkers et al., 2021). This, combined with a snowballing approach (Wohlin, 2014), resulted in several interesting and relevant publications for the purpose of this paper.

2.2 Interactive research and workshop typology

An interactive research approach was applied in the empirical part of this paper. During interactive research, practitioners and researchers collaborate during all phases (Nielsen and Svensson, 2006). Well-designed collaboration arenas are essential to allow for joint reflection, interpretation and development of new knowledge that is relevant for both practitioners and researchers (Ellström et al., 2020; Van de Ven, 2018). A common collaboration arena is workshops, which can be an arena for joint learning, but also a source of data collection (Berglund et al., 2020). To support different stages of the interactive research processes, different types of workshop designs are necessary. With a focus on two dimensions:

a the purpose of the workshop (x-axis)

b the participants (y-axis).

Four types of workshop designs were developed (see Figure 1). The focus of the workshop could be on development of knowledge, through joint analysis, problem solving, innovation or on the dissemination and validation of knowledge. Workshop participants were categorised as internal or external to the core team of the interactive research process, often a formal research project. Based on these two dimensions, four different types of workshops evolved based on their main purpose:

a knowledge creation workshop

b inspirational workshop

c results workshop

d knowledge sharing workshop.

Figure 1 Workshop typology developed to support interactive research processes

		Focus of the workshop			
		Development of knowledge[a]		*Dissemination and validation of knowledge*	
Participants	*Internal* (project partners)	a	Knowledge-creation workshop	c	Result workshop
	External (outside the project)	b	Inspirational workshop	d	Knowledge sharing workshop

Note: [a]Joint analysis/problem-solving/innovation

Collaborative workshops with a focus on joint creation of new knowledge are necessary elements of an interactive research process (Berglund et al., 2020; Ellström et al., 2020). Therefore, knowledge creation workshops with involved partners are key. According to the developed typology, joint analysis, problem-solving and innovation can also be done together with external participants, invited for a specific purpose. Inspirational workshops aim to provide participants with mental nourishment and inspire them with insights from external sources. In a similar way, workshops with a focus on dissemination can be limited to the core team of an interactive research process or stretch beyond the core team. During a result workshop, results are presented, refined and validated within and among the core team, whereas in a knowledge-sharing workshop, results are shared with a broader community.

2.3 Empirical study

The empirical data for this paper includes the current practice from five companies; see Table 1 for an overview. Among these companies, manufacturing, component suppliers, manufacturing equipment suppliers and construction project management were represented and selected to provide different perspectives (Eisenhardt, 1989). Four of the five participating companies can be classified as small- or medium-sized (SME), according to the EU's definition in which an SME employs fewer than 250 persons and has an annual turnover not exceeding EUR 50 million, and/or an annual balance sheet total not exceeding EUR 43 million (http://data.europa.eu/eli/reco/2003/361/oj). The fifth company, Company Generation, was slightly larger (260 employees).

Table 1 Overview – industrial partners

Company	*Description*
Company Planet	Manufacturing company, start-up, greenfield production systems, SME
Company Turning	Manufacturing company, component supplier, brownfield production systems, SME
Company Automation	Automation solution supplier supporting industrial production development, SME
Company Project Management	Industrial consultant supporting organisations in different sectors with construction project management, SME
Company Generations	Manufacturing company, greenfield and brownfield production systems

For this paper, empirical data was collected during knowledge-creation workshops. The workshops were recorded, and detailed notes were taken. As input for the workshops, the involved companies had prepared presentations of their current positions. Questions were sent to the companies beforehand and thereby their input during the workshops was grounded in current practice in their company. In addition, empirical data was collected from the company-specific 'progress maps' including an overview of each company's vision related to resilient and sustainable production systems, their current state, challenges and enablers, and planned actions. The progress maps were established jointly between the practitioners and researchers and updated 2-3 times a year during the research project.

2.4 Analysis of data

A structured process for analysis of the qualitative data was applied, involving three steps: data condensation, data display, and drawing and verifying conclusions (Miles et al., 2019). Considering the production system as a socio-technical system calls for a holistic perspective, including people, technology and organisation (Brandt and Hartmann, 1999). To guide the analysis according to this perspective, a priori codes were selected. The technology, organisation and people (TOP) framework was applied, which is a classic framework for analysis related to management of socio-technical systems (Stenholm and Bergsjö, 2020). The technology dimension in the TOP framework is related to tools, IT systems, machinery, etc. The organisation dimension is related to management processes, organisational structure and aspects involved may be responsibilities, roles, work processes, leadership, strategy, goals, measurement and control. Finally, the people in the system, with a focus on culture and human factors such as recruiting, training and learning patterns, are considered in the people dimension of the framework.

3 Results from the literature review

This chapter presents current research related to the development of resilient and sustainable production systems, based on the narrative literature review.

3.1 Characteristics of resilient and sustainable production systems

Resilience is a multifaceted concept applied in a variety of fields and multiple definitions exist (Alexander, 2013; Angeler and Allen, 2016; Bhamra et al., 2011). A literature review carried out by Hosseini et al. (2016), identified four domains of resilience definitions: organisational, social, economic and engineering. The latter, resilience related to engineering, a fairly new area, is concerned with technical systems, including humans and technology (Hosseini et al., 2016). A similar concept is operational resilience, referring to the ability of the production system to change, recover and adapt during times of stress, disruption or uncertainty (Essuman et al., 2020). Theoretical frameworks primarily focus on wider aspects of resilience related to enterprises or business resilience, and there is a gap regarding resilience at the operational level within manufacturing companies (Thomas et al., 2015). Resilience is defined in this paper as being inspired by the field of resilient engineering and referred to as the ability of a production system to "adjust its functioning prior to, during or following events (changes disturbances, and opportunities), and thereby sustain required operations under both expected and unexpected conditions" [Hollnagel, (2011), p.xxxvi].

The Lowell Center for Sustainable Production (LCSP) defined sustainable production as "the creation of goods and services using processes and systems that are: non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for workers, communities, and consumers; and socially and creatively rewarding for all working people" (Veleva and Ellenbecker, 2001). A similar definition of sustainable manufacturing is "the ability to smartly use natural resources for manufacturing, by creating products and solutions that, thanks to new technology, regulatory measures and coherent social behaviours, are able to satisfy economical [sic], environmental and social objectives, thus preserving the environment, while continuing to improve the quality of human life" (Garetti and Taisch, 2012). Both definitions include the three dimensions of sustainability – social, environmental and economic – commonly used to conceptualise sustainable development (Purvis et al., 2019). Referred to as the triple bottom-line, this perspective is commonly applied in research, although some of the dimensions are more explicitly addressed. Research on sustainable or green manufacturing focuses mainly on environmental/ecological dimension of sustainability. When lean and resource-efficient production systems are considered, economic aspects are implicitly included (Rahimifard et al., 2017). The social aspects of sustainability in industrial development have so far been less reported in the literature, but have risen in attention in the light of Industry 5.0 (Leng et al., 2022; Lu et al., 2022).

3.2 Barriers and enablers related to resilient and sustainable production systems

Research has addressed different aspects of resilient and sustainable production systems; however, implementation of approaches towards such targets requires that the prerequisites for implementation where technological aspects in relation to social, human and societal aspects are well understood (Leng et al., 2022). Therefore, knowledge about enablers and barriers related to both the development and implementation of resilient and sustainable production systems might be useful. However, in the literature, these aspects are most often treated separately, i.e., in relation to either sustainability or resilience.

A literature review including the integration of resilient, lean, green and smart manufacturing pointed out that the main challenge was the lack of expertise and training programs (Touriki et al., 2021). The same review identified barriers towards the amalgamation such as resistance to change, lack of management involvement, lack of time and resources, lack of communication and technological issues. Similar barriers have been identified in several studies. The book *Sustainable Manufacturing* categorised the barriers affecting the way manufacturing companies work with sustainability into economic barriers, lack of top management support and commitment, lack of knowledge and lack of environmental data (Johansson et al., 2019). Enabling factors identified in the above-mentioned literature review included top management commitment, communication, cooperation, and collaboration, change readiness, training and project management (i.e., the inverse of the identified barriers). In their resulting framework, smart manufacturing was expected to unlock potential trade-offs and support lean, green and sustainable production (Touriki et al., 2021). Another study has pointed out that flexibility and a high degree of automation might be a way for small manufacturing companies to become more resistant to disruptive events (Johansen, 2020). In complex systems, such as production systems, the ability to manage flexibility and balance between robustness and transformation/innovation are identified as key enablers contributing to resilience (Asokan et al., 2017). Cooperation between designers and engineers at different stages of the value chain, from the development of renewable materials to enhancement of services, are identified as enablers for development of solutions related to circular economy (De los Rios and Charnley, 2017). The same study stresses that new skills and capabilities are needed to reduce sustainability impacts, ranging from deeper knowledge of materials usage to a rich understanding of social behaviour. Enabling technologies for sustainable manufacturing, including advanced manufacturing technology, manufacturing ICTs, and new production processes, has been pointed out as an area that needs further research (Garetti and Taisch, 2012). In a similar vein, sustainable machining and sustainable Industry 4.0 have been recognised as R&D needs supporting sustainable manufacturing (Jamwal et al., 2021).

A systematic literature review identified internal and external barriers as well as enablers' adoption of sustainable manufacturing in small and medium-sized manufacturing companies (Alayón et al., 2022). A taxonomy has been suggested in which enablers and barriers were grouped into seven categories:

a organisational, managerial and attitudinal

b training and skills

c technological

d financial

e informational

f market and business context

g governmental barriers and enablers.

Many of the identified barriers were internal and related to organisational, managerial and attitudinal aspects. Among the barriers were low managerial priority towards sustainable manufacturing practices, organisational culture, lack of time, and perceived conflicts between environmental practices and other business objectives. The informational barriers include, among others, lack of sustainability knowledge, lack of knowledge about environmental systems and poor communication. Only a few technological barriers were mentioned, including them outdated and unavailable technology. The taxonomy included several mitigating enablers for each identified barrier. Some enablers could mitigate more than one barrier. Among the most frequently used enablers are knowledge networks, external cooperation, environmental management systems (EMAS and ISO 14001) and managerial support (Alayón et al., 2022).

Another set of barriers to sustainable manufacturing, similar to those already mentioned, was presented in a study including both small-, medium- and large-sized manufacturing companies (Bhanot et al., 2015). In this study, barriers such as lack of awareness of sustainability concepts, negative attitude towards sustainability concepts, lack of funding, high costs, lack of standards and metrics, and lack of support from senior leaders were identified (Bhanot et al., 2015). In the same study, improving quality, innovation and technology investments, and training and education systems were mentioned as enablers (Bhanot et al., 2015). In addition, market pressure, government regulations and promotions, economic benefits and lowering manufacturing costs were also mentioned as enablers. However, these aspects have been addressed as drivers, i.e., reasons for a manufacturing company to engage in sustainable manufacturing, rather than enabling factors (Johansson et al., 2019). Other drivers for sustainable manufacturing include strengthened competitiveness, cost reduction, improved branding and environmental image, the ability to meet new customer/market demands, and compliance with environmental standards regulations (Johansson et al., 2019). Similar drivers were also identified in the study holistically integrating resilient, lean, green and smart manufacturing (Touriki et al., 2021). They identified competitiveness, environmental regulations, changing customer needs, corporate images, and social responsibility as drivers for development towards resilient, lean, green and smart manufacturing.

3.3 Development of resilient and sustainable production systems

To create preconditions for resilient and sustainable production systems, relevant aspects need to be identified and considered in the early development phases. A sustainable production system is expected to support multiple generations of products; therefore, a long-term perspective is essential during the development process (Bellgran and Säfsten, 2010). Product and production systems must be aligned and developed with a life-cycles perspective (Guðlaugsson et al., 2017; Stoffels et al., 2018). Manufacturing companies require a variety of new capabilities to reduce their sustainability impacts, ranging from increased knowledge related to materials usage to a rich understanding of social behaviour (De los Rios and Charnley, 2017). The capabilities rest on cross-disciplinary competencies and collaboration. However, such collaboration is challenging, where, for example, organisational and geographical dispersion causes separation between technology development, product development and production activities (Lakemond et al., 2013).

A challenge is to design flexible production systems that function in the case of disturbances (Dalziell and McManus, 2004) and still maintain systems efficiency (Erol et al., 2010). The present literature stresses that context-specific aspects need to be considered to recognise enablers and barriers, assess preconditions and develop approaches that push the system towards resilient performance as the context of a system varies according to the nature of changes and disturbances they are subjected to (Hillmann and Guenther, 2021).

Most of the literature on production system development (or manufacturing), as mentioned, focused on either the development of resilient or sustainable production systems. However, recent papers addressing Industry 5.0 as enabling successful industrial development include both aspects. In Industry 5.0, the technology focus in Industry 4.0 is complemented with three desired characteristics: human-centricity, sustainability and resilience (Breque et al., 2021). According to Leng et al. (2022), Industry 5.0 places the well-being of the workers at the centre of the manufacturing process. This is done through production, respecting the boundaries of our planet and aligning humans and machines. Human-centric manufacturing addresses human needs – from basic needs related to safety and health to higher levels of esteem and self-actualisation (Lu et al., 2022). Furthermore, the social sustainability dimensions related to work need to be integrated and considered in the early phases of production system development (Harlin and Berglund, 2021; Sutherland et al., 2016). New generations of work and workplaces will be developed in modern industrial contexts, requiring new abilities; hence, knowledge of planned changes is necessary from the perspective of future work (Johansson and Abrahamsson, 2009).

During the development of a sustainable production system, aspects related to the three dimensions of sustainability are to be considered with a holistic perspective, which is particularly relevant when the surrounding environment and the internal organisation are characterised by a faster pace of change (Backström et al., 2002; Zink, 2014). Furthermore, the complexity of many parallel work processes related to the industrial development towards green transformation requires continuous transparency and collaborations across traditional borders in the value chain and actors in the society (Harlin et al., 2022). However, in such development phases, contradictory demands and multiple tensions may arise, requiring managerial approaches with attention to such potential problems in early development phases (Smith and Lewis, 2011). In the literature, the multifaceted social dimension of sustainability has been perceived as challenging to operationalise, especially in the manufacturing domain (Sutherland et al., 2016). A lack of a shared understanding of the essence of human-centric manufacturing has also been observed (Lu et al., 2022).

Production system development implies that needs are converted via functional requirements into relevant physical solutions (Cochran and Rauch, 2020). Thereby, the inclusion of resilience and sustainability aspects in the production system development process requires operationalisation of the abstract concepts. One way to operationalise sustainability has been through the formulation and implementation of performance indicators related to sustainability (Veleva and Ellenbecker, 2001). Key performance indicators are tools for aligning business objectives and strategies with business operations. Thus, a prerequisite to reaching the business objectives in a manufacturing company is that production systems are developed in alignment with the overall objectives (Almström et al., 2017). Similarly, several attempts have been made to quantify and measure resilience (Hosseini et al., 2016). According to a thorough review, both quantitative and qualitative approaches for assessing resilience were identified, both of which were found in the engineering domain (Hosseini et al., 2016). In another review related to measurement of organisational resilience, Hillmann and Guenther (2021) pointed out that the nature of uncertainties in a system must be understood as their impacts on a system (i.e., their expected and realised outcomes) to allow for managerial actions.

4 Empirical results

4.1 Drivers for development towards resilient and sustainable production systems

Among the participating companies in the empirical study, the drivers for achieving resilient and sustainable production systems were expressed from several perspectives. From an overarching perspective, drivers were expressed as 'wanting to contribute to a sustainable world', 'reduce climate impact', 'offer attractive or healthy products for future generations' and 'improve life quality, justice and equality in the society'. When approaching production system development, drivers were mentioned as "opportunities of being in the forefront of creating conditions for sustainable production that strengthens the company's talent attraction and competitiveness". The development of both short-term and long-term manufacturing strategies was mentioned as important, as well as the ability to translate these visions and goals into practice, so that it permeates the entire business. Furthermore, the creation of opportunities for acceleration in the desired direction through product, production and organisational development is similarly crucial. Create insights and a company culture permeating all functions and activities so that sustainability would be considered in all processes and 'everything that is done' was named an ambition. A need for more systematic management, design and further development in all project phases was also mentioned. The increasing pace of change in a fast-moving environment, market demands and the experiences from the COVID-19 pandemic was among the drivers within the companies for creating conditions for increased preparedness towards external influences, uncertainties and disturbances. The ability to constantly meet customer's demands was deemed crucial among the participating companies, as customer demands concerning environmental aspects constantly changed.

4.2 Characteristics of resilient and sustainable production systems

A starting point among the involved manufacturing companies was to increase the understanding of what resilient and sustainable production entails and how it can be achieved. During a knowledge creation workshop (see Figure 1 for the workshop typology), the following characteristics of resilient production systems were described among the practitioners:

- flexibility in enabling rapid changes in the surrounding environment
- capability of changing quickly enough to survive
- secured competences to avoid vulnerability
- ability to manage staff turnover
- being an attractive employer
- manage to handle changes in required capacity
- capable of developing and changing according to preconditions
- understand the need from the customer – dynamic work methods
- ability to quickly change/find solutions if there is minor/medium disruption in the logistics chain.

Practitioners from one of the companies referred to the surrounding environment, the planet, when asked to define resilience. According to them, resilience was related to the planet and how a manufacturing company interacts with the surrounding environment. In the context of production systems, the industrial participants in the same knowledge creation workshop characterised sustainability as:

- the ability to communicate how the selection of suppliers affects climate footprint
- good working environment and working conditions for people throughout the value chain
- minimum carbon footprint without risking quality
- circularity (for example, residual streams become raw materials for new products)
- climate-neutral transport/logistics chain.

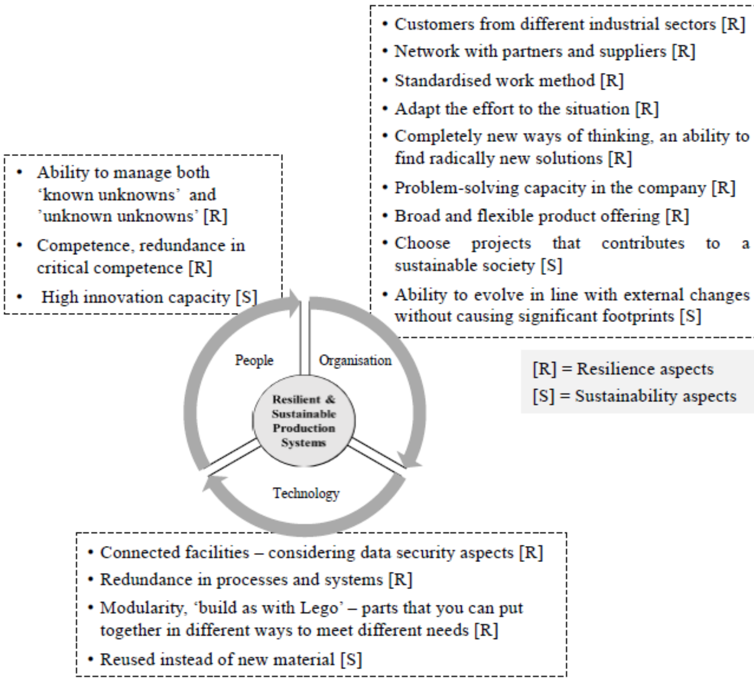
4.3 Enabling a resilient and sustainable production system

In addition, during the knowledge creation workshop, means to achieve resilient and sustainable production were identified (see Figure 2). The identified means were categorised according to the TOP framework, including technology (T), organisation (O) and people (P).

Enabling aspects related to technology include high automation levels with redundance in processes and systems, modular solutions, solutions that connect facilities in which data security aspects are considered, and solutions enabling the reuse of materials.

Organisational enablers included cross-functional inter- and intra-organisational collaboration. For example, collaboration within production system development projects in the early design phases and solution-oriented collaboration in networks with partners, suppliers and customers from different industrial sectors. In addition, collaboration with consumers and other stakeholders aiming to develop sustainable solutions was mentioned during the workshops. Furthermore, standardised work methods with the capability to adapt to new conditions and situations were identified as enabling the problem-solving capacity in one of the companies. Business development that is adaptable to different customers and markets, broad and flexible product offerings, and the ability to evolve in line with external changes without severely increasing the company's carbon footprint were also mentioned as enablers from a strategic perspective.

Figure 2 Means to achieve resilient and sustainable production systems (see online version for colours)



Among the people-related enablers were insights and drivers towards sustainability at all levels and functions and abilities to manage uncertainties (abilities to manage both 'known unknowns' and 'unknown unknowns'). Furthermore, people-related enablers were related to access to relevant competences within existing and new domains and to minimise vulnerability by creating redundancy in critical competences. Renewal capability and high innovation capacity were identified as enabling the development of, for example, new offerings. Additionally, communication and cross collaborations that share experiences and information from different workplaces and industries were considered beneficial.

Apart from enabling factors, several barriers were mentioned during the workshops. Some companies mentioned change aversion and having too little time for strategic issues as hindering factors. Another barrier was the lack of staff. Furthermore, customers and consumers were not always willing to pay for sustainability – a critical factor.

The companies addressed a need for further support on addressing aspects related to resilience and sustainability in their production development projects. An identified challenge was when and where specific aspects with an impact on resilient and sustainable production systems should be addressed in different phases and work processes during production development. None of the companies described a systematic process for the development of production systems. One of the participating manufacturing companies expressed the benefits of a strong, clear, top management that supports sustainability strategy and guides the development of new factories, as well as the benefits of investments in existing production plants. However, they still perceived the operationalisation of the sustainability strategy as somewhat challenging. In addition, challenges related to complexity, speed and supply of competences within new domains were addressed, with a potential of collaborations within and outside the own organisation for competence development and joint development efforts.

5 Resilient and sustainable production systems – towards a research agenda

As we have seen in the previous sections, developing resilient and sustainable production systems requires that a multitude of influencing factors be considered in parallel. The industrial practice when it comes to long-term manufacturing strategies and the use of systematic production system development processes is limited, and the operationalisation of sustainability and resilience in a production context remains a challenge. Furthermore, contextual understanding is needed to be able to create appropriate prerequisites for the desired performance of a system. With this foundation, potential research areas related to the development of resilient and sustainable production systems are outlined here.

5.1 Holistic and long-term perspectives

Literature that considers both resilience and sustainability aspects in production systems development is lacking. In addition, the different aspects of sustainability (environmental, economic and social) are not always considered in conjunction, either in practice or in theory (Alayón et al., 2017). Furthermore, a system perspective, including technology, people and organisation, is advocated when developing production systems are advocated (Bellgran and Säfsten, 2010). The lack of a holistic perspective may result in locked structures and rigid solutions, which may counteract the possibility of resilient and sustainable product systems in the future.

A quest for long-term solutions when developing production systems was observed during the empirical study. Challenges related to upgradable production systems and updates of software in technical systems were mentioned, as was modularity akin to *Lego* blocks, which allow system components to be combined in different ways to meet various future demands. In addition, redundancy related to competence, processes and systems was mentioned. The literature emphasises the need for a life-cycle perspective on both the product and production system (Bruch and Bellgran, 2014; Stoffels and Vielhaber, 2016), but also points out that the transformation towards sustainable manufacturing follows an evolutionary road, from focus on compliance to an innovative approach, supporting long-term values development (Machado et al., 2017). To support a circular life-cycle perspective, strategies related to the circular economy are commonly used, including recover, recycle, repurpose, remanufacturing, etc. (Blomsma et al., 2019; Skärin et al., 2022). However, the importance of combining circular solutions with the sustainability component has been emphasised (Bjørnbet et al., 2021).

5.2 Transforming visions and strategies into practice

Several of the companies participating in the empirical study had taken initiatives related to the development of sustainable offers, product development, and investments in production system development. As expressed by one of the companies in the empirical study, "it is a big challenge of how to translate these visions and goals into practice, so that it permeates the entire business"; that is, approaches are necessary to support operationalisation of sustainability and resilience aspects.

There was a consensus in the literature and among the companies that it was important for the company's brand to genuinely take environmental responsibility when developing operations. The ability to meet new customer/market demands and the potential for increased competitiveness was also reported in the literature (Touriki et al., 2021).

One way to align business objectives and strategies with operations is through performance measures and key performance indicators (KPI) (Almström et al., 2017). There are already measures and frameworks available for both sustainability and resilience, but the focus has so far been on what measures to use rather than how the measures can be used to support implementation.

5.3 Collaboration and management

Many of the identified means of achieving resilient and sustainable production systems were related to organisational aspects. Several of these were related to cross-functional collaboration both within the company and with external partners. To achieve sustainable and resilient production systems, trustful collaboration within and between organisations striving towards common targets is expected to support proactive, solution-oriented solutions (Harlin et al., 2021). To achieve the mission observed in the empirical study and to contribute to overarching goals and a sustainable world for future generations, professional project management and leadership, strategies for communication, cooperation, and collaboration are required (Touriki et al., 2021), both within and beyond organisational borders.

Willingness to take social and societal responsibility was identified during the empirical study, in combination with a potential competitive advantage from doing so, by being at the forefront for development of their business, products and production systems. The literature confirms that these are common visions for the manufacturing industry (Bosma et al., 2020; Johansson et al., 2019). However, strategies and top management commitment are needed in combination with increased knowledge and ability of how to transform these visions into practice (Touriki et al., 2021).

5.4 Competence needs, organisational learning and innovation capability

A desired ability to meet new market demands and contribute to the acceleration towards a green transition was expressed by the participating companies. The strategic supply of competences, including reskilling needs among many functions to be able to develop circular solutions, new business models, etc. was identified as a challenge. Despite the challenges related to the development of resilient and sustainable production systems, the participating companies expressed high ambitions to learn and develop transformation abilities enabling green industrial transformation.

In addition, to remain competitive, long-term production innovation capability is required, enabling the continuous transformation of production capabilities and business processes to achieve increased levels of flexibility and intelligence in production systems (Larsson, 2020). Hence, the key for achieving resilient and sustainable production systems that support the continuous upgrading of the system is increased and maintained production innovation capability (Romero et al., 2021).

5.5 Understanding critical events

Knowledge of the critical events, such as disturbances, disruptions, problems and uncertainties – both planned and unplanned—that might influence the production system is required to proactively develop resilient ability in production systems (Fjällström et al., 2009). During the development of a production system, it is challenging to predict everything, and as stressed in the empirical study, enabling factors are, for example, the ability to manage both ‘known unknowns’ and ‘unknown unknowns’, as well as to have a change-positive culture, also referred to as change readiness in the literature (Touriki et al., 2021). In addition, experiences from the recent COVID-19 pandemic, which has caused serious disturbances, gave rise to drivers related to the development of resilient organisations and production systems (Berglund et al., 2022; Johansen, 2020). Several examples of vulnerability in the supply chains were mentioned during the empirical study, as was the lack of key competences since there were variations in terms of accessible workforces. Hence, there is a need for knowledge on how critical events may affect the production system’s performance, positively or negatively/short and long term, knowledge on foreseeing critical events and new opportunities, and creating preconditions for utilising learnings from previous critical events. Due to uncertainties in a dynamic environment, it is desirable if a production system can perform in a resilient manner, i.e., absorb disruption and recover with a minimum of effort (Essuman et al., 2020), together with the ability to respond, monitor, learn and anticipate (Hollnagel, 2011).

5.6 Understanding and overview of enablers and barriers

Besides contextual understanding, manufacturing companies also need increased knowledge of enablers and barriers to realising sustainable manufacturing (Bhanot et al., 2017; Johansson et al., 2019). Both in the literature and during the empirical study, enablers and barriers related to resilient and sustainable production systems were identified. Enablers and barriers are two sides of the same coin, as preventive actions can be made based on barriers, and enablers can proactively be used as mitigation strategies (Alayón et al., 2022). The empirical study identified several means to achieve resilient and sustainable production systems (for an overview, see Figure 2), of which several can be adopted during the development of production systems.

To allow an overview of all aspects that need to be considered and facilitate supportive actions, a systematic approach is needed. In this study, the technology, organisation and people (TOP) framework was applied, due to its applicability to socio-technical systems (Stenholm and Bergsjö, 2020). Since this framework allows the categorisation of enablers and barriers, an overview was achieved. In addition, it has been shown to be essential to distinguish between internal and external barriers (Alayón et al., 2022), which further support where actions can be made.

5.7 Supporting the production system development process

From the perspective of development processes towards resilient and sustainable production systems, the literature stresses the benefits of considering aspects in early development phases (Bruch and Bellgran, 2014; Stoffels et al., 2018), however, none of the companies in the empirical study described a systematic process for development of production systems nor approaches for including aspects related to sustainability or resilience in a systematic way.

So far, research related to the work procedures for the development of resilient and sustainable production systems is limited. The focus has been on sustainable products or production processes. In addition, the literature on production system development seldom includes aspects related to both resilience and sustainability. Yet another limitation in the current literature is the fragmented handling of the economic, ecological and social aspects of sustainability (Alayón et al., 2017). Thus, there is a need for a supporting framework for development processes that holistically includes the triple bottom line together with consideration of prerequisites needed to be considered to achieve resilient production systems.

5.8 Elements of resilient and sustainable production systems

The elements of resilient and sustainable production systems are related to technology, organisation and people. A necessity for manufacturing resilience is flexibility and the capability for transformation (Johansen, 2020; Khan et al., 2012). Flexibility is identified as key in balancing robustness and transformation, the needs of a complex system, although both contribute to resilience (Asokan et al., 2017). Increased digitalisation in combination with emerging technologies challenges the IT structure. In the future, the selection and configuration of technologies, interfaces and processes will be even more important than today. Enabling technologies for sustainable manufacturing, including advanced manufacturing technology, manufacturing ICTs, and new production processes, have been pointed out as relevant for further research (Garetti and Taisch, 2012). Research needs raised in an overview of focusing on sustainable manufacturing during the period from 1999 to 2020, pinpointed research themes such as sustainable machining, decision making, lean and environmental management, and sustainable Industry 4.0 (Jamwal et al., 2021).

The need for a human-centric approach during the development of production systems is emphasised in Industry 5.0 (Breque et al., 2021). Thus, a deep understanding of social sustainability is necessary in the context of production system development. As social sustainability dimensions may influence the possibility of achieving resilient production systems, elements such as working conditions, human resources, support and structures are essential to consider for operational performance and the ability to manage change and increased complexity, as well as to create renewal and innovative capability (Harlin and Berglund, 2021). A holistic understanding of sustainability is needed where specifically aspects related to the social dimension of work are important to consider in early development phases, in parallel with the economic and ecological dimension, due to its significance for socially sustainable work, well-being and performance (Harlin and Berglund, 2021; Leng et al., 2022; Nielsen et al., 2017). To maintain long-term sustainability, manufacturing companies must have, or develop, capabilities to continuously adapt towards new and changed sustainable needs, i.e., sustainable resilience (Souza et al., 2017).

6 Conclusions

Developing a resilient and sustainable production system is a complex activity, requiring an understanding of prerequisites for sustainability and resilience, together with a system perspective on the production system. To achieve a resilient and sustainable production system, a joint strategic vision that includes technology (selection, development and implementation), organisations (structure, agility, management, stakeholder collaborations and work environment) and people (skills and competences, participation, innovation, socially sustainable work, creative collaborative culture and change readiness) is considered essential.

Existing research agendas address manufacturing as a broader term than production (i.e., the process of making goods), including all industrial activities connected to the manufacturing chain (Garetti and Taisch, 2012; Jamwal et al., 2021), and are thereby not focused on the operational aspects. In an industrial production system context, the accelerating pace of change and increasing complexity challenges production system development and conditions for resilience and sustainability need to be created.

The literature and the industrial partners, representing different industrial segments, contributed with aspects related to the development of resilient and sustainable production systems, and several potential areas for further research have been identified:

- A holistic and long-term perspective is required to avoid sub-optimisation and short-term solutions. Research on how long-term and circular business models and strategies can be applied to support development towards resilient and sustainable production systems is one potential research area.
- Transforming sustainability vision and strategies into practice (i.e., operationalisation) is key. The visions, strategies and concepts need to be clearly defined and communicated within the companies, among actors in the value chain, and among other stakeholders. Of interest for future work in this area is, for example, how performance measures and KPIs related to resilience and sustainability can support its realisation.
- Trustful collaboration within and across organisations is essential, as is top management, leadership, team and individual support. How to best support the cross-functional collaboration of resilient and sustainable production systems, needs further studies.
- New competences, organisational learning and innovation capability are crucial. The green transition requires new competences within emerging domains. Individuals involved in an organisation need to understand how to contribute within their role/function, but also increase the ability to adapt. Innovative capability must be supported, opening up completely new solutions.

- Deeper understanding of potential disturbances and relevant mitigating strategies, contributing to a resilient capability of the production system, that is, the ability to absorb disruption and recover, together with the ability to respond, monitor, learn and anticipate, is needed.
- Understanding enablers and barriers related to the development of resilient and sustainable production systems. Enablers and barriers are two sides of the same coin, and a proactive approach during the production system design phase may prevent potential barriers. Categorisation based on the TOP framework provides an overview that facilitates systematic considerations of the identified aspects and further work on developing preparedness and mitigation strategies is needed.
- It is necessary to integrate aspects and develop systematic work procedures for production system development, including aspects supporting resilient and sustainable production systems.
- Knowledge about the elements of resilient and sustainable production systems and their interdependencies and potential contradictory demands is required. A system perspective is required to combine emerging technologies with human needs and perquisites for socially sustainable work and the sustainable development of organisations in fast-moving and increasingly complex environments.

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