JÖNKÖPING UNIVERSITY
School of Engineering

Licentiate Thesis

On Circularity in Production Systems

Exploring the Realization Through Circularity Practices

Filip Skärin

Jönköping University
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Dissertation Series No. 081 • 2023

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Don’t criticize what you can’t understand.

Bob Dylan

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Filip Skärin
Jönköping, September 2023

Abstract

The manufacturing industry stands in front of huge challenges. Negative environmental impacts must be drastically reduced and new sustainable products must be introduced at an accelerating pace. Coping with these challenges are significant in order to deal with the increasingly emerging climate crisis. To slow down the climate crisis, the approach of circularity wherein the utilization and lifetimes of resources and materials are maximised with the aim to achieve a near perpetual closed material loop has gained a significant increase in attention. However, most research within circularity has emphasised on the product, especially practices occurring after being produced. A seldomly studied perspective involves exploring the realization of circularity within the production system. A clear description is lacking regarding what circularity in production systems actually constitutes of, and how this can be realized. Therefore, the purpose of this thesis is to expand the knowledge regarding the realization of circularity in production systems. To fulfil the purpose, this research was initiated by a literature review and a document study, which were conducted in order to describe which circularity practices exist in production systems, both form an academic and practical point of view. Subsequently were workshops with industrial experts within production systems held in order to identify challenges with realizing circularity in production systems. The literature review, document study, and workshops laid the foundation for support development, which was the final phase in the thesis. This included supporting the longevity of production systems by adopting circularity theories to cover production system, as well as investigating how to analyse and evaluate circularity in production systems. The results from this were incorporated in a conceptual framework for circular production systems and in a tool for rapid assessment of circularity in production systems.

Keywords: circularity, circular economy, production systems, circularity practices, manufacturing, industry, reconfigurability, sustainability

Sammanfattning

Tillverkningsindustrin står inför enorma utmaningar. Miljöpåverkan måste drastiskt minska och nya hållbara produkter måste introduceras i allt snabbare takt. Att hantera dessa utmaningar är betydande för att hantera den alltmer framväxande klimatkrisen. För att bromsa klimatkrisen har cirkularitet, där utnyttjandet och livslängden för resurser och material maximeras med målet att uppnå en nästan evig sluten materialslinga, fått en betydande uppmärksamhet. Hittills har forskning inom cirkularitet fokuserat på produkterna som tillverkas, framför allt under användningen av produkten. Ett sällan studerat perspektiv innebär att undersöka hur cirkularitet i produktionssystem kan uppnås. En tydlig beskrivning saknas gällande vad cirkularitet i produktionssystem egentligen innebär och hur detta kan realiseras. Därför är syftet med denna avhandling att utöka kunskapen om realiseringen av cirkularitet i produktionssystem. För att uppfylla syftet initierades denna forskning av en litteraturgenomgång och en dokumentstudie. Dessa genomfördes för att beskriva arbetssätt kopplat till realiseringen av cirkularitet inom produktionssystem, både från en akademisk och praktisk ståndpunkt. Vidare hölls även workshops med experter inom produktionssystem för att identifiera utmaningar med att uppnå cirkularitet inom produktionssystem. Litteraturgenomgången, dokumentstudien och workshops lade grunden för stödutveckling, som var den sista fasen i avhandlingen. Denna inkluderade att stödja produktionssystemens livslängd genom att anpassa existerande teorier om cirkularitet till produktionssystem, samt att undersöka hur man analyserar och utvärderar cirkularitet i produktionssystem. Resultaten från detta införlivades i ett konceptuellt ramverk för cirkulära produktionssystem och i ett verktyg för snabb utvärdering av cirkularitet i produktionssystem.

Keywords: cirkularitet, cirkulär ekonomi, produktionssystem, tillverkning, industri, rekonfigurerbarhet, hållbarhet

Appended papers

The following papers are enclosed as appendices.

Paper I

Skärin, F., Rösiö, C., and Andersen, A-L. (2022). *Considering Sustainability in Reconfigurable Manufacturing Systems Research – A Literature Review*. In A. H. C. Ng, A. Syberfeldt, D. Högberg, and M. Holm (eds.) Proceedings of the 10th Swedish Production Symposium (SPS), vol. 21, pp. 781-792. Amsterdam: IOS Press.

Contribution to paper: Skärin initiated the paper. Skärin, together with Rösiö and Andersen, planned and structured the study. Skärin carried out the literature review and analysed the data, supported by Rösiö and Andersen. Skärin wrote the paper, supported by Rösiö and Andersen through constructive comments. Skärin revised the paper after reviewers' comments. Skärin presented the paper at the conference.

Paper II

Skärin, F., Rösiö, C., and Andersen, A-L. (2022). *Circularity Practices in Manufacturing - A Study of the 20 Largest Manufacturing Companies in Sweden*. In D. Y. Kim, G. von Cieminski, and D. Romero (eds.) Advances in Production Management Systems - Smart Manufacturing and Logistics Systems: Turning Ideas into Action. Proceedings of the IFIP International Conference: Advances in Production Management Systems (APMS), vol. 663, pp. 399-407. Cham: Springer.

Contribution to paper: Skärin initiated the paper. Skärin, together with Rösiö and Andersen, planned and structured the study. Skärin read and analysed the sustainability reports, supported by Rösiö and Andersen. Skärin wrote the paper, supported by Rösiö and Andersen through constructive comments. Skärin revised the paper after reviewers' comments. Skärin presented the paper at the conference.

Paper III

Skärin, F., Rösiö, C., and Andersen, A-L. (2023). *Towards Circular Production Systems: Outlining the Concept, Challenges and Future Research Directions*. In M. Valle, D. Lehmhus, C. Gianoglio, E. Ragusa, L. Seminara, S. Bosse, A. Ibrahim, and K-D. Thoben (eds.) Advances in System-Integrated Intelligence. Proceedings of the International Conference on System-Integrated Intelligence (SYSINT), vol. 546, pp. 616-625. Cham: Springer.

Contribution to paper: Skärin together with Rösiö and Andersen initiated, planned and structured the study. Skärin and Rösiö collected the data. Skärin, Rösiö and Andersen jointly wrote the paper. Skärin revised the paper after reviewers' comments. Skärin presented the paper at the conference.

Paper IV

Skärin, F., Rösiö, C., and Andersen, A-L. (2023*). Rapid Assessment of Circularity Practices Within the Manufacturing Industry*. In: Galizia, F.G., Bortolini, M. (eds) Production Processes and Product Evolution in the Age of Disruption. Proceedings of the 9th Changeable, Agile, Reconfigurable and Virtual Production conference (CARV), pp.442-451. Cham: Springer.

Contribution to paper: Skärin initiated the paper. Skärin, together with Rösiö and Andersen, planned and structured the paper. Skärin and Rösiö ideated and developed the Rapid Circularity Assessment tool. Interviews and testing the Rapid Circularity Assessment tool was mainly conducted by Skärin, supported by Rösiö. Skärin wrote the paper, supported by Rösiö and Andersen through constructive comments. Skärin revised the paper after reviewers' comments. Skärin presented the paper at the conference.

Additional publications

Skärin, F., Rösiö, C., and Andersen, A-L. (2022). An Explorative Study of Circularity Practices in Swedish Manufacturing Companies. *Sustainability*, 14(12):7246.

Skärin, F., Rösiö, C., and Andersen, A-L. (2023). Sustainability and Circularity in Reconfigurable Manufacturing – Literature Review and Future Research Directions. *International Journal of Manufacturing Research* [in production]. doi: 10.1504/IJMR.2024.10058562.

Andersen, A-L., Andersen, R., Napoleone, A., Brunø, T. D., Kjeldgaard, S., Nielsen, K., Sorensen, D. G. H., Raza, M., Bilberg, A., Rösiö, C., Boldt, S., and Skärin, F. (2023). *Paving the way for changeable and reconfigurable production: Fundamental principles, development method & examples*. (1 ed.) REKON Press. ISBN: 978-87-974066-3-2.

Skärin, F., Abdelmageed, M.E., Linnéusson, G., Rösiö, C. (2022). *Supporting Manufacturing Investment Decisions in New Product Introduction Through Line Balancing Techniques*. In A. H. C. Ng, A. Syberfeldt, D. Högberg, and M. Holm (Eds.) Proceedings of the 10th Swedish Production Symposium, Vol. 21, pp. 89-100. IOS Press, Amsterdam.

Raza, M., Bilberg, A., Brunø, T.D., Andersen, AL., Skärin, F. (2023). *Role of Discrete Event Simulation in the Assessment and Selection of the Potential Reconfigurable Manufacturing Solutions*. In: Galizia, F.G., Bortolini, M. (eds) Production Processes and Product Evolution in the Age of Disruption. Proceedings of the 9th Changeable, Agile, Reconfigurable and Virtual Production conference (CARV), pp. 286-292. Cham: Springer.

Table of Contents

1. Introduction

In this chapter, the background and problem statement are presented. Based on the problem statement, the purpose and research questions are described. Thereafter, the scope of the research and delimitations follow. Finally, the rest of the thesis is outlined.

1.1. Background

The manufacturing industry faces large challenges. Negative environmental impacts must be drastically reduced (Hauschild, 2015; Lieder and Rashid, 2016), and new sustainable products must be introduced at an accelerating pace (Huang and Badurdeen, 2017; Koren *et al.*, 2018; Khajuria *et al.*, 2022). It is imperative to cope with these challenges to deal with the increasingly escalating climate crisis. These challenges also imply that manufacturing companies cannot continue as they have done in the past, and major changes are needed. This is especially relevant for manufacturing companies because they are responsible for a large portion of the ongoing climate crisis (Garetti and Taisch, 2012). For example, in terms of CO_2 emissions, which is a major driving factor in the climate crisis, in 2019, the Swedish manufacturing industry was responsible for 32% of the country's total emissions (Statistiska Centralbyrån, no date). Another example is the United States of America, wherein the manufacturing industry in 2019 year accounted for 23% of the emissions (United States Environmental Protection Agency, 2021).

Reducing the environmental impact is needed in multiple ways. One way involves changing the way resources are managed because during the past few decades' industrial evolution, manufacturing companies have managed production and products according to a '*take-make-use-dispose*' mindset (Bonciu, 2014; Jawahir and Bradley, 2016; Kara *et al.*, 2022). The main limitation with this linear mindset is its unrealistic view of bottomless access to natural resources while failing to see scarcity or a slowdown in economic growth (Pitt and Heinemeyer, 2015; Franco, 2017). To slow down the climate crisis, the approach of circularity, wherein the utilisation and lifetimes of resources are maximised, has gained a significant increase in attention. The aim of circularity is to achieve a near perpetual closed resource loop (Webster, 2013; Bocken *et al.*, 2016; Bressanelli *et al.*, 2020). Nowadays, circularity is generally accepted as a significant way to support sustainable development (Ghisellini, Cialani and Ulgiati, 2016; Lieder and Rashid, 2016; Franco, 2017).

Circularity can be realised by manufacturing companies through circularity practices, whereas practices can be defined as '*actions, initiatives and techniques*' (Alayón, Säfsten and Johansson, 2017, p. 4). However, circularity practices are most often associated with extending the lifetimes of products because the products have a large climate impact. A prominent example is the automotive industry, where approximately 80% of the total CO_2-equivalitent emissions (i.e., climate impact) occur downstream from the manufacturing company, that is, when being used (Meinrenken *et al.*, 2020). Similarly, much attention within academia has been directed at extending product lifetimes. For instance, this can be seen in the R framework, which is one way of describing how companies can transition towards circularity, and focuses on products (see e.g. Jawahir *et al.* (2006) Potting *et al.* (2017)). The framework includes several circularity practices to be realised by manufacturing companies to achieve circularity. Examples of circularity practices include creating business models that enable reusing products between customers, remanufacturing and repairing products to extend to several life cycles and recycling the product once no other practice is possible (Jawahir and Bradley, 2016; Kirchherr, Reike and Hekkert, 2017; Potting *et al.*, 2017). The R framework also briefly includes production, which should be realised as efficiently as possible to minimise resources used in production (Potting *et al.*, 2017).

Although manufacturing companies might be able to reduce their environmental impact by being more resource efficient in production and carrying out practices to extend product lifetime, additional changes, especially to the production system, are also needed to ensure that the production is capable of managing the introduction of new sustainable products. This is particularly evident because a drastic reduction of environmental impact is needed in the manufacturing industry.

1.2. Problem statement

For companies to minimise environmental impacts and be capable of introducing new sustainable products, solely limiting attention to products is no longer enough. Instead, taking novel perspectives on the matter is needed. A largely overlooked perspective involves studying the realisation of circularity within production systems. In the production system, input resources are transformed by production systems to produce products. The production system consists of several subsystems, for example, the technical system and material handling system, which are typically described as the hardware (ElMaraghy, 2006; Rösiö, 2012). There are also other subsystems, such as the human system and computer and information system (Rösiö, 2012). These subsystems can be specified even further; for instance, the technical system consists of stations, machines, fixtures and tools (ElMaraghy, 2006; Koren, 2010; Rösiö, 2012; Wiendahl, Reichardt and Nyhuis, 2015).

Realising circularity in production systems would involve reducing usage and extending the lifetimes within three areas: 1) input resources used in the production system, such as raw materials, energy or water (Jawahir *et al.*, 2006; Koren, 2010), 2) the production system itself, as described above, and 3) the products, scrap and waste exiting the production system (Koren, 2010), which might return to the production system in the future (see Figure 1).

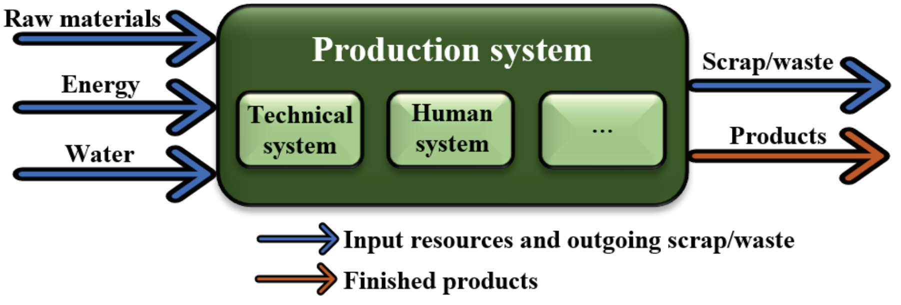

Figure 1. Production systems, adapted from Koren (2010) and Rösiö (2012).

Furthermore, because manufacturing companies clearly have a great impact on the global climate, further efforts to expand the knowledge regarding circularity in production systems are needed. Studying circularity from a product perspective has been realised in various ways, wherein the production system clearly plays an important part. However, circularity in production systems has still received comparatively limited attention in research, wherein, in most cases, it has simply been described as efficient production or recirculating materials and products with the purpose of, for example, remanufacturing returning products (see, e.g., the summaries by Hartley *et al.* (2023) and Kirchherr *et al.* (2023)). Even in attempts to expand existing circularity theories, such as by Blomsma *et al.* (2019), the production system is still scarcely mentioned.

Therefore, it is highly relevant to investigate how circularity in production systems can be realised regarding the three areas described in Figure 1. This is foremost related to the production system itself by exploring how the production system can be used for as long as possible while being capable of efficiently producing new, sustainable products. However, it also entails the input resources used in the production system, more specifically exploring how these can be used as efficiently as possible and the practices related to prolonging their lifetimes. Finally, it would also involve exploring how the production systems aid in extending the lifetimes of products returning to the production system.

One way of achieving lifetime extension, especially regarding the production system itself, is through reconfigurability (Koren *et al.*, 1999; Bi, 2011). Reconfigurability might be a solution because it enables quick and resource-efficient responses to changing requirements, for instance, in terms of increasing the need for new product introductions. This is possible through its core characteristics, such as modularity, integrability, convertibility, diagnosability and customisation (Koren *et al.*, 1999; Koren and Shpitalni, 2010). By incrementally updating and changing the production system, a long-term and resource-efficient development can occur as the extension of these systems lifetimes is realised because minor modules are sufficient to change rather than the entire system (Koren *et al.*, 2018).

To summarise, spreading awareness and increasing the insights regarding circularity in production systems can act as a key solution in the battle against climate crisis, in reducing the environmental impacts of manufacturing companies and in supporting companies in introducing new, sustainable products at a faster pace.

1.3. Purpose and research questions

There is an urgent need for manufacturing companies to reduce their environmental impact and introduce new, sustainable products. A key solution might be to realise circularity in production systems; however, knowledge regarding this is currently lacking. Hence, the purpose of this research is to:

expand the knowledge regarding the realisation of circularity in production systems

To fulfil this purpose, three research questions have been formulated. First, to describe what circularity in production systems implies, both from an academic and practical standpoint, the first research question is as follows:

RQ1: Which practices can realise circularity in production systems?

Second, to further enhance the understanding of circularity in production systems, challenges with such realisation need to be investigated. Hence, the second research question was formulated as follows:

RQ2: Which challenges exist with realising circularity in production systems?

Third, after investigating the existing practices and challenges with circularity in production systems, it is possible to describe the ways to facilitate the identified practices and overcome some of the identified challenges. Therefore, the third research question was formulated as follows:

RQ3: How can the realisation of circularity in production systems be supported?

1.4. Scope of the research and delimitations

The present thesis is limited to focusing solely on circularity within the production system. Thus, it does not emphasise circularity practices occurring outside the production system, for example, at suppliers and customers. Also, the main focus is the hardware in production systems, for example, the technical system and the material handling system. Hence, the software in production systems is less emphasised. Furthermore, the current thesis primarily focuses on circularity from an environmental perspective; hence, social and economic aspects are not addressed in particular, apart from in the literature review.

1.5. Thesis outline

The thesis consists of six chapters and four appended papers. Below is a description of each chapter.

Chapter 1: Introduction. This chapter introduces the topic and problem statement upon which the thesis builds. Furthermore, the purpose and research questions are presented. Thereafter, ***Chapter 2: Frame of reference*** is presented, which includes the frame of reference for the thesis, including the subchapters production systems, production system development, reuse and reconfiguration of production systems, circularity and the R framework. ***Chapter 3: Methodology*** contains the research methodology used to fulfil the research purpose and research questions, including the research approach, research process, data collection and analysis, research quality and ethical considerations. ***Chapter 4: Summary of appended papers*** provides a summary of each of the four appended papers. A respective summary is given with the purpose of the paper, followed by an explanation of how the paper was realised before giving a brief description of the findings. In ***Chapter 5: Results & discussion***, the answers to the three research questions posed in the thesis are presented and discussed. The research methodology is also discussed in this chapter. Finally, ***Chapter 6: Conclusions and further research*** summarises the findings and conclusions are drawn. The thesis ends with suggestions for further research.

2. Frame of reference

This chapter covers the theoretical frame of reference, including production systems, production system development, reuse and reconfiguration of production systems, circularity and the R framework.

2.1. Production systems

The terms ‘production’ and ‘manufacturing’ have been used differently within academia. A common definition of production, which is also used in the present thesis, is as follows: *‘The pure act or manufacturing process (or the connected series of acts or processes) of actually physically making a product from its material constituents, as distinct from designing the product, planning and controlling its production, assuring its quality*’ (CIRP, 2004, p. 995). Therefore, production is comprised of processing input materials, such as energy, water and raw materials, to finished products through the use of production systems. In contrast, manufacturing can be described as a more overarching term, which does indeed include the latter activities described above. In the current thesis, the following definition for manufacturing is used: ‘*The entirety of interrelated economic, technological and organisational measures directly connected with the processing/machining of materials, that is, all functions and activities directly contributing to the making of goods*’ (Segreto and Teti, 2014, p. 828).

Furthermore, adopting a systems perspective on production enables the ability to study all parts within the system and the interplay between those parts. These activities have been identified as crucial factors if wanting to successfully achieve production development (Bellgran and Säfsten, 2010). In terms of the definitions presented above, the manufacturing system serves as the overarching level of the production system. The former includes, according to Bellgran and Säfsten (2010), additional systems, for example, parts production system(s) and assembly system(s) (see Figure 2).

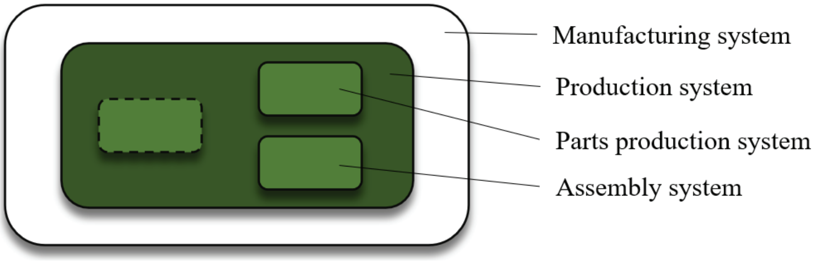

Figure 2. Production system as a part of the manufacturing system, adapted from Bellgran and Säfsten (2010).

The production system consists of several subsystems that enable the transformation of inputs to outputs. These involve technical systems, material handling systems, human systems, building and premise systems and computer and information system (Rösiö, 2012). Each of these systems then comprises components and jointly acts together. For instance, the technical system that regards the hardware directly related to the production process includes, for example, stations, machines, fixtures and tools (ElMaraghy, 2006; Koren, 2010; Rösiö, 2012; Wiendahl, Reichardt and Nyhuis, 2015), as depicted in Figure 3.

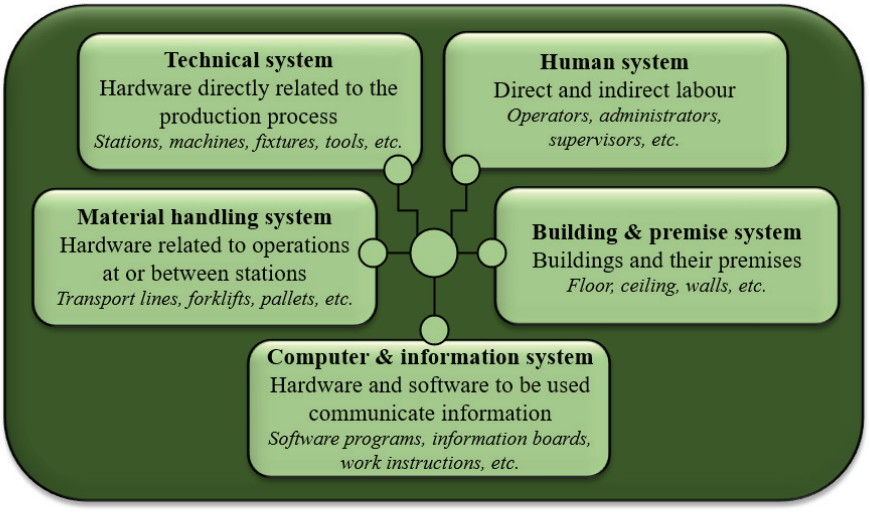

Figure 3. The production system and its substituent parts, adapted from Rösiö (2012).

2.1.1. Production system development

The design and development process in engineering has been depicted in a substantial number of models. Many of these models focus on the procedural aspects of the process to provide guidance and best practice for a 'real-world problem' (Wynn and Clarkson, 2018). However, the production system development is mostly in reality and research regarded as 'partial' problems or as small pieces in the puzzle, focusing on, for example, layout methods (Maganha, Silva and Ferreira, 2019; Ghanei and AlGeddawy, 2020; Gao, Daaboul and Le Duigou, 2021), quantitative optimisation (Yelles-Chaouche *et al.*, 2020; Khezri, Benderbal and Benyoucef, 2021) and operations research models (Badurdeen and Jawahir, 2017; Dubey *et al.*, 2017; Koren *et al.*, 2018; Dahmani, Benyoucef and Mercantini, 2022). Rarely is the entirety of the production system development process emphasised and elaborately described. Instead, product development or engineering design/design methodologies are more frequently addressed (see, e.g., Wynn and Clarkson (2018). As such, these are not directly adopted for production systems. Nevertheless, one of the process models that indeed emphasises production development was described by Bellgran and Säfsten (2010). In their model, production development is recognised as part of the product realisation process. It regards improvements of the process(es) or act(s) that transform inputs into outputs and include activities such as production planning and production assembly (Säfsten and Johansson, 2005; Bellgran and Säfsten, 2010).

2.2. Reuse and reconfiguration of production systems

The life cycle of production systems has been described in various models throughout the years (Attri and Grover, 2012). Several of these contain aspects of reusing the production systems to cope with changing volumes and products, as illustrated through the cyclic sequence of development activities (see, e.g., Bellgran *et al.* (2002) and Nakano *et al.* (2008)). The iterative approach of prolonging the usage of the production system is also evident in the description of life cycle phases by Wiktorsson (2000), who proposed a life cycle model of production systems that included operation refinement and reuse, as illustrated in Figure 4.

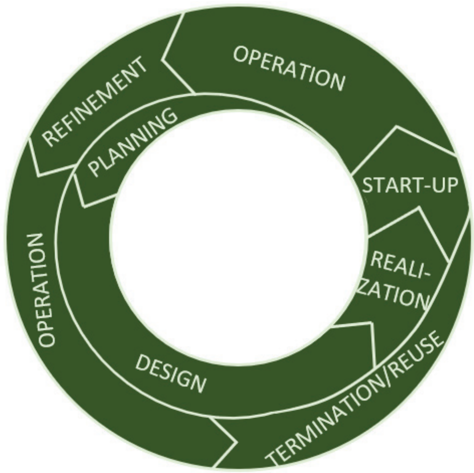

Figure 4. Lifecycle phases of a production system, adapted from Wiktorsson (2000)*.*

According to Wiktorsson (2000), the life cycle of a production system is initiated by a planning phase in which the desired requirements of the production system are developed. Thereafter, the system is designed, and subsequent realisation occurs. Once start-up is completed and operation has occurred for a period of time, adaptations of the production system capabilities might be required to be carried out to extend its relevance in the factory, thereby prolonging its lifetime. For instance, adjustments and re-engineering are activities in need of being realised to cope with, for example, changing product requirements (Wiktorsson, 2000).

However, the phases within the life cycle of a production system rarely occur in sequential order, and the planning, design and realisation of a new production system often occur in parallel while also using the existing production system (Wiktorsson, 2000). The need for designing a production system capable of being reused and changed has for a long time been regarded as crucial (Bi, 2011; Garetti and Taisch, 2012), however, nowadays, that need is perhaps greater than ever. A possible way forward in this matter might lie within the possibility of reconfiguring the production system (Koren *et al.*, 1999; Bi, 2011). Reconfigurability is, along with flexibility, a part of the umbrella term changeability, which is defined as the ability to realise adjustments on various levels of production, from workstations to production networks, in a timely and economically feasible way (ElMaraghy and Wiendahl, 2009; Andersen, 2017).

Reconfigurability might be a solution to realise circularity because it, according to Koren *et al.* (1999), enables quick and resource-efficient responses to changing requirements, for instance, in terms of increasing new product introductions. Hence, termination of the production system can be avoided, and the production system is instead reconfigured and, thus, also reused (Rösiö, 2012). This is possible through the enablers of modularity, integrability, diagnosability, convertibility, scalability and customisation (Koren *et al.*, 1999; Koren and Shpitalni, 2010). The foremost – modularity – implies that the hardware of production systems, as well as the software (e.g., planning and scheduling), consists of easily changeable modules (Mehrabi, Ulsoy and Koren, 2000; ElMaraghy, 2006). Integrability involves sets of mechanical, informational and control interfaces that enable rapid and accurate integration of modules (Koren and Shpitalni, 2010). Easy diagnostics, that is, diagnosability, lead to the possibility of identifying and managing the root causes of errors and defects occurring within the production system (Koren and Ulsoy, 2002; Koren and Shpitalni, 2010). This is a crucial component in ensuring satisfactory product quality after reconfiguring the production system (Benyoucef, 2020). The convertibility of a production system enables a rapid changeover between existing produces, but also the possibility of adapting the system to manage future products as well (Koren and Shpitalni, 2010; ElMaraghy *et al.*, 2021). Scalability leads to the capability of efficiently changing the production capacity by, for example, adding or removing machines in accordance to changing requirements (Koren and Ulsoy, 2002; Koren and Shpitalni, 2010). Finally, customised flexibility, that is, customisation, is enabled through having system flexibility linked to a single product family (Koren and Ulsoy, 2002; Koren and Shpitalni, 2010). To summarise, by incrementally updating and changing the production system, long-term and resource-efficient development might occur. This is because the extension of these production systems' lifetimes is realised because modules are sufficient to change rather than the entire system (Koren *et al.*, 2018).

2.3. Circularity

Circularity has received increased attention in the past few years (Geissdoerfer *et al.*, 2017; Kirchherr, Reike and Hekkert, 2017), causing severe terminology confusion (Kirchherr, Reike and Hekkert, 2017; Alhawari *et al.*, 2021). In the current thesis, circularity regards improving the utilisation and extending the lifetimes of resources gathered from the earth (Ellen MacArthur Foundation, 2013), for example, raw materials and water. The aim of circularity is to aid in achieving sustainability, which can be divided into three pillars: environmental, economic and social (Elkington, 1994). From a manufacturing company perspective, sustainability can be achieved through sustainable manufacturing, which can be defined as '*the creation of manufactured products through economically sound processes that minimise negative environmental impacts while conserving energy and natural resources. Sustainable manufacturing also enhances employee, community and product safety*' (United States Environmental Protection Agency, 2023). Circularity foremost emphasises the environmental aspects of sustainability and might be achieved by closing the loop of resources (Kara *et al.*, 2022).

However, achieving circularity is clearly not manageable by a single company but rather occurs in collaboration with entities on the micro (e.g., single company or consumer), meso (e.g., industrial networks, eco-industrial parks), and macro (e.g. city, region, nation, global) levels (Ghisellini, Cialani and Ulgiati, 2016; Vanhamaki *et al.*, 2019). Research directed at all three areas of circularity has been extensively conducted, not the least with a focus on circularity practices related to extending the lifetimes of products, for instance, as described and illustrated by the Ellen MacArthur Foundation (2013) (see Figure 5 below).

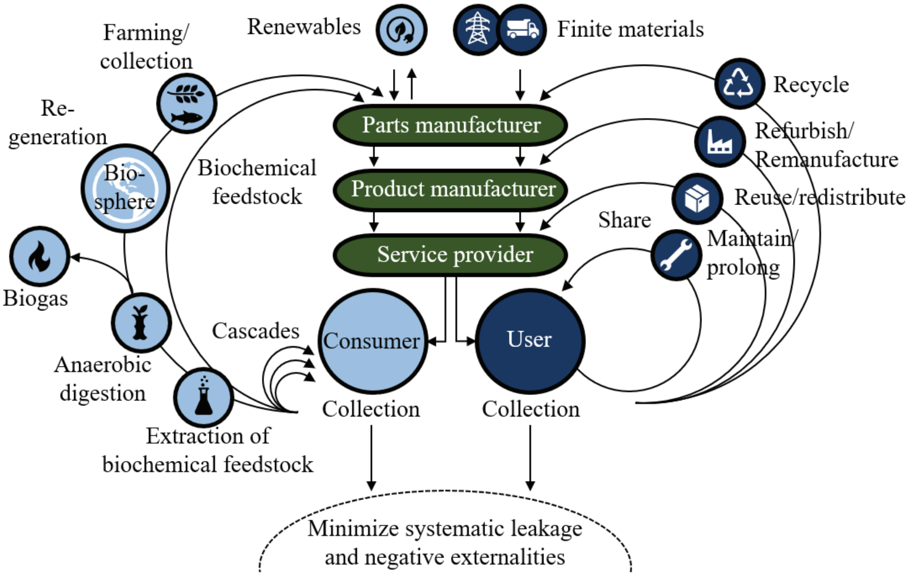

Figure 5. Circularity, adapted from the Ellen MacArthur Foundation (2013).

Circularity in production systems entails an aim at prolonging the lifetimes of the resources used within the production systems; this includes inputs, the production system itself and outputs. Hence, the focus is not limited to the products produced and ability to prolong their lifetimes through, for example, remanufacturing and refurbishing. This product-centred production system perspective has previously been explored. For instance, in Asif (2020), a framework for implementing circular manufacturing systems is presented and defined as a system designed with the purpose of enabling the possibility to manage a product throughout several life cycles (Asif, 2020). This definition implies a product circularity focus, whereas the manufacturing system's main purpose in realising circularity is to enable the reusability of the product. Similarly, Lieder (2017) developed an analysis method and decision-supporting tools to support circular manufacturing systems using the same definition as Asif (2020). Realising circularity is achieved by enhancing resource management, by, for example, reducing, reusing, remanufacturing and recycling, which is frequently described as the R framework.

2.3.1. The R framework

Historically, the R framework stems from lean manufacturing, wherein the primary aim is reducing waste. During the 1990s, the R framework was developed to include reusing and recycling, along with reducing waste. These actions, frequently termed 3Rs, were adopted by many companies to establish greener manufacturing (Wu *et al.*, 2014). This was perhaps in line with the increasing awareness of the necessity of CO_2 reduction, highlighted through, for example, the introduction of the Kyoto Protocol (United Nations Framework Convention on Climate Change, no date), wherein United Nations countries committed to take action against climate change.

The 3Rs alone are not recognised as sufficient for guaranteeing a total life cycle focus of resources, including stages such as premanufacturing, manufacturing, use and post use. As a result, it is also not capable of ensuring sustainable manufacturing on its own (Badurdeen *et al.*, 2009; Jawahir and Bradley, 2016) and solely supporting a linear approach of managing resources and products (Bradley *et al.*, 2018). To accommodate realising a more circular way of managing resources, the R framework has developed into incorporating at least 6Rs. Although alternative variations of the 6Rs have been put forward, and a common distinction includes the addition of recover, redesign and remanufacturing to the aforementioned 3Rs. According to Jawahir and Bradley (2016), a closed loop of resources and products can be implemented within the supply chain to set the foundation for sustainable manufacturing by implementing the 6Rs.

Yet as circularity research has progressed, further elaborations of the R framework have continued, which has led to numerous Rs being added to the aforementioned 6Rs. For instance, Potting *et al.* (2017) presented an additional 4Rs, resulting in a total of 10Rs (henceforth the 10R framework). However, differences exist between variations in the R framework regarding the contents and descriptions of Rs. In the 10R framework, Potting *et al.* (2017) used similar, but not identical terms, as the previously mentioned 6Rs, while also adding refuse, rethink, repurpose and recover.

The general rule of thumb in Potting *et al.*'s (2017) reasoning implies that, by achieving a higher degree of circularity, the utilisation of resources and products can be maximised, and thus, manufacturing companies might be able to reduce their environmental impacts. The 10R framework comprises three main sets of Rs: i) efficient use of products and manufacturing operations, ii) extension of the product life cycle to several life cycles and iii) maximisation of the usefulness of materials, as illustrated in Figure 6.

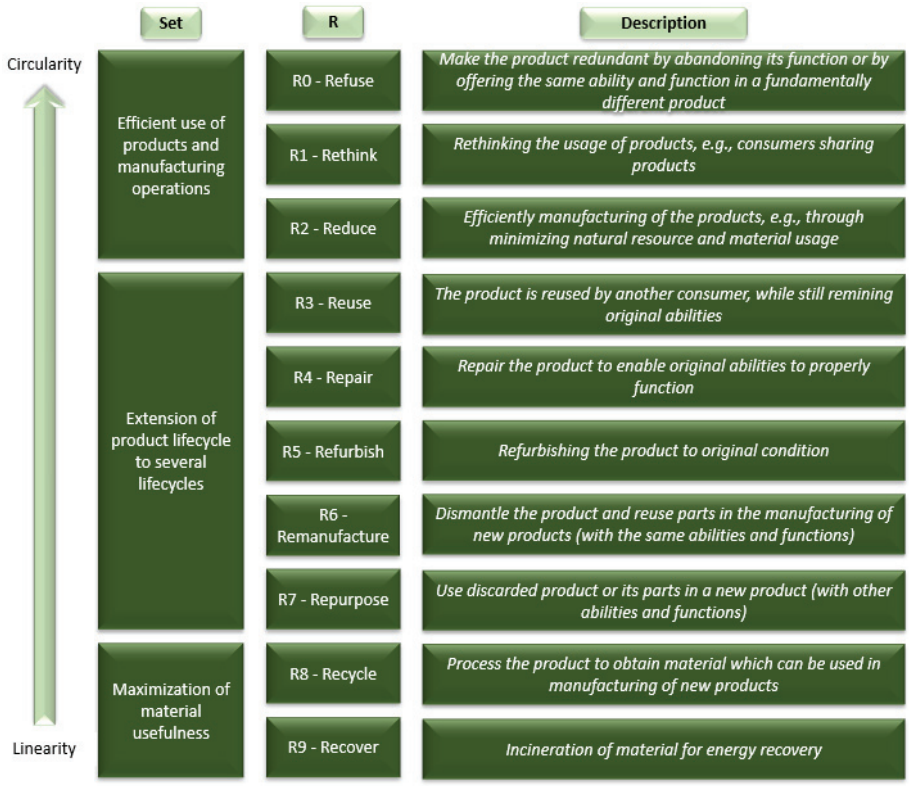

Figure 6. 10R framework, adapted from Potting et al. (2017).

The 10R framework mainly focuses on the product and limits attention towards production systems, which, apart from reduce, is indirectly connected to several of the other Rs, such as remanufacture and repair. Blomsma *et al.* (2019) further developed the 10R framework, wherein production systems were condensed into actions within the umbrella term '*restore, reduce & avoid*'. This includes using less energy and materials through lean manufacturing and cleaner production, reworking pre user products through refurbishment or remanufacturing, utilising pre user recycling, creating value for manufacturing waste either in-house or through industrial symbiosis and utilising energy recovery or composting (Blomsma *et al.*, 2019).

2.4. Summary of the theoretical background

In the theoretical background, a production system was described as a constituent part of the manufacturing system, wherein the former was explained as consisting of the technical system, the material handling system, the human system, the building and premise system and the computer and information system. This was followed by the need for using the production system as long as possible to support circularity, thus aiding manufacturing companies in reducing their environmental impact. In this matter, reconfigurability was further described as a key factor.

Subsequently, circularity was described as a means of improving the utilisation and extending the lifetimes of resources gathered from the earth. To elaborately describe circularity, the evolution of the R framework was depicted, including how it has evolved from focusing solely on reducing waste to incorporating 10Rs, including refuse, rethink, reduce, reuse, repair, refurbish, remanufacturing, repurpose, recycle and recover. However, it was also stressed that the R framework, including more recent alterations of the framework, is heavily emphasised on products and the production system's ability to extend the lifetimes of such, without providing sufficient insights into how circularity within input resources and the production systems can be realised.

3. Methodology

In this chapter, the research approach and process are described. Subsequently, a further explanation of the data collection and analysis within each phase of the research is presented. Finally, the research quality and ethical considerations are described.

3.1. Research approach and process

The purpose of the present research is to *expand knowledge regarding the realisation of circularity in production systems*. Neither circularity nor production systems are novel research areas; however, studying circularity in production systems is indeed a novel research area. Hence, the maturity level of this research area can be seen as being low. Therefore, an exploratory research approach has been adopted (Säfsten and Gustavsson, 2020; Tang, 2021), wherein a large portion of the time has been dedicated to initiation. The research is heavily focused on building a theoretical foundation, and thus, several literature reviews have been carried out. However, only the systematic literature review in Chapter 3.2.1 has been elaborately described, while the others are described in the papers. The research was conducted between August 2021 and June 2023. Three research questions have been formulated, each related to a research phase, as follows: i) initiation, ii) in-depth and iii) support development. A total of four papers have been produced within the research and appended to this licentiate thesis, as depicted in Figure 7.

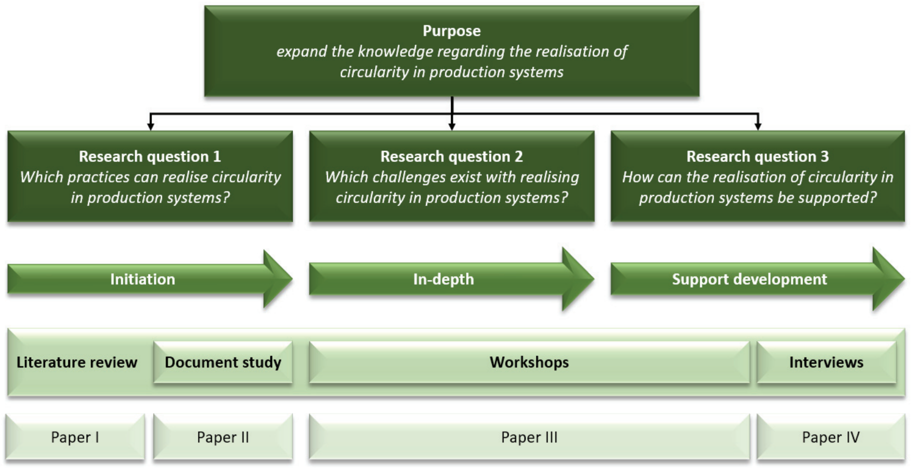

Figure 7. Research design.

3.2. Phase 1: Initiation

The first step in the present research was aligned with RQ1 and involved analysing the state-of-the-art within sustainability and circularity in reconfigurable manufacturing research through a systematic literature review. The results from the systematic literature review were published in Paper I. The initiation phase also involved describing circularity practices that manufacturing companies are realising in their production systems to complement the systematic literature review in answering RQ1. This was covered by a document study that included the investigation of circularity practices in production systems. Apart from the systematic literature review, another literature review was also conducted with the aim of investigating the circularity focus in research wherein sustainability reports were analysed. To collect large amounts of data from several companies, conducting a document study of manufacturing companies' sustainable reports was found to be suitable. Moreover, according to Patel and Davidson (2011), document studies like this can be used to find information about actual events. Thus, studying sustainability reports enabled an investigation of the practices described by the manufacturing companies themselves. The results from the document study were published in Paper II.

3.2.1. Systematic literature review

Conducting literature reviews in research is important to base the research on existing knowledge (Thiel, 2014). As circularity is a broadly used term that is increasingly researched (Geissdoerfer *et al.*, 2017; Kirchherr, Reike and Hekkert, 2017), the terminology has also become fragmentedly used (Kirchherr, Reike and Hekkert, 2017; Alhawari *et al.*, 2021). Initiating the systematic literature review by searching for the broader area 'sustainability' rather than limiting it to 'circularity' was necessary to avoid missing any relevant research. Additionally, focusing on reconfigurability in the systematic literature review was considered suitable because it has been widely expressed as an enabler for the long-term usage of production systems through incremental updates (Koren *et al.*, 1999; ElMaraghy and Wiendahl, 2009). This could potentially be recognised as key to circularity. Hence, exploring the connection between reconfigurability and sustainability/circularity was considered a viable starting point for the current thesis.

The systematic literature review was conducted by following a process inspired by Booth *et al.* (2016), as shown in Figure 8. It was conducted in Scopus and consisted of a final selection of 52 papers, which were analysed and categorised. The final selection included papers from 2011 to 2021. No publication date filter was used, and the reasons for the nonexistence of papers older than 2011 were simply because of the filtering process of relevant papers.

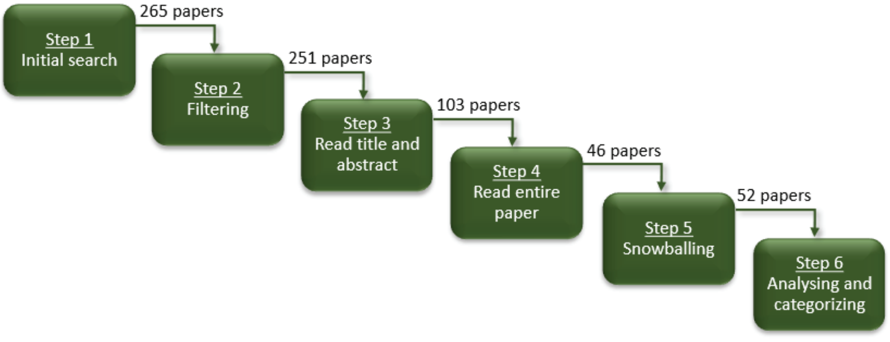

Figure 8. Systematic literature review steps.

To analyse the sample, a thematic analysis was used since it supports summarising the papers within categories and areas, but it also enables describing patterns in the sample (Booth, Sutton and Papaioannou, 2016). The papers were analysed according to the three pillars of sustainability, that is, environmental, economic and social (Elkington, 1994). Further categorisations within each pillar were created during the analysis to further elaborate how sustainability has been included in previously conducted research on reconfigurable manufacturing. These categorisations are further explained in Chapter 4.1 and Chapter 5.1.

3.2.2. Document study

An extensive document study was also conducted to answer RQ1, along with the aforementioned systematic literature review. Conducting a document study was considered suitable to gather data from many companies and enable the possibility of gaining extensive insights into the topic, that is, to describe existing circularity practices in production systems. Sustainability reports were studied as they summarise a company's efforts to improve sustainability, thereby also including circularity practices in production systems. The companies write the sustainability reports themselves, with the aim of providing stakeholders and the public with a processed piece of information that, on an overarching level, indicates the company's circularity practices.

The reports were easily findable on the companies' webpages since sustainability reports are publicly available and a mandatory document for Swedish companies if fulfilling two of the following requirements: (i) having a total asset of more than 175 million, (ii) having net sales of more than 350 million SEK or (iii) having an average of 250 employees or more (Swedish Parliament, no date).

The sample size in the document study consisted of the 20 largest manufacturing companies in Sweden, according to a company information website (https://www.allabolag.se), as depicted in Table 1. The sample size was determined through an evaluation of similar papers that examined sustainability reports (see, e.g., Stewart and Niero (2018), Marke *et al.* (2020), Rhein and Sträter (2021), Tiscini *et al.* (2021)). The largest manufacturing companies in Sweden were selected because of the perceived possibility that higher revenue implies greater opportunities for both carrying out circularity practices and writing an elaborate sustainability report. The document study involved studying the latest sustainability reports from each company.

Table 1. Document study sample.

#	Company	Manufacturing industry	Report language	Net turnover*
1	Volvo Group	Automotive	English	338 446
2	LM Ericsson	Communication equipment	English	232 390
3	Volvo Cars	Automotive	English	184 417
4	Scania CV	Automotive	Swedish	125 125
5	Electrolux	Household appliances	Swedish	115 960
6	Atlas Copco	Machines	Swedish	99 787
7	AstraZeneca	Medicine	English	87 469
8	Sandvik	Engineering in mining/quarry	Swedish	86 404
9	SKF	Machines	Swedish	74 852
10	Husqvarna	Machines	English	41 943
11	NIBE Industrier	Machines	Swedish	27 146
12	SSAB EMEA	Metal	English	22 829
13	SCA	Paper and packaging	Swedish	18 410
14	Holmen	Paper and packaging	Swedish	16 327
15	Arla Foods	Diary	Swedish	16 717
16	Swedish Match	Tobacco	Swedish	16 698
17	Essity Hygiene and Health	Hygiene and health	Swedish	15 391
18	BillerudKorsnäs	Paper and packaging	Swedish	14 519
19	ABB	Electronics	English	14 120
20	Elekta	Electronics	English	13 860

*In million Swedish Kronor (SEK)

A data analysis process inspired by Miles *et al.* (2014) and Calzolari *et al.* (2021) was followed to analyse the sustainability reports. The first step involved data reduction, which included transcribing and coding the data. This was realised with the aim of reducing the nonessential contents of the data. When reading the sustainability reports, the parts related to circularity were extracted and pasted in a Microsoft Word document. If the sustainability report was written in Swedish, the extracted parts were also translated into English. Subsequently, the extracted parts were inserted into NVivo, which was used to categorise the identified circularity practices. The 10R framework (Potting *et al.*, 2017) was used as a foundational guideline to ease the process. The framework was chosen because of its extensiveness compared with similar circularity frameworks, such as the 6R (see, e.g., Jawahir and Bradley (2016), which enabled a detailed description of the circularity practices. Once the circularity practices had been identified, a differentiation was carried out regarding whether these practices are ongoing/realised or simply planned/visioned to be realised at some point in the future. This separation was done to provide insights into the state of implementation of circularity practices among the manufacturing companies and was achieved by analysing how the circularity practices were explained in the sustainability report (i.e., in the tempus and wording used).

3.3. Phase 2: In-depth

The in-depth phase of the research involved digging deeper into the matter, with the aim of identifying challenges with realising circularity in production systems. To achieve this, workshops with industrial representatives were conducted. A literature review was also conducted to compare the development of products and production systems. The results from the workshops and literature review are presented in Paper III.

3.3.1. Workshops

Workshops were carried out to identify the challenges with realising circularity in production systems (i.e., to answer RQ2). Workshops are recognised as suitable to use to generate new ideas and insights through participant interactions (Ørngreen and Levinsen, 2017; Säfsten and Gustavsson, 2020); they are considered particularly useful when exploring emerging areas (Ørngreen and Levinsen, 2017), which circularity can be labelled as. Workshops have also been useful in '*identifying, articulating, and exploring*' (Ørngreen and Levinsen, 2017, p. 77) unexplored and ill-defined challenges within technology research (Darsø, 2001; Phaal, Farrukh and Probert, 2007; Ørngreen and Levinsen, 2017). As the present research involved such endeavours in RQ2, carrying out workshops was found to be an appropriate approach.

In the present research, two online workshops were carried out with participants specialised in production system development, for example, production managers, project managers and production engineers. The workshops were conducted with a structure covering both a theoretical introduction to the topics and time for discussions between participants. Discussion questions were established prior to the occasions, and the participants were divided into smaller groups for discussion. The insights and conclusions from each discussion were thereafter shared among all participants in the workshop, and a joint discussion was facilitated by the researchers. The workshops were not recorded to avoid risking participants' withholding from actively engaging. However, in both workshops, two of the authors of Paper III were participating: one was assigned a facilitator role, and the other was responsible for taking detailed notes from the discussions (Ørngreen and Levinsen, 2017; Säfsten and Gustavsson, 2020). The first workshop was carried out in October 2021 and consisted of 12 participants from six companies/organisations. The emphasis during the workshop was on how to establish sustainability in production and the foundations of circularity. This broader scope was deemed necessary to clarify prior to the subsequent workshop to enable a deeper discussion about circularity in the production systems domain. The second workshop was intended as a follow-up to the first workshop, digging deeper into circularity in the production systems domain. This workshop was organised in March 2022, and seven participants from five companies/organisations joined. To analyse the data gathered from the workshops, the detailed notes taken by one of the authors of Paper III were reviewed, and challenges were identified during the analysis.

3.4. Phase 3: Support development

The research concluded by exploring how realising circularity in production systems can be supported, that is, answering RQ3. The outcomes of this phase were twofold. First, it was deemed relevant to support the realisation of circularity in production systems by providing insights into possible circularity practices to prolong the lifetimes of production systems, especially emphasising the production system itself. The results were disseminated as a conceptual framework for circular production systems. The framework was presented in Paper III, along with the challenges identified in the in-depth phase. Second, an investigation regarding how to analyse and evaluate circularity in production systems was carried out. The result from this was a tool for the rapid assessment of circularity, which eases the implementation and consideration of circularity in the production system. This was based on the insights gained from the literature review, document study and workshops. A literature review was also conducted to review previous adaptations of the rapid plant assessment tool. The rapid circularity assessment (RCA) tool was presented in Paper IV.

3.4.1. Circular production systems framework

To answer RQ3, it was deemed necessary to facilitate a deeper understanding of circularity in production systems. Because the results from the document study and the workshops indicated that the production system itself was limitedly emphasised, it was deemed relevant to support the realisation of circularity in production systems by providing insights into possible circularity practices to prolong the lifetimes of production systems. In the workshops, this was especially articulated as an existing challenge for the manufacturing companies. The results from the previous phases provided insights into both the theoretical and practical constituents of circularity in production systems, which enabled the possibility of describing relevant circularity practices.

The results were disseminated in a conceptual framework. Creating a conceptual framework as a fundamental basis for the research is regarded as a suitable strategy to force the researcher to evaluate possible key factors and variables within a study (Miles and Huberman, 1994; Karlsson, 2016); hence, it was chosen as a way to disseminate the new insights and facilitate a deeper understanding of circularity in production systems. The 10R framework (Potting *et al.*, 2017) was used as the theoretical foundation for the framework. This was deemed appropriate because of its comprehensiveness compared with similar theories. Although the 10R framework (Potting *et al.*, 2017) emphasises circularity practices from a product perspective, the circularity practices and their descriptions were altered to cover the production system instead. Hence, the conceptual framework was developed to support the longevity of production systems by adopting circularity theories, which often entails an emphasis on a product view to cover the production system instead.

3.4.2. Rapid circularity assessment tool

The results of the workshops, document study and systematic literature review indicated that many manufacturing companies still struggle with realising circularity in production systems. Thus, apart from developing support in terms of the circular production systems framework to answer RQ3, the present research also involved investigating how to analyse and evaluate circularity in production systems. This was realised based on previous research, both within the current thesis, primarily the document study and systematic literature review, but also other research, for example, Johansson *et al.* (2019) and Koren (1999). The results were encapsulated in a tool for the initial evaluation of circularity in production systems, henceforth the RCA. By emphasising, for example, input resources, generated residual resources, produced products, and the production system itself, the tool provides a general overview of circularity in production systems.

To ensure that circularity in production systems was encapsulated within the tool, it was tested in five manufacturing companies. The focus during these tests was to ensure that circularity in production systems could be analysed and evaluated by using the tool, not the companies' results from using it. Hence, the results of using the RCA will not be displayed in the present thesis. The testing on two of these occasions was facilitated by two of the authors of Paper III. The rest were carried out by the companies themselves without the presence of the authors and thereafter sent to the authors who reviewed the results and made minor adjustments to, for example, clarify the questions and categories. The tests that were observed by the authors were also accompanied by short semistructured interviews prior to and after using the RCA. In each company, a single respondent answered the questions. The interviews were of a semistructured nature and consisted of open-ended questions, which are appropriate to use during semistructured interviews (Saunders, Lewis and Thornhill, 2016). Prior to testing the RCA, the questions involved the focal company's circularity practices. After the testing, the questions covered questions about the experience of using the RCA, as well as about the next steps in the company's journey towards circularity. The answers were jotted down, analysed and then used to further improve the RCA.

Several practically oriented tools for improving and creating knowledge about circularity in the production system domain already exist, for example, the circular scanner (Blomsma *et al.*, 2019), environmental value stream mapping (United States Environmental Protection Agency, 2007), green performance map (Kurdve and Wiktorsson, 2013; Shahbazi, Wiktorsson and Kurdve, 2019) and waste flow mapping (Kurdve *et al.*, 2015). However, providing manufacturing companies with the possibility of rapidly gaining insights into the current circularity was seen as a well suited for facilitating an initial step towards realising circularity in production systems and can act as a complement to the aforementioned tools. Also, because the circular production systems framework emphasises the production system, the RCA might be seen as a complement as it provides a more overarching view of circularity in production systems, also including input resources and products.

3.5. Research quality

Ensuring high quality is an essential part of research. Some common criteria for assessing the quality of research, sometimes referred to as objectivity (Kirk and Miller, 1986) or trustworthiness (Lincoln and Guba, 1985; Karlsson, 2016), involve the ability to establish valid facts, guaranteeing that the research is free of the researcher's values and unbiased. A well-established way for researchers to transparently share how objectivity has been realised is to present this in terms of validity and reliability (Kirk and Miller, 1986).

3.5.1. Validity

Validity comprises two parts: 1) the ability to measure what is intended to be measured, that is, internal validity and 2) the generalisability of the results, that is, external validity (Cook and Cambell, 1979; Lincoln and Guba, 1985; Leedy, Ormrod and Johnson, 2019).

Internal validity implies robustness in the research design, leading to research findings and results stemming from intended interventions (Saunders, Lewis and Thornhill, 2016). Internal validity was relevant to consider in the workshops and interviews because it was necessary to enable the possibility to draw reasonable conclusions (Yin, 2018) about existing challenges and circularity practices. Internal validity was attained in the workshops by ensuring that the workshop consortia consisted of participants with different roles in the development of production systems, as well as from different companies, thereby providing sufficient insights into the challenges of realising circularity in production systems.

External validity regards the generalisation of the results to other contexts, for example countries, industries and companies (Cook and Cambell, 1979; Bell, Bryman and Harley, 2022). The external validity of research can be strengthened by repeating the research and ensuring that it is carried out in a natural environment (Saunders, Lewis and Thornhill, 2016; Säfsten and Gustavsson, 2020). An appropriate sample size in the document study was determined based on a benchmarking with similar studies, wherein studying sustainability reports was the main means of data collection. Hence, the external validity has been strengthened as it is likely that studying other companies might result in similar results. Furthermore, because the sample consisted of the largest manufacturing companies in Sweden, which actually are large international companies, the results can also be seen to be applicable to other countries as well. Finally, as the sustainability reports analysed in the document study were developed and written by the companies themselves in a natural environment, these provide the possibility for the companies to convey a large amount of text with their own formulations. This minimises the risk of bias by affecting the respondents' answers during the data collection (Williamson, 2002).

3.5.2. Reliability

The reliability of research can be defined as '*the extent to which data collection technique or techniques will yield consistent findings, similar observations would be made or conclusions reached by other researchers or there is transparency in how sense was made from the raw data*' (Saunders, Lewis and Thornhill, 2016, p. 726). According to Williamson (2002), an indicator for high reliability involves stable and consistent research results, which would imply that the research can be replicated by other researchers. One key activity to ensuring the reliability of a research involves systematically collecting data, and transparency describes the process (Säfsten and Gustavsson, 2020). Both the literature review in the initiation phase and the document study have been systematically conducted and described in detail in this kappa and in the appended papers. These have been carried out by following established structured processes, that is, Booth *et al.* (2016) in the systematic literature review and Miles *et al.* (2014) and Calzolari *et al.* (2021) in the document study. Furthermore, ensuring transparency is also of significance (Saunders, Lewis and Thornhill, 2016), for example, in terms of data display. In the present research, the Scopus database was used in the systematic literature review, which enables the possibility for high repeatability for other researchers. Finally, the sustainability reports analysed in the document study are publicly available, thereby implying a high level of repeatability.

3.6. Ethical considerations

Considering ethicality and morality is an essential part of research. In the present research, three key ethical considerations were realised. First, the research conducted was not required to be tested according to the Swedish Ethics Review Act SFS 2003:460 (Regeringskansliet, 2003) because the research did not entail any of the requirements outlined in the act. For instance, the research has not involved any physical intervention; it was not used with a method that would have any psychological or physical effect on individuals. Second, the data collected were handled according to the data management plans set up within the projects the present research has been carried out in. These follow the GDPR and guidelines from Jönköping University (no date). Third, when applicable, informed consent (Saunders, Lewis and Thornhill, 2016) was secured prior to data collection, for example, in the case of the interviews, wherein the respondents were informed about the interviews' purpose and subsequently consented to partake.

4. Summary of the appended papers

This chapter provides summaries of the appended papers, including the purpose of each paper and a brief description of the findings.

4.1. Paper I: Considering sustainability in reconfigurable manufacturing systems research - a literature review

The purpose of Paper I was to explore what circularity practices exist in production systems from a theoretical perspective. More specifically, the aim was to investigate how sustainability and circularity have been considered in previously conducted reconfigurable manufacturing systems research. This was realised through a systematic literature review, which was conducted by following a procedure inspired by Booth *et al.* (2016). Because sustainability is such a broadly used term, a key aspect in the analysis was to explore and describe in detail what previous research entails regarding sustainability, divided into the three pillars of sustainability: environmental, economic and social (Elkington, 1994). The findings from this process indicate that sustainability can be included in manufacturing research in a wide range of ways. Moreover, dividing these into the three pillars of sustainability is not sufficient. Thus, to further describe the content of sustainability, categories within each pillar were developed during the literature review process.

In terms of the environmental sustainability pillar, the following breakdown was identified through the analysis: *water usage, greenhouse gas emissions, energy consumption, resource efficiency, hazardous waste* and *circularity*. The latter was found in the systematic literature review to be primarily related to reconfiguring the production system into, for example, a remanufacturing practice (see, e.g., Brunoe *et al.* (2019) and Aljuneidi and Bulgak (2017)). A similar approach was realised by Barwood *et al.* (2015), who utilised reconfigurability in a production system specified for recycling. Bockholt *et al.* (2022) conducted a case study that emphasised how reconfigurability in a production system enables the possibility to overcome challenges related to product take-backs to realise circularity. Furthermore, the systematic literature review findings indicate that, although circularity has been addressed in several ways, for instance in terms of remanufacturing, recycling and reducing the environmental impact of the production system, there is a lack of further clarifying how the production systems can, for example, be reused, refurbished and repaired to achieve circularity.

Moreover, there seems to be a general lack of common terminology when discussing economic, environmental and social sustainability in relation to reconfigurability. Few researchers are clearly defining sustainability, which impedes the analysis. It was also found that sustainability frequently had been included in the papers through the addition of specific parts of sustainability in novel optimisation models and mathematical equations for designing, using and reconfiguring production systems. The majority of these papers were related to reducing the environmental impact during the usage of the production systems, foremost in terms of models aiming at reducing energy consumption have been proposed (see, e.g., Ghani *et al.* (2011), Massimi *et al.* (2020), and Singh *et al.* (2021)). A similar attempt at adapting optimisation models to include sustainability involves adding the objective of minimising greenhouse gases alongside other commonly used optimisation objectives such as cost and time (see, e.g., Touzout and Benyoucef (2018) and Touzout *et al.* (2018)). These papers indicated that reconfigurability can aid in enhancing production efficiency, thus reducing the amount of input resources needed.

4.2. Paper II: Circularity practices in manufacturing – a study of the 20 largest manufacturing companies in Sweden

The aim of Paper II was to describe existing circularity practices in production systems, particularly from a practical point of view. More specifically, Paper II covered the investigation of which and to what extent circularity practices in production systems are carried out by manufacturing companies. This was realised by studying the sustainability reports of the 20 largest manufacturing companies in Sweden. Following the 10R framework (Potting *et al.*, 2017) as a theoretical foundation, the sustainability reports were scrutinised, and their contents were analysed. By doing so, a total of 38 unique circularity practices were identified, which provided a detailed description and insight into the state-of-practice of Swedish manufacturing companies. Depending on how the circularity practices were described in the sustainability reports, their level of implementation was also determined, either as visualised/planned (V/P) or ongoing/realised (O/R), see Table 2. The majority of circularity practices were solely mentioned by a single or a few companies; however, some were more frequently mentioned. For instance, reducing greenhouse gas emissions, reducing generated waste and reusing materials were all mentioned by approximately half of the companies.

Table 2. Identified circularity practices, from Skärin et al. (2022).

R	Circularity practice	V/P	O/R	Sum
R0 - Refuse	No practice identified			
R1 - Rethink	Apply sustainable chemical management		1	1
	Implement circular production processes		1	1
	Increase available data from production		1	1
	Increase usage of renewable energy	1	7	6
	Rethink existing production to make more sustainable and circular	1	1	
	Use new sustainable processes and technologies	1	3	2
R2 - Reduce	Reduce chemical usage		1	1
	Reduce energy usage		8	8
	Reduce environmental impact	1	2	1
	Reduce fuel usage	1	1	
	Reduce greenhouse gas (GhG) emissions	2	11	9
	Reduce resource usage	3	9	6
	Reduce generated waste	3	11	8
	Reduce water usage		3	3
R3 - Reuse	Reuse components	1	6	5
	Reuse heat and steam	1	2	1
	Reuse materials	1	10	9
	Reuse packaging material		2	2
	Reuse products		1	1
	Reuse water		2	2
R4 - Repair	Repair own products (as service)		3	3
R5 - Refurbish	Refurbish own products and parts		7	7
R6 - Reman-ufacture	Remanufacture products, parts and components		3	3

R7 - Repurpose	Repurpose packaging materials		1	1
	Repurpose product		1	1
	Repurpose residual products		4	4
R8 - Recycle	Recycle energy		1	1
	Recycle hazardous waste		2	2
	Recycle heat from wastewater and machines		1	1
	Recycle metals		3	3
	Recycle packaging materials	1	2	1
	Recycle thermoplastics		1	1
	Recycle in general		3	3
	Recycle waste	1	5	4
	Recycle water		2	2
R9 - Recover	Recover for incineration (energy recovery)		7	7
	Recover for landfill		2	2
	Recover - undefined (only disposal mentioned)		1	1

The findings from the document study show that the majority of circularity practices has already been realised or is currently being realised. This finding is in line with Tiscini (2021), who suggested that many companies have, at least to some degree, initiated circularity practices, especially as reported in sustainability reports. However, this might plausibly be linked to the purpose and structure of sustainability reports because they are mostly written to summarise the activities of the past year.

Although the 10R framework (Potting *et al.*, 2017) was used as a theoretical foundation for clustering circularity practices, the definitions were not strictly followed because of the heavy emphasis on the products. Instead, the intention was to broaden the scope of understanding of circularity in the production domain, which is not limited to a product focus. By doing so, many of the identified circularity practices relate to the input resources used in the production system. However, some Rs were still found to be limited to the products, for instance, repair, refurbish and remanufacture. Interestingly, although 38 circularity practices have been identified, the production system was almost entirely neglected from being mentioned in sustainability reports. Most of the identified circularity practices involve the input resources used to create the product within the production system, but also the resources generated within the production system, for example, waste, residual materials, heat, steam and wastewater. Nevertheless, many of these categories are intertwined, and thus, the effect on several areas simultaneously is evident. Hence, the production system might also be distinguished as a crucial factor to facilitate a circularity practice, for example, in the case of reducing energy consumption, which might involve improving the management of the production system. Although not necessarily directly connected to the production system, many of the identified circularity practice categories can be seen as realised when using the production system, for example, the machines and tools. Thereby, the production system might be seen as more significant for realising circularity than what is actually described in Table 2.

4.3. Paper III: Towards circular production systems: outlining the concept, challenges and future research directions

The purpose of Paper III was to identify challenges with realising circularity in production systems and propose how circularity theories can be applied to the production system domain, thereby supporting the realisation of circularity in production systems. By conducting workshops with companies, several challenges were identified, as seen in Table 3 (see Chapter 5.2 for a thorough description of the challenges).

Table 3. Identified challenges with realising circularity in production systems, from Skärin et al. (2023).

Challenges
Lacking competence in purchasing
Lacking knowledge of how to design and develop circular production systems
Inability to reconfigure and continuously update the production system
Lacking collaboration between manufacturing company and system supplier
Uncertain decision making in prolonging the system's lifetime
Future legal demands

The challenges can be recognised as occurring at different times in the production system's life cycle, wherein the importance of long-term thinking in the management of production systems is highlighted. To address some of the identified challenges and facilitate a deeper understanding of circularity in production systems, a conceptual framework for how to develop and manage production systems from a circularity perspective was developed (see Figure 9). Basing the practices on the 10R framework (Potting *et al.*, 2017), the purpose of the conceptual framework was to provide insights into possible actions to prolong the lifetimes of production systems. A key component of the proposed framework is the ability to extend the lifetime of the production system through continuous adaptation to adhere to changing demands. New sustainable products must be introduced at an accelerating pace (Huang and Badurdeen, 2017; Koren *et al.*, 2018; Khajuria *et al.*, 2022); ensuring that the production system is capable of being reconfigured might be seen as a key component, both from an environmental and economic point of view.

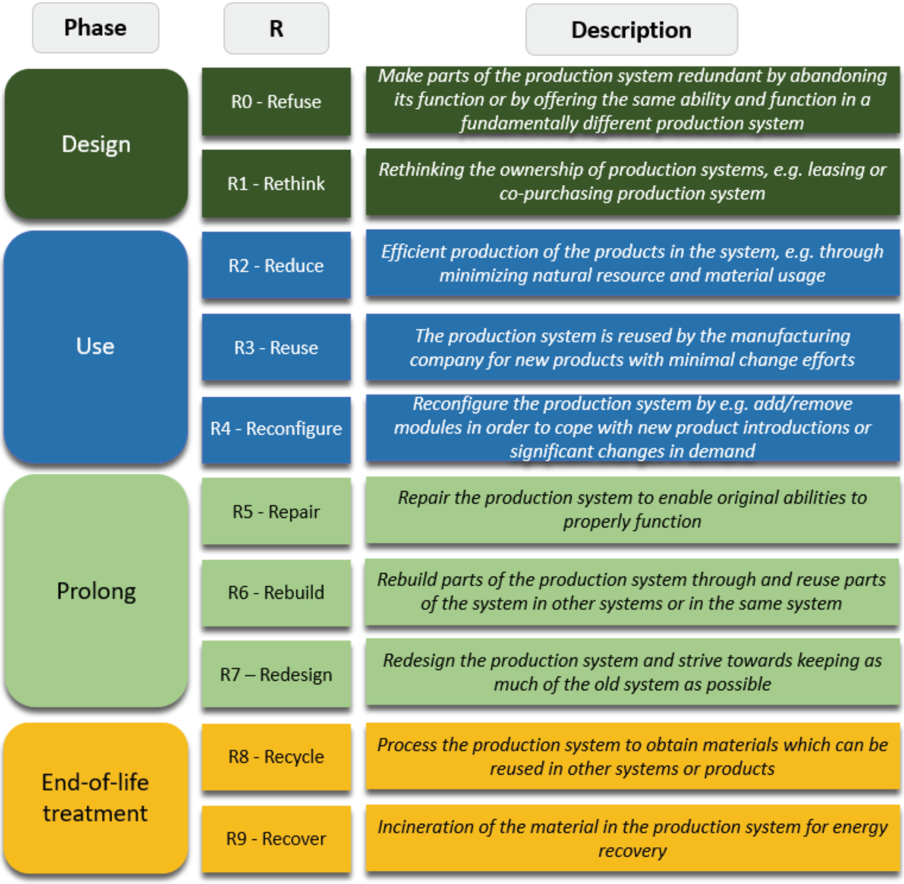

Figure 9. Conceptual framework for circular production systems, from Skärin et al. (2023).

However, the framework does not visualise circularity as an iterative process; instead, this can be viewed as a simplified illustration of a long-term development that, in reality, might be iterative and much more complex than actually conveyed. This is especially true in terms of production systems, which consist of, for example, the technical system containing cells, stations, machines and equipment (ElMaraghy, 2006; Koren, 2010; Rösiö, 2012; Wiendahl, Reichardt and Nyhuis, 2015), whereas these parts alone could be considered to have their own life cycle and perhaps should be considered through a lens of circularity. Nevertheless, to resemble the circular approach intended in the framework, Figure 10 illustrates the iterative proof in four phases: design, use, prolong and end-of-life (EoL) treatment.

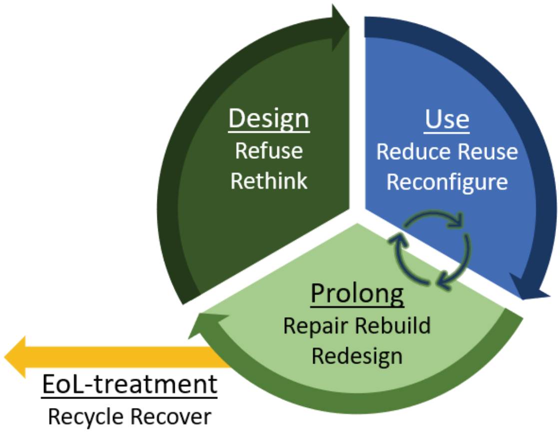

Figure 10. Phases in the production system life cycle, from Skärin et al. (2023).

4.4. Paper IV: Rapid assessment of circularity practices within the manufacturing industry

The purpose of Paper IV was to investigate how to analyse and evaluate circularity in production systems. This was realised by creating an easy-to-use tool for the initial evaluation of circularity practices in manufacturing companies. Although several practically oriented tools for improving and creating knowledge about circularity in the production system domain already exist (United States Environmental Protection Agency, 2007; Kurdve and Wiktorsson, 2013; Kurdve *et al.*, 2015), many companies are still struggling with initiating circularity practices. Therefore, developing a rapid assessment tool of circularity practices used to initiate the discussion on where to start carrying out such activities was considered relevant. Based on the well-renown rapid plant assessment (RPA) (Goodson, 2002), a novel assessment tool was developed. The RCA consists of two parts: 1) a questionnaire of 20 yes/no questions to be answered during a walkthrough of the plant (Table 4), and 2) ranking the plant in 10 categories based on the answers in the questionnaire. The questions and categories were developed based on the insights gained from the document study and the systematic literature review, as well as other research, for example, by Johansson *et al.* (2019) and the 10R framework (Potting *et al.*, 2017). The aim was to capture the circularity practices involving the production system by including aspects of reconfigurability to prolong its longevity. However, circularity practices concerning extending the lifetimes of input resources used in the production system, as well as managing products returning to the production system, were also included.

Table 4. Questions for evaluating circularity in production systems, from Skärin et al. (2023).

#	Question	Phase
1	Does the production equipment consist of easily demountable parts?	EoL treatment
2	Does the production equipment have sensors and measurement devices that continuously check for quality issues?	Prolong
3	Is there an abundance of production equipment in the area, seemingly not having been used for a long time?	
4	Do capabilities for repairing the production equipment exist within the company?	
5	Can the production equipment be incrementally adapted for new products and fluctuating demand?	Use
6	Are the environmental impacts from production processes continuously displayed for production personnel?	
7	Is it possible to digitally check the production equipment's' status to ensure proactive maintenance, e.g. the scrap rate and causes for stops?	
8	Is production equipment easily movable, for example, by being placed on wheels?	
9	Does relevant waste bins/containers exist close to working stations?	
10	Are defect products taken care of in the production system? (new products only)	
11	Is packaging material reused? (e.g. pallets, plastics)	
12	Is heat/steam from own production reused?	
13	Is residual material directly fed back into the production system?	
14	Is residual material from production reused outside the company premises?	
15	Is ventilation in the production area placed for best efficiency?	
16	Is renewable energy used to power the production plant?	Design
17	Is it possible to measure the environmental impacts from production? (e.g. in terms of energy consumption, raw material efficiency, etc.)	
18	Are harmful and/or nonrecyclable materials used in the products?	
19	Is a circular business model developed and implemented? (e.g. is remanufacturing, refurbishing and/or repairing products established?)	
20	Would you buy the products produced in the plant?	

After answering the questions, users also rate the company's circularity in 10 different categories. This step was achieved by a cumulative consideration of the answers to the questions (see Table 5 below). The rating scale used in the RCA is identical to the RPA (Goodson, 2002), that is, on a scale of 1 to 11 (1 = poor, 11 = best in class).

Table 5. Categories for evaluating circularity in production systems, from Skärin et al. (2023).

#	Rating category	Connected R	Connected questions
1	Ability to sustainably manage EoL production equipment	Recycle/ Recover	1
2	Maximising production equipment lifetime	Repair/Rebuild/ Redesign	2, 4, 7
3	Reusing production equipment	Reuse/ Reconfigure	1, 3, 5, 8
4	Reusing residual material	Reuse	11, 12, 13, 14
5	Raw material efficiency	Reduce/Reuse	6, 10
6	Waste management and reduction	Reduce	6, 9
7	Energy efficiency	Reduce	15, 16
8	Ability to meet future legal requirements	Rethink	17, 18
9	Sustainable product material and high product quality	Refuse	10, 20
10	Circular business implementation	Refuse/Rethink	16, 19

To verify the questions answerability, category content and general structure of the tool, testing was done in five Swedish manufacturing companies. The RCA was found applicable to gaining insights into the current state of circularity practices and providing hints where to continue. Furthermore, the RCA served as an eye opener to widen the perception of the complexity of circularity and minimise the risk of disregarding important factors that otherwise might be neglected if staring blindly at certain entities, for example, the products produced in the production system. Instead, the RCA provided broadened insights into the constituents of circularity in production systems, covering more aspects than just the products produced.

5. Results and discussions

In this chapter, the results of answering the three research questions are presented and discussed.

5.1. RQ1

In this subchapter, the results of RQ1—‘*Which practices can realise circularity in production systems?*’—will be presented and discussed. The aim of the questions was to describe what circularity in production systems implies and how this has been addressed in both the literature and in practice.

By combining the insights from the systematic literature review and the document study, it was evident that circularity could be applied in a wide range of ways during the lifetime of production systems. The results from both the systematic literature review and document study are summarised in Figure 11, which covers circularity practices in production systems and conveys circularity in production systems from three areas: input resources, production systems and products. These are explained in detail in the subsequent text.

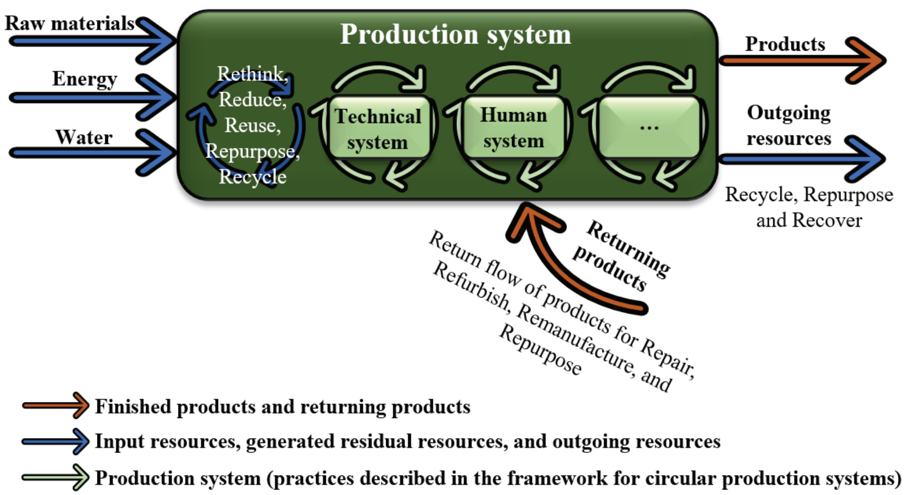

Figure 11. Circularity in production systems.

First, circularity in production systems might be recognised as the effort to extend the lifetimes of the resources used in the production system, both regarding input resources, for example, raw materials, energy and water (Jawahir *et al.*, 2006; Koren, 2010), but also the resources generated within the production system, for example, waste, residual materials, heat, steam and wastewater. Several circularity practices related to prolonging the lifetimes of these inputs have been identified in the document study, as illustrated in Table Table 2 in Chapter 4.2. Some of these circularity practices involve reducing usage, reusing and repurposing resources as a means to enhance efficiency and extending the resources' lifetimes. Recycling and recovery for incineration and landfill were also identified as possible to realise whenever no other alternative is possible, which is in line with the findings from Potting *et al.* (2017).

While the present thesis focused on circularity practices occurring within the production system, it is important to stress that many of these circularity practices might occur in collaboration between the manufacturing companies and other actors in society (Ghisellini, Cialani and Ulgiati, 2016; Vanhamaki *et al.*, 2019). For instance, realising all the recycling activities might not entirely be possible by a single manufacturing company, and creating close collaborations with external parties might be required, thereby acting on a meso level. Nevertheless, it is also evident that manufacturing companies indeed have the possibility to further improve circularity by realising these practices on all input resources used within the production system. The document study indicated that many Swedish manufacturing companies have yet to realise this effort.

Although the document study provided an overarching view of which circularity practices are occurring in practice, the systematic literature review provided insights into the emphasis on hitherto conducted research. In previous research, several solutions for primarily optimising input resource usage by minimising consumption in the production system has been described (see, e.g., Ghanei and AlGeddawy (2020), Massimi *et al.* (2020), and Singh *et al.* (2021)). The results also indicate that research has involved reducing the usage of inputs in terms of water (Lee, Ryu and Shin, 2017; Huang, Badurdeen and Jawahir, 2018; Koren *et al.*, 2018) and energy (Ghani, Monfared and Harrison, 2011; AlGeddawy and ElMaraghy, 2016; Khezri, Benderbal and Benyoucef, 2019; Ghanei and AlGeddawy, 2020; Massimi *et al.*, 2020; Singh, Madan and Singh, 2021), but also hazardous waste (Massimi *et al.*, 2020; Singh, Madan and Singh, 2021) generated in production and greenhouse gas emissions (Touzout and Benyoucef, 2018, 2019; Touzout *et al.*, 2018). These insights might be considered as complementing the existing circularity theories, wherein, for example, the 10R framework (Potting *et al.*, 2017) provides limited insights into how the reduction of manufacturing impact might actually be realised and what is sought to be reducibly used.

Second, an aspect that has been briefly mentioned in the systematic literature review and the document study involves the production system itself. The production system should be considered a key component of circularity in production systems because of its high environmental impact. Here, the extension of the lifetime of production systems by, for example, continuous reconfiguration and reusing should be recognised as significant enabling practice (Koren *et al.*, 1999, 2018; Bi, 2011). A long-term perspective in the use and development of the production systems is arguably needed to overcome the challenges identified in the workshops, rather than the outdated linear management, wherein the production system is limited solely to products produced in the near future. The systematic literature review results indicated that there is a lack of emphasis on increasing the longevity of production systems, so future research is needed to describe how this can be achieved. For instance, a lack of research exists on design and development process models for realising circularity in production systems. Additionally, only a few studies have been conducted wherein the production system actually is in focus, contrasting the input resources and products produced, at least in manufacturing research.

Similar results were found in the document study, wherein the production system was scarcely mentioned. Only circularity practices related to rethink were possible to link to the production systems, wherein, for example, implementing circular production processes, using new sustainable processes and technologies and rethinking existing production to make more sustainable and circular were identified. These circularity practices were vaguely described in the sustainability reports, which has further stressed this as a crucial area for further research to realise circularity in production systems.

Third, circularity in the production system might also involve the extensions of the product life cycle, that is, actions occurring subsequently of being used by the customer. The document study provided insights into several companies practicing repairing, refurbishing, remanufacturing and repurposing to enhance the circularity of the product. Whether these practices occur within the same production system or even facility, wherein the product was first produced, were not explained in detail and not explored any further in the current thesis. Nevertheless, they can be regarded as potential practices in need of consideration in the use of production systems. These findings support the existence of content in the 10R framework (Potting *et al.*, 2017). However, as identified in the document study, many Swedish manufacturing companies have yet to initiate, for example, remanufacturing and refurbishing of their own products. These activities were mentioned infrequently in the sustainability reports. From a theoretical perspective, reconfigurability was found to be used as an enabler for production systems specialised in handling the return flow of used products. For example, recycling systems (Barwood *et al.*, 2015) and remanufacturing (Aljuneidi and Bulgak, 2016, 2017; Brunoe, Andersen and Nielsen, 2019) has been touched upon. Moreover, empirical insights regarding how reconfigurability might be used as a building block in production systems to overcome challenges in closing the product loop have also been described (Bockholt *et al.*, 2020).

To summarise, circularity practices within the input resources used in the production system, the production system itself, as well as the products and resources exiting and returning to the production system have been identified and described through the systematic literature review and document study. Reconfigurability has been described as an enabler of, for example, reducing energy and water consumption, but also for managing returning products to, for example, the processes of remanufacturing and refurbishing. It was also concluded that there was a lack of focus on the production system, and future research in this area is needed.

5.2. RQ2

In this subchapter, the results of RQ2—'*Which challenges exist with realising circularity in production systems?'*—will be presented and discussed. The challenges derived from workshops with experts within production systems are presented in Paper III. Hence, the challenges are the result of a limited number of workshops, and other challenges probably exist as well. However, limited research exists to validate and compare the findings in RQ2 as research on the challenges of realising circularity has yet to focus on production systems.

In the workshops, it became evident that purchasing is often limited to solely taking the next products into consideration when investing in new production systems. Seldom is it the case that the essential capability of producing next generations of products is included in the purchasing phase, wherein static systems incapable of being reconfigured to changing requirements are purchased because of the simple reason that cost is the main factor influencing the decision. These purchasing practices could be recognised in line with the linear economy, wherein the 'take-make-use-dispose' philosophy dictates, as described in RQ1. This is in line with, for example, Kirchherr *et al.* (2018), who similarly found limited circular purchasing a challenge with circularity. In this regard, there is a need to adapt obsolete and linear economy descending investment models to include possibilities for production systems to be relevant for a longer period of time. This has also been identified as a challenge in reconfigurability research (see, e.g., Millberg and Möller (2008)).

Linked to this was also a lack of collaboration between manufacturing company and production system supplier brought up as a challenge during the workshops. Extending the lifetime of production systems might include continuous adaptation to avoid, for example, having to purchase new production systems when introducing new products (Koren *et al.*, 1999; ElMaraghy and Wiendahl, 2009). To enable continuous adaptation, long-term collaboration between a manufacturing company and production system suppliers might be required, as mentioned in the workshops. Simple buy/sell relations between these two actors might counteract the circularity intentions if the focus shifts to profit making rather than lifetime extension.

Furthermore, many current production systems have been developed for a single product or product family; thus, they do not possess the technical capability of being reconfigured to manage changing requirements, as described during the workshops. As a result, the extension of their lifetime might be labelled as more difficult compared with systems that are easily adaptable (Rösiö, 2012). In Wiktorsson's life cycle model (2000), this could be translated to the operation phase being shortened, so the termination of the production system instead is expedited. New sustainable products need to be introduced at an accelerating pace (Huang and Badurdeen, 2017; Koren *et al.*, 2018; Khajuria *et al.*, 2022). Similarly, companies currently lack knowledge regarding how to design and develop circular production systems. This lack of knowledge might be caused by the current tendency to manage resources in a linear manner (Pitt and Heinemeyer, 2015; Franco, 2017), including production systems. Therefore, manufacturing companies are required to rethink ways to design and develop circular production systems. The knowledge regarding how this might be realised is currently lacking, according to the workshop participants, although the results of the present thesis might provide initial insights into the matter. However, along with attempting to realise circularity, the challenge of uncertain decision making in prolonging the system's lifetime also arises. During the production system life cycle, crucial choices, including multiple factors, need to be made. These involve, for instance, whether to purchase new, renovate or rebuild a production system when it is obsolete, as mentioned during the workshops. Although the logical answer from a circularity perspective would be to extend the production system's lifetime as long as possible, when including other factors, such as energy and water usage, another answer might be more suitable. The participants also mentioned a lack of in-house competence and know-how regarding rebuilding and renovating production systems as further complications of the issue. Creating decision-supporting models and tools, for example, for comparing and calculating the financial result and environmental impact for the options, might be a solution for this challenge. Such support was reportedly lacking by the companies.

The workshop participants also raised the expected stricter legal demands as a challenge to which companies need to adhere at some point in the future. These legal demands could, for example, include the requirement to manage residual materials from production and a limited CO_2 emission budget, which the company needs to operate according to, as specified by one of the participants. Although such demands may push the implementation of circularity practices in production systems, creating a foundation for managing these demands might be seen as crucial and in need of future consideration. This finding is in line with previous circularity research as legal demands have been described as both a challenge for companies to adhere to (Kirchherr *et al.*, 2018) but also a key enabler for realising circularity (Kumar *et al.*, 2019).

To summarise, most of these challenges relate to converting the current linear economy's descending development and use of production systems towards a circular way. By doing so, it might be avoidable to postpone the necessity of purchasing new systems whenever the requirements put on the production system change, for instance, when introducing new product variants. However, some of the identified challenges also involve circularity in terms of managing the resources used within these systems, for instance, in terms of reducing the CO_2 emissions during production. Similarly, the management of the return flow of products from customers could be covered through a long-term development of production systems, if recognising the need to gradually combine remanufacturing processes and the production of novel products within the same production system.

5.3. RQ3

In this subchapter, the results of RQ3—'*How can realising circularity in production systems be supported?*—will be presented and discussed.

As an initial attempt to address the research gaps in RQ1 and the challenges identified in RQ2, the present thesis facilitates a deeper understanding of circularity in production systems, supporting the realisation of circularity in production systems by providing insights into possible circularity practices to prolong the lifetimes of production systems. This presented a framework that covers a future state of circularity in the production systems domain. In this regard, a strong emphasis is on the management of production systems, which was scarcely emphasised previously, as indicated by the results of the systematic literature review and the document study. The circular production systems framework, as presented in Paper III, can serve as foundational guidelines based on the 10R framework (Potting *et al.*, 2017) and expand insights regarding how to manage the production system in line with circularity, rather than in a linear manner. This provides insights into how to manage production systems throughout their entire lifetime. The framework extends previous research, perhaps most prominently by Potting *et al.* (2017). However, the framework can also be seen as combining circularity research with production systems research, for example, by Wiktorsson (2000) and Koren *et al.* (1999).

The conceptual framework contains four main phases (design, use, prolong, EoL treatment), each comprising a set of circularity practices (Rs). The first phase, *Design*, shares similarities with the 10R framework by Potting *et al.* (2017) because it focuses on ensuring that the entire functionality of the production system actually is needed to avoid excessive purchase of new production systems or parts of it. Moreover, the ownership of the production system is up for evaluation. For instance, is it necessary for a manufacturing company to own the entire production system if it is only used for a brief period of time, or could leasing or co-purchasing with other companies be a more suitable solution? During the *Use* phase, enhancing the resource efficiency and, thus, reducing, for example, the resources used and the environmental impact can be seen as key activities. Also, the reuse and reconfiguration of the production system can be regarded as essential for extending the lifetime of the production system to ensure relevance for as long as possible. However, it might not be economically sound to purchase excess flexibility in the entire production system to cope with changing requirements. In the *Prolong* phase, the intention for the production system is similar to as for the product (Potting *et al.*, 2017), wherein requirements for either reparation of rebuilding of the system, for example, because of technical breakdowns or greater needs of change, where reconfiguration simply is not sufficient. When a complete redesign of the production system is needed, the aim is to keep as much of the existing system as possible, either within the replacement system or in other systems within the manufacturing company. This phase shares similarities with the refinement stage in Wiktorsson's model (2000), wherein the production system's lifetime is extended through certain practices. In the *EoL treatment* phase, which should be realised whenever no other option is viable, the production system is processed in order for components or materials to be used in other systems, either in-house or through external collaboration. Finally, energy recovery during incineration instead of landfill is realised whenever applicable, as also described by Potting *et al.* (2017).

Using the framework can arguably aid in overcoming some of the challenges posed in RQ2, especially in terms of aiding manufacturing in understanding how to design and develop circular production systems. However, although the framework does not include detailed descriptions of how each R can be achieved, it does provide knowledge in what to strive for, outlining key activities in such achievement. Nevertheless, because the framework currently does not include a high level of detail in the Rs, future research is needed for continued development. The framework can also be used as a starting point for transforming the purchasing process and investment models towards recognising circularity as an important factor in decision making. This might be supported by using the framework as a discussion material jointly between production development and the people involved in the purchasing process.

Even though the conceptual framework for circular production systems emphasises the production system, the existing scarcity in the reported circularity practices might indicate that many companies are still in the early phases of realising circularity in their production systems. Also, as shown in RQ1, although circularity practices regarding input resources are reported in sustainability reports, most of the circularity practices found in the document study were mentioned solely by a few companies out of the total sample of 20. Therefore, to bridge the challenge of understanding current circularity practices in the production system and provide a platform for discussion where to improve within the area, it was deemed necessary to investigate how to analyse and evaluate circularity in production systems. The results from this investigation were incorporated into the RCA (as explained in detail in Chapter 4.4). The RCA incorporates the insights found in the systematic literature review, wherein the reconfigurability in a production system plays an essential part in prolonging the lifetime of the production system. It also covers input resources, as well as the overarching aim of managing the product over several life cycles, without forcing the necessity to combine returning flows of used products with the manufacturing of new products.

By using the RCA, manufacturing companies are provided with an initial circularity evaluation, which forms insights and an understanding of the topic. The results gained from using the RCA might also be used to increase the external visibility of the circularity practices occurring within production. By doing so, the transparency between the manufacturing company and its customers might be enhanced. Moreover, it can be expected that an increased implementation of circularity practices is needed, not only to counteract the global climate crisis, but also to ensure adherence to upcoming stricter legal demands. The latter might imply that more effective resource management is required by manufacturing companies in the near future, which has been described as one of the challenges in RQ2. The RCA can provide manufacturing companies with the crucial first step in such attainment, especially if used in a larger group, for instance, together with the management team, as also brought up during testing.

To summarise, both the framework for circular production systems and RCA were intended to provide an overview of how to achieve circularity during the lifetime of production systems. However, these should not be regarded as 'one-size-fits-all' solutions for achieving circularity but rather as complementary to existing support, such as the circular scanner (Blomsma *et al.*, 2019), environmental value stream mapping (United States Environmental Protection Agency, 2007), green performance map (Kurdve and Wiktorsson, 2013; Shahbazi, Wiktorsson and Kurdve, 2019) and waste flow mapping (Kurdve *et al.*, 2015).

5.4. Discussion of method

In the present thesis, a systematic literature review, a document study and workshops, and interviews were carried out to *expand the knowledge regarding the realisation of circularity in production systems*. These have provided insights into different parts of the matter, that is, i) circularity practices, ii) challenges and iii) support for realising circularity in production systems.

The present thesis builds upon several studies that have been carried out during the research process. By conducting multiple literature reviews, this thesis can be seen as clearly emphasising theoretical profoundness.

Conducting literature reviews arguably leads to the thesis being well grounded in theory. First and foremost, a systematic literature review was carried out during the initiation phase. This provided extensive insights into the state of the art and laid the foundation for the subsequent research activities. Literature reviews were also conducted in the other phases, with the aims of investigating circularity focus in previous research, wherein sustainability reports were analysed (also in the initiation phase), to compare product and production systems (in the in-depth and support development phase) and to review previous adaptations of the RPA (in the support development phase). Although these were less comprehensive compared with the systematic literature review and, thus, also less described in the present thesis, they provided the necessary insights into the topics to answer the research questions.

Furthermore, finding a suitable sample size sufficient for generating generalisable results is important (Patel and Davidson, 2011) to ensure external validity. In the document study, the sample size was determined based on a comparison with similar research, which also analysed the contents of sustainability reports and, thus, was found sufficient for the purpose of the study. Furthermore, analysing the contents of sustainability reports was found to be an appropriate way of collecting a large amount of data suitable to fulfil the research purpose. Within a Swedish company context, only two previously conducted research studies were carried out: Carlsson Kanyama *et al.* (2018) and Paulson and Sundin (2018).

Although analysing the content of sustainability reports was found suitable to explore circularity practices, these were rarely found to be thoroughly explained in detail. The lack of detailed explanations of the circularity practices might stem from the purpose of the sustainability reports, which is to provide stakeholders and the public with an overarching insight into the company's ongoing and planned sustainability work. However, this also highlights the need to complement other data collection techniques, such as interviews because the documents were developed with a non-research-related purpose (Säfsten and Gustavsson, 2020). Therefore, complementary interviews could possibly have been conducted to ensure that the documents were correctly interpreted by the researchers. However, as circularity practices can be seen as extensive and occurring over a long period of time, it was recognised as difficult to identify suitable respondents with sufficient knowledge about existing circularity practices in production systems. Hence, a large interview study with several respondents from different functions would have been necessary to conduct in each company. This was not seen as achievable in the present research.

Another aspect in need of discussion regards data collection, which involved both primary and secondary data. Although conducting a literature and document study was deemed suitable given the purpose of the research, it also implied relying on a large portion of secondary data. This type of data might require extra careful analysis since the data were not originally intended for research purposes (Säfsten and Gustavsson, 2020). In this research, this issue was addressed by following structured processes by Booth *et al.* (2016) in the systematic literature review and Miles *et al.* (2014) and Calzolari *et al.* (2021) in the document study.

In the in-depth phase, two workshops were conducted. These were found suitable to provide profound insights into existing challenges (Darsø, 2001; Phaal, Farrukh and Probert, 2007; Ørngreen and Levinsen, 2017), while the setting of workshops generated the desired discussions among the participants, which would have been difficult to achieve in a different way. However, it is possible that carrying out additional workshops might have provided both additional challenges and more detailed descriptions. Also, as the workshops were not recorded, there is a risk that misinterpretation of the discussions occurred, which stresses the importance of conducting further research, possibly by using complementary methods such as interviews and surveys.

Furthermore, testing the RCA occurred at five companies, thereby ensuring its applicability in a natural setting. The results of these tests indicate that the RCA indeed encapsulated circularity in production systems and can be used to analyse and evaluate circularity in production systems. Hence, it provides manufacturing companies with valuable insights about circularity in their own production system. However, an issue regarding researcher subjectivity during the creation of the questions and categories might exist. Jointly developing the questions and categories with industrial partners might have enhanced the probability of ensuring practical applicability prior to the testing.

However, this approach might have negatively affected the generalisability because it would have been based on the view of a few companies; hence, it was not carried out.

6. Conclusions and further research

In this final chapter, concluding remarks for each RQ are provided. Thereafter, the main contributions to theory and practice are presented, followed by suggestions for future research.

6.1. Concluding remarks

The purpose of the present research was to *expand the knowledge regarding the realisation of circularity in production systems.* This was achieved in three parts. First, in RQ1, the focus was to describe which circularity practices exist in production systems, both from a theoretical and practical perspective. Second, in RQ2, existing challenges with realising circularity in production systems were identified through workshops with experts from the industry and from a systematic literature review. This opened up for RQ3, which covered supporting the longevity of production systems by adopting circularity theories to cover production systems, as well as investigating how to analyse and evaluate circularity in production systems. Answering the three RQs has enabled the purpose of the present thesis to be fulfilled. In the following section, a short summary of the conclusions in each RQ is presented.

RQ1: '*Which practices can realise circularity in production systems?'* This RQ was approached by exploring circularity within three areas of production systems: 1) input resources used in the production system; 2) the production system; and 3) the products, scrap and waste exiting the production system. The former involves efficiently using input resources, such as raw materials, water and energy, but also resources generated in the production system, for example, waste, residual materials, heat, steam and wastewater. Several circularity practices have been identified, including reducing the usage of, reusing and repurposing these resources as a means to enhance efficiency and extend the resources' lifetimes. Extending the lifetime of the production system itself, not solely what is used within the system, was also recognised as a constituent part of circularity in production systems. In the systematic literature review, reconfigurability was found to be an enabler for circularity because of the ability to incrementally adapt the production system according to changing volume and product requirements. Finally, managing returning products from various states was touched upon and described, which was addressed in both the systematic literature review and document study. This has been found to be achievable through, for example, remanufacturing and refurbishing.

RQ2: '*Which challenges exist with realising circularity in production systems?'* Several challenges have been identified, including a lack of competence in purchasing, a lack of knowledge of how to design and develop circular production systems, the inability to reconfigure and continuously update the production system, a lack of collaboration between manufacturing company and system supplier, uncertain decision making in prolonging the system's lifetime and future legal demands.

RQ3: '*How can realising circularity in production systems be supported?'* This RQ was answered in two ways. First, it was deemed necessary to facilitate a deeper understanding of circularity in production systems and support the realisation of circularity in production systems by providing insights into possible circularity practices to prolong the lifetimes of production systems. As a result, a conceptual framework was developed that supports the longevity of production systems. Second, an exploration regarding how to analyse circularity in production systems was realised. The results were incorporated into a tool for rapid assessment of circularity in production systems. By emphasising, for example, input resources, generated residual resources, produced products and the production system itself, the tool provides a general overview of circularity in production systems. The RCA aids manufacturing companies in initiating circularity practices and providing insights into the current state of practice.

6.2. Contributions to theory and practise

The present thesis has contributed to theory by summarising, describing and analysing state-of-the-art, thus expanding the knowledge regarding which practices can realise circularity in production systems. Previously, there was a clear theoretical gap in summarising and analysing the hitherto conducted research emphasising sustainability and circularity. Moreover, the 10R framework (Potting *et al.*, 2017) has been expanded and adjusted for production systems rather than products, as it was originally used for. Hence, a theoretical contribution includes adding another perspective to a well-established theoretical framework. In this regard, the research can also be considered as complementary to previous research, wherein the production systems in most cases have simply been described as efficient production or recirculating materials and products with the purpose of, for example, remanufacturing of returning products (see, e.g., the summaries by Hartley *et al.* (2023) and Kirchherr *et al.* (2023)). The present thesis has provided insights into what circularity constitutes in production systems by translating the insights from the document study and systematic literature review into three main areas and specifying what these might consist of. Such a description was previously lacking.

The knowledge gained from exploring the realisation of circularity in production systems not only contributes to filling a theoretical gap, but it can also be considered crucial in the practical domain as well. Apart from accommodating manufacturing companies with insights into which circularity practices exist, the present research has also further supported manufacturing companies in initiating circularity practices in the production system domain. This was achieved by developing a conceptual framework for circular production systems, which might serve as a guiding light when managing production systems. Likewise, the RCA might provide an initial evaluation of current circularity practices, spur discussions of what is lacking and provide insights into next steps to take. This might be the first vital incremental step of realizing circularity, which is required for a full-scale change towards reducing environmental impact and being capable of introducing new sustainable products at an accelerating pace.

6.3. Suggestions for further research

As circularity in production systems is a rather novel area, several suggestions for further research have been specified in each of the appended papers. In terms of future research in the continuation of the present thesis, there is still a lack of empirical studies focusing on circularity in production systems. Following the development and use of production systems either longitudinally or retrospectively would provide detailed information on how this can be realised. Using the conceptual framework for circular production systems as foundational guidelines for such research might partly aid in achieving circularity, but it can also act as a verification of the framework.

Furthermore, each of the described challenges in RQ2 needs to be addressed in more detail. For instance, further research in terms of developing economic and environmental calculation methods is needed because doing so would ease decision making throughout the production system's lifetime. This could entail decisions during the purchasing phase, to value reconfigurability and environmental impacts, that is, to enable a long-term perspective from the very beginning, but also throughout the production systems' lifetime, for example, to aid in deciding whether to repair or redesign a production system and which alternative is the most environmentally and economically sound.

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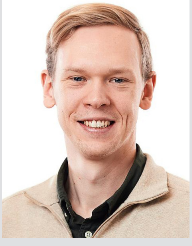
On Circularity in Production Systems

Exploring the Realization Through Circularity Practices

The manufacturing industry stands in front of huge challenges. Negative environmental impacts must be drastically reduced and new sustainable products must be introduced at an accelerating pace. Coping with these challenges are significant in order to deal with the increasingly emerging climate crisis. To slow down the climate crisis, the approach of circularity wherein the utilization and lifetimes of resources and materials are maximised with the aim to achieve a near perpetual closed material loop has gained a significant increase in attention. However, most research within circularity has emphasised on the product, especially practices occurring after being produced. A seldomly studied perspective involves exploring the realization of circularity within the production system. A clear description is lacking regarding what circularity in production systems actually constitutes of, and how this can be realized. Therefore, the purpose of this thesis is to expand the knowledge regarding the realization of circularity in production systems. To fulfil the purpose, this research was initiated by a literature review and a document study, which were conducted in order to describe which circularity practices exist in production systems, both form an academic and practical point of view. Subsequently were workshops with industrial experts within production systems held in order to identify challenges with realizing circularity in production systems. The literature review, document study, and workshops laid the foundation for support development, which was the final phase in the thesis. This included supporting the longevity of production systems by adopting circularity theories to cover production system, as well as investigating how to analyse and evaluate circularity in production systems. The results from this were incorporated in a conceptual framework for circular production systems and in a tool for rapid assessment of circularity in production systems.



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