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Sustainability and circularity in reconfigurable manufacturing – literature review and future research directions

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Abstract: Reconfigurability is widely acknowledged as a foundation for achieving sustainable manufacturing, while also being an enabler for establishing circular manufacturing. However, further clarifications of how reconfigurable manufacturing can support sustainable manufacturing are necessary. Thus, there is a need to further investigate how reconfigurability can help companies in achieving sustainable manufacturing and to identify future research directions. In this paper, a literature review was conducted to categorise, describe, and summarise the previously conducted research on reconfigurable manufacturing in relation to sustainability. The literature review was conducted in the database Scopus and 265 papers were initially reviewed. After excluding papers not fulfilling the inclusion criteria, 79 papers were analysed in detail using five different categorisations. Based on these categorisations, the previously conducted research on sustainability and reconfigurable manufacturing was analysed. Several frequently discussed sustainability focus areas were identified and described, as well as suggestions of future research directions.

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1 Introduction

Sustainable manufacturing plays a major role in reducing negative environmental impacts, developing social welfare and contributing to sustainable economic growth (Johansson et al., 2019; Garetti and Taisch, 2012). As a way of conceptualising the notion of sustainability in the manufacturing industry, the idea of sustainable manufacturing has emerged (Johansson et al., 2019). This is based on the Brundtland commission's definition of sustainable development: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). The tripartite focus within this definition sets the foundation for the triple bottom line concept of sustainability, which was coined by Elkington (1994). The concept is based on the idea that a company's success and well-being should not be evaluated solely in terms of financial performance, but also regarding social and environmental performance (Norman and Macdonald, 2004). Thus, sustainable manufacturing can be recognised as one of the key components in achieving a global sustainable development (Johansson et al., 2019). Similarly, the notion of circular economy has started to excel in both academia and industry. Circularity is seen as a central part of sustainability, focusing on maximising resource utilisation (e.g., raw material, energy) and prolonging the lifetimes of offered products and manufacturing equipment (e.g., machines and tools). Within manufacturing, circularity is first and foremost related to activities such as reuse, reduce, repair, remanufacture, and recycle of the manufacturing equipment, resources, and products. However, due to the severe problems existing in the world, including the climate crisis and employee inequalities, companies must rapidly transform in order to achieve sustainable manufacturing and start to manage manufacturing equipment, resources, and products in accordance with the circular economy.

Adapting to sustainable manufacturing and a circular economy is often challenging for most manufacturing companies (Tan et al., 2022). One of the most prominent challenges is to succeed in such a major change, while keeping the cost down (Tan et al., 2022; Bhanot et al., 2015) and continuously satisfying changing customer demands. An important part of this is the capability of the companies to apply reconfigurability principles in the manufacturing, as a means to ensure rapid adaptations and long-lasting systems and equipment. Reconfigurable manufacturing have since the introduction almost two decades ago been recognised as the future of manufacturing (Mehrabi et al., 2000). In line with a rapidly increasing customer demand for mass customisation, the characteristics of reconfigurable manufacturing have been found to be a solution for managing frequent product introductions and fluctuating capacity requirements, thus, providing a prolonged system lifetime. In contrast to, i.e., flexible and dedicated manufacturing, reconfigurable manufacturing is based on an inherent ability to reconfigure manufacturing equipment towards current and changing needs. This is enabled through six core characteristics: modularity, scalability, integrability, diagnosability, convertibility, and customisation (Koren and Shpitalni, 2010; Koren and Ulsoy, 2002).

Reconfigurable manufacturing was introduced mainly for reaching goals of cost-efficiency and responsiveness. However, reconfigurable manufacturing is able to accomplish more than this and might be a step towards sustainability (Koren et al., 2018a). Reconfigurability has been expressed as being the foundation for achieving sustainable manufacturing (Khezri et al., 2020), while also being an enabler for establishing circular manufacturing, mainly regarding remanufacturing from a supply chain perspective (Brunoe et al., 2019). Still, further clarifications of how reconfigurable manufacturing specifically can support sustainable manufacturing are necessary. Thus, there is a need to dig deeper into how reconfigurability can help companies in achieving sustainable manufacturing. One way of achieving this is to categorise, describe, and summarise the previously conducted research on reconfigurable manufacturing in relation to sustainability. Particularly should this be done in terms of clarifying which parts of sustainability that have been connected to reconfigurability, how the connection was substantiated, as well as describing the strength of used argumentations and evidence for such claims. Furthermore, it is also necessary to expand the knowledge regarding of which viable future research directions that can support companies in the transition to sustainable manufacturing through reconfigurability. Therefore, the following research questions are addressed in this paper:

1 How has sustainability been considered in previously conducted research on reconfigurable manufacturing?

2 What future research directions exist based on the identified research gaps?

The rest of the paper is structured as follows: Section 2 introduces the methodology applied for the literature review, while Section 3 presents the classification of the reviewed papers. Section 4 covers the discussion, emphasising the triple bottom line, reconfigurability as an enabler for sustainability and whether reconfigurability actually aids in achieving sustainability. Lastly, in Section 5, conclusions and suggestions of further research directions are presented.

2 Research methodology

A literature review was systematically carried out with the objective of identifying and describing how sustainability previously has been addressed in research on reconfigurable manufacturing, and to identify future research directions. The search was carried out in the database Scopus, using a tripartite area search, including 'reconfig*' or 'changea*', 'manufacturing' or 'production' and 'sustaina*' or 'circular'. The search was carried out in mid-August 2022. The literature review initially included a total of 326 papers (see Figure 1). After the search, a filter excluding papers not written in English was added, thus, removing 15 papers. The abstracts of the remaining papers were read, and papers considered relevant were included for the next step, i.e., the papers which covered both sustainability and reconfigurability in a manufacturing context, or any of the synonyms expressed in the keywords above. In total 131 papers remained after reading the abstract. The majority of the removed papers were identified as non-relevant due to irrelevant subject. Many of these removed papers discussed the development and production of reconfigurable antennas, hence belonging to an irrelevant area for this literature review. The next step included reading the entire paper. In total, 74 papers remained after finalising this step. Hence, 57 papers were excluded from the literature review. The inclusion criteria when reading the entire paper was that both sustainability and reconfigurability in a manufacturing context needed to be included in the full text. The removed papers did not include sustainability or reconfigurability in the full text, solely in the abstract, or did not include the manufacturing context in the full text, hence they were removed from the literature review. Thereafter, an additional five papers were added through applying backwards snowballing, based on a few prominent papers.

The last step in the literature review included analysing and categorising the remaining papers. A total of 5 different categorisations were used in this study. Firstly, all papers were analysed according to their focus on sustainability and/or reconfigurability. This initial categorisation (category 1) was inspired by Boldt et al. (2021) and involved a matrix consisting of four fields, including whether reconfigurability had been in focus or only mentioned in the paper, and whether sustainability had been in focus or only mentioned. Since the purpose implied a focus on both sustainability and reconfigurability, the papers included for further analysis in the literature review had to focus on both areas. In this regard, in focus meant that reconfigurability and/or sustainability was not simply added as a motivation or briefly discussed in the paper, but rather was the explicit focal point in the research. The initial categorisation comprised of 79 papers which were divided in a four-fielded matrix. Out of these papers, two papers were found to have mentioned both sustainability and reconfigurability, five papers focused on sustainability but only mentioned reconfigurability, 22 papers focused on reconfigurability but only mentioned sustainability, and 50 papers focused on both sustainability and reconfigurability (see Figure 2). As an example, Azab et al. (2013) developed a framework for planning, evaluating and restructuring reconfigurable manufacturing systems. Hence a clear focus on reconfigurability was present. The suggested framework was proposed to be synchronised with sustainable methods, otherwise sustainability was not discussed any further. Hence, the paper was found to be solely mentioning sustainability whilst focusing on reconfigurability and thereby not included for further analysis.

Figure 1 Literature review procedure (see online version for colours)

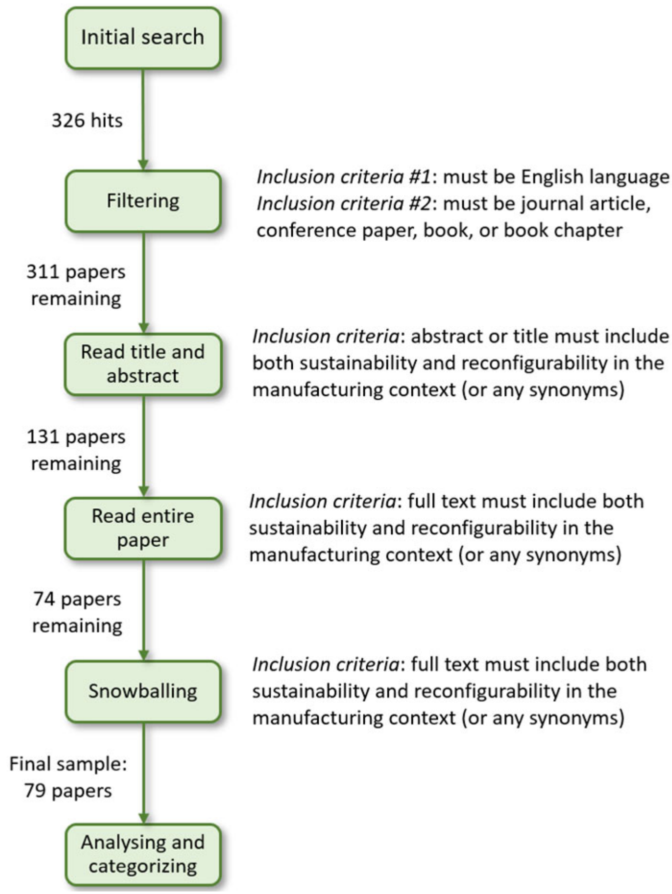
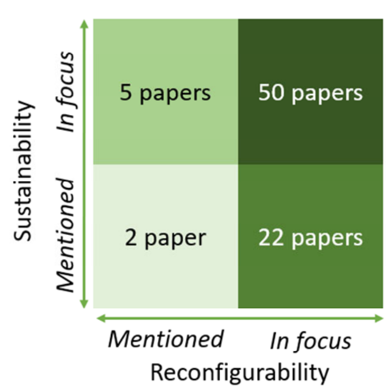
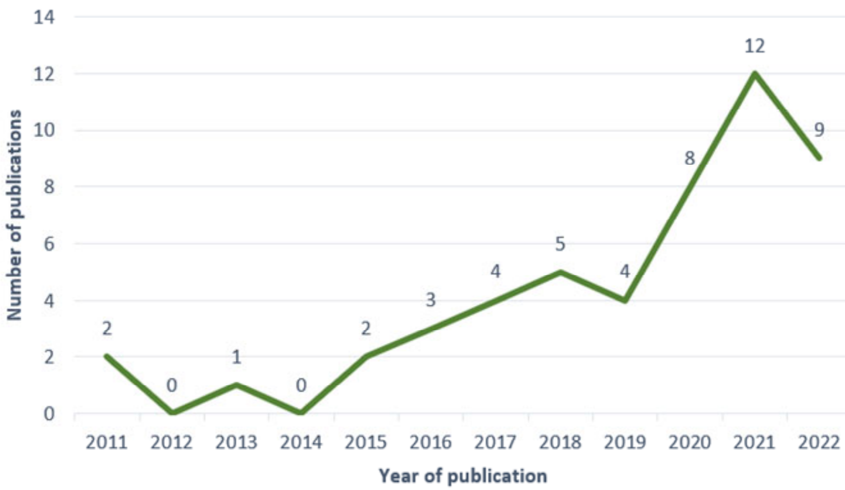


Figure 2 Sustainability and reconfigurability matrix (category 1) (see online version for colours)



Only the 50 papers categorised as focusing on both reconfigurability and sustainability were included for further analysis and categorisation. These papers were published between 2011–2022. In fact, the majority was published in 2020 or later, as illustrated in Figure 3. The assemblage of papers categorised as focusing both on sustainability and reconfigurability consisted of 20 journal articles, two book chapters, and 28 conference papers.

Figure 3 Year of publication summary (see online version for colours)



The subsequent analysis involved categorising the papers according to which and how the papers incorporated the three pillars of sustainability into their research, i.e., environmental, social, and economic sustainability (category 2). The categorisation was based on the papers having a clear connection to sustainability, either through an explicit statement or a clear focus in the full text. During the review of full papers, focus areas of sustainability were identified and patterns recognised. These ended up being the focus areas stated in Table 5 and 6 and elaborated further in the results. Hence, the focus areas were not predetermined prior to conducting the literature review. Furthermore, as circularity is a top focus area within economic and environmental sustainability the findings related to circularity needed further description. Therefore, the 10R framework (Potting et al., 2017) was used as a theoretical foundation. The framework includes the areas refuse, rethink, reduce, reuse recycle, repair, refurbish, remanufacture, Repurpose, recycle, and recover. These have been recognised as enabling an elaborate description of different activities related to circularity from a manufacturing resource and product view (Skärin et al., 2022a; Potting et al., 2017).

Thereafter, the papers were divided in terms of structural level of the factory, (category 3). This included categorising the papers into either being on *tool, machine, system, or network* level, inspired by Westkämper (2007). Specifying the structural level in the papers was deemed especially important since reconfigurability can be applied in several structural levels, which affects the detailedness in the results of the research.

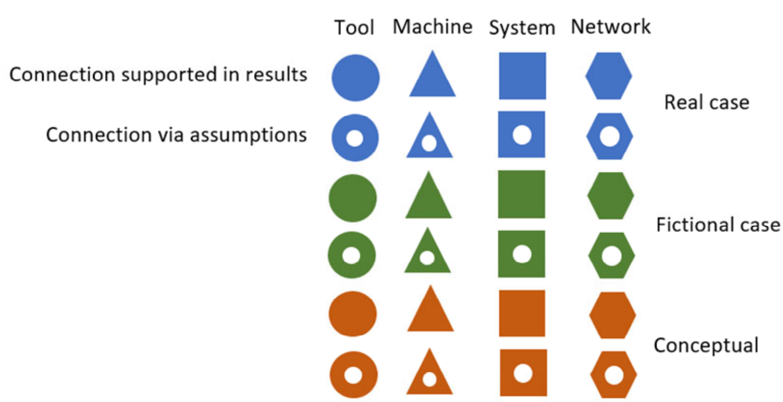
Subsequently, a categorisation describing how the connection between sustainability and reconfigurability was carried out (category 4). This categorisation was added due to the importance of tracking the origin of the connection to further elaborate on the conclusions. Two areas were used: *Support in results* and *Via assumptions*. The former implied a clear connection between the two areas supported by the results in the focal study. The latter involved assumptions made in, e.g., a theoretical chapter or solely adding the aspect of sustainability in optimisation models, mathematical equations, or similar. In these papers no distinct connections between reconfigurability and sustainability were made. To ease the distinguishment between the areas, a rule was followed which implied that if the connection was not explicitly mentioned in the conclusion chapter or similar chapter it was not categorised as *Support in results*, but rather *Via assumptions*.

Lastly, due to the importance of describing the strength of the connection between sustainability and reconfigurability, a categorisation covering study validation was made (category 5). This included dividing the papers into *real case, fictional example* and *conceptual research*. The first implied that the study's conclusion was supported in a real case, i.e., testing and validating had occurred using real data. The *fictional example* involved drawing conclusions based on fictional case, e.g., using numerical examples to illustrate the applicability of a mathematical model. The last area, i.e., *conceptual research*, implied solely presenting a purely conceptual idea shaped, e.g., through a framework, while no empirical data was used to validate the results. All the categories used in the literature review are described in Table 1.

Table 1 Summary table of categories used in the literature review

No.	*Category*	*Areas*
#1	Initial matrix	Sustainability: focus or mentioned reconfigurability: focus or mentioned
#2	Sustainability pillars	Identified focus areas within the three pillars of sustainability
#3	Structural level of the factory	Tool, machine, system, network
#4	Connection between sustainability and reconfigurability	Support in results, via assumptions
#5	Study validation	Real case, fictional example, conceptual research

Figure 4 Categorisation clarification (see online version for colours)



To summarise the findings from the literature review, a figure logic and structure for category 3–5 was used (see Figure 4) and connected to each paper's sustainability focus areas (category 2). This was inspired by Bjørn et al. (2020), and includes:

- structural level of the factory (circle, triangle, square, or hexagon)
- connection between sustainability and reconfigurability (solid or hollow)
- study validation (blue, orange, or green).

3 Results

The results of the analysis are displayed and summarised in Figures 5 and Figure 6. Further descriptions of each categorisation are presented in the following subchapters.

Figure 5 Environmental and social sustainability categorisations (see online version for colours)

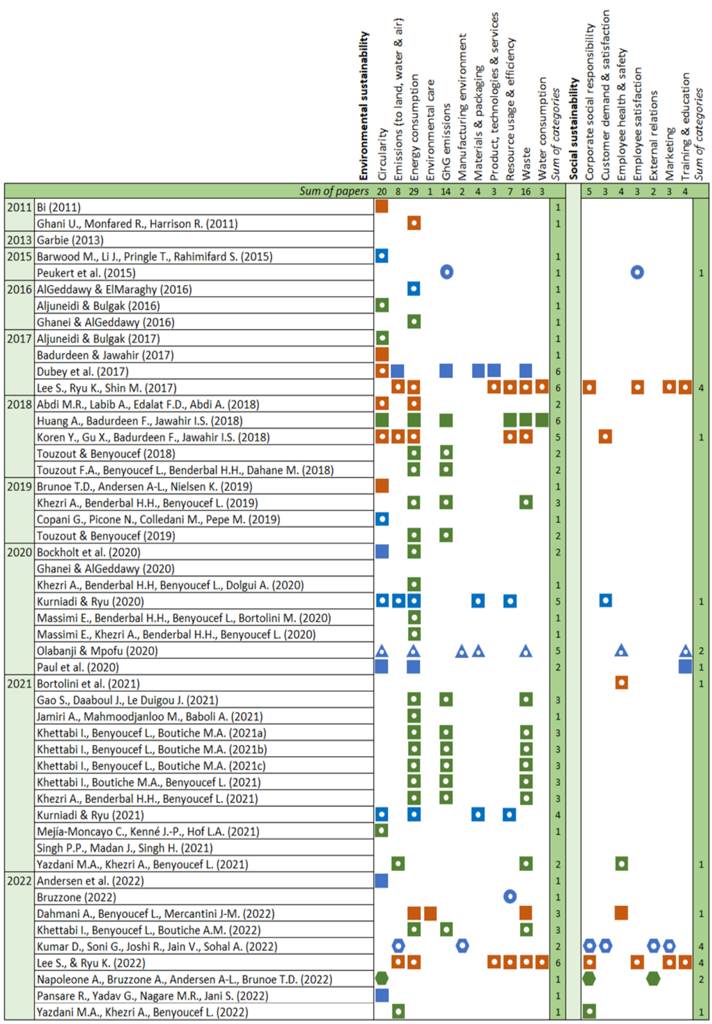
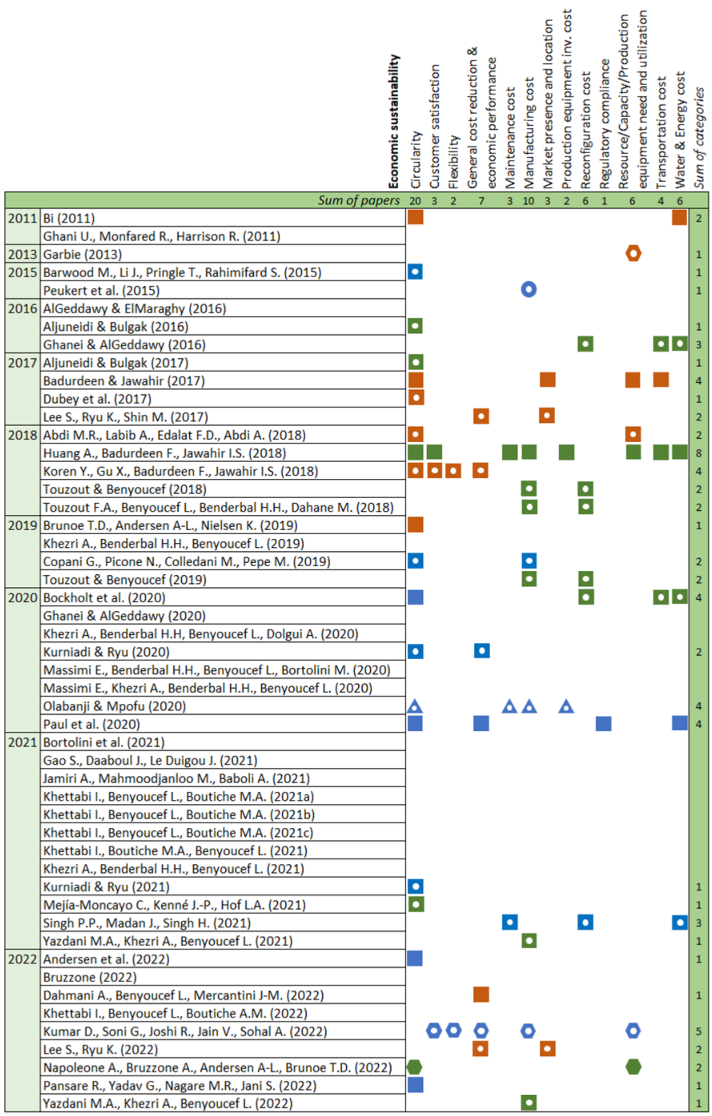


Figure 6 Economic sustainability categorisation (see online version for colours)



3.1 *Category 2 – three pillars of sustainability and pertinent focus areas*

Out of the 50 papers included in the literature review, 46 papers were identified as having adopted an environmental sustainability perspective, whereas 10 of these solely included circularity in their research (as seen in Figure 5 and Figure 6). 13 papers included a social sustainability perspective. 33 papers were found to have an economic sustainability perspective, whereas seven only focused on circularity. Moreover, out of all the papers, 12 papers were identified as taking all three sustainability perspectives into consideration. In the following subsections, further breakdown and explanation of each sustainability pillar are presented.

3.1.1 Environmental sustainability

In total, 46 of the reviewed papers included environmental sustainability in the research. The identified focus areas were: *Manufacturing environment, environmental care, materials and packaging, product, technologies and services, energy consumption, emissions of GhGs, emissions (to land, water and air), resource usage and efficiency, waste (hazardous and non-hazardous), water consumption, and circularity*.

- Energy consumption was found to be a frequent topic in reconfigurability research. Several authors included energy consumption as an important factor to reduce when developing mathematical models to support various decisions (e.g. (Singh et al., 2021; Ghanei and AlGeddawy, 2020; Massimi, Benderbal, et al., 2020a)). For example, Ghani et al. (2011) developed a conceptual approach used to minimise energy consumption through integrated monitoring systems in reconfigurable manufacturing systems. AlGeddawy and ElMaraghy (2016) developed a design synthesis to enhance the energy sustainability in manufacturing systems. In their case study, a changeable assembly system was used to demonstrate and validate the synthesis. The authors found that by enhancing system design, the minimisation of energy consumption is possible (AlGeddawy and ElMaraghy, 2016). Khezri et al. (2020) proposed a model used to integrate diagnosability, i.e., a core characteristic of reconfigurability, into the system design in order to achieve sustainability. In their model, one of the objectives involved minimising energy consumption and energy losses (Khezri et al., 2020).

- Emissions of greenhouse gases (GhGs) in relation to reconfigurability were discussed in several papers. In some of these, GhGs were touched upon as a factor aimed at minimising in the manufacturing system. Touzout et al. (2018) presented a hybrid multi-objective approach for creating a sustainable process plan. This approach was specifically designed for reconfigurable manufacturing systems, given its ability to quickly adapt to changes in the production. In their research, sustainability was taken into consideration in the shape of GhGs as a criterion alongside time and cost (Touzout et al., 2018). Similar research were conducted by Touzout and Benyoucef (2018, 2019).

  In contrast to the focus area posed above, papers which did not specify what type of gases and liquids that were considered in the study were labelled within the *emissions to land*, *water and air* focus area. These include, for instance, focusing on limiting the amount of harmful gasses and liquids emitted by machines during production (Yazdani et al., 2021, 2022; Lee et al., 2017).

- Resource usage and efficiency was found by several researchers to be achieved through the typical structure and characteristics of reconfigurability. Bi et al. (2011) found that in terms of sustainability, one of the key objectives in reconfigurability is to reduce waste, which is accomplished by reusing manufacturing resources and, thus, optimising the resource efficiency. Similarly, Koren et al. (2018) argued for the idea that modularity in a manufacturing system leads to an optimal resource efficiency by reducing the frequency of underutilising resources. Dubey et al. (2017) conducted empirical research on reconfigurable manufacturing and sustainability from a top management perspective. They concluded that

> "our results fully support the hypothesis that the higher the adoption of reconfigurable manufacturing systems that is, the higher the reconfigurability of the manufacturing systems within an organisation the higher their environmental performance is". [Dubey et al., (2017), p.63].

Hence, implying that there is a clear connection between environmental performance and top management commitment, when including the impact of top management beliefs and participation in the implementation of reconfigurability (Dubey et al., 2017).

- Waste (both hazardous and non-hazardous) has been regarded similarly to the sustainability focus areas *GhGs and energy consumption*, i.e., that it foremost has been related to research aiming at minimisation through adding it as a factor in models and programs (e.g. (Khettabi et al., 2021c, 2021b, 2021a; Khettabi et al., 2021; Massimi et al., 2020b)). For instance, Khettabi et al. (2021a) developed a non-linear multi-objective program where four objectives were minimised; total production cost, total production time, waste (incl. oils, water, industrial waste disposal, etc.) and greenhouse gas emissions. The model was specifically designed to enable the consideration of a sustainability perspective in reconfigurable manufacturing systems design.
- Water consumption was foremost found to be included in novel models specifically designed for reconfigurable manufacturing. For instance, Lee et al. (2017) developed a novel simulation model used to include sustainability factors in a self-reconfigurable manufacturing systems. In their research, water usage was applied as a sustainability factor (Lee et al., 2017). Furthermore, Huang et al. (2018) developed a performance assessment model for sustainable reconfigurable manufacturing systems. The model consisted of several economic and environmental clusters, where water usage and efficiency were considered. In contrast, Koren et al. (2018), argued that reconfigurability aids in the capability of improving environmental sustainability by the ability to reduce water usage.

Lastly, some of the less common environmental sustainability focus areas involved *manufacturing environment, environmental care, materials and packaging*, and *product, technologies and services*. The former was included since some research relate environmental sustainability to the manufacturing environment, e.g., by taking the operator's health (Olabanji and Mpofu, 2020), safety compliance of electrical gadgets (Olabanji and Mpofu, 2020), and the work environment's dangerous factors (Kumar et al., 2022) into consideration.

3.1.2 Social sustainability

In total, 13 of the reviewed papers included social sustainability in the research. Focus areas derived from the analysis included: *Corporate social responsibility (CSR), customer demand and satisfaction, employee health and safety, employee satisfaction, external relations, marketing, and training and education*.

A few of the social sustainability categories involved the ability to realise larger societal needs, primarily concerning *CSR* which included the company's ability to interact with human rights, anti-corruption, public policy, and minimising the social impacts for local communities (Kumar et al., 2022; Napoleone et al., 2022; Yazdani et al., 2022; Lee et al., 2017). Other focus areas have been more closely related to the focal company, e.g., in terms of *Employee health and safety and Training and education*. The former has been described in research in terms of ergonomic principles, enhanced operational safety, and improved individual health (Dahmani et al., 2022; Bortolini et al., 2021; Olabanji and Mpofu, 2020). The latter was mentioned by, e.g., Paul et al. (2020, p.505) who argued that: "*Reconfigurability enables socially appropriate alignment of employees' skills with the new tools of the production system*".

The focus area *External relations* has been addressed through programming algorithms and models. Napoleone et al. (2022) used mixed integer programming algorithms to enable the reuse of manufacturing resources and thereby stimulate customer-centric collaboration between companies. Kumar et al. (2022) developed a model for supply chain viability which incorporates trust between buyer and supplier. The latter also included Marketing as a component (Kumar et al., 2022). *Marketing*, as well as *employee satisfaction*, was also included as performance measures in simulations models (Lee et al., 2017) and reconfiguration methods (Lee and Ryu, 2022).

Furthermore, while the categories presented above provide insights into the specifications of how social sustainability has been mentioned in reconfigurability research, a scarcity exist regarding the clarity of connection between the areas. Some authors have described social sustainability in imprecise terms and focus on the general factors which a manufacturing system can lead to. For example in Kurniadi and Ryu (2020) where the ability to reconfigure a manufacturing system leads to the possibility to match requirements in terms of quantity and products to changing demands. Thus, they recognise that the ability to satisfy a societal need is achieved (Kurniadi and Ryu, 2020). Koren et al. (2018) found the merging reconfigurability and sustainable manufacturing is necessary in order to achieve social sustainability. In their research, reconfigurability was recognised as a profound enabler to supply high-quality products exactly at the time customers need them. However, a detailed description how this is achieved was not provided.

Other authors, primarily those who develop novel optimisation models, seem to have had a more detailed description of which social sustainability focus areas to include to achieve social sustainability in reconfigurability. Nevertheless, among these there was no apparent commonality in what social sustainability includes, instead these definitions differed quite drastically. For instance, Peukert et al. (2015) developed a model where social sustainability was included through adding the factor of performing a fair wage assessment. Olabanji and Mpofu (2020) on the other hand, developed a novel sustainability assessment model for reconfigurable machines. In their model, a social indicator was taken into consideration where, for instance, operator training, required level of maintenance, patenting and usage regulation, ethical issues/responsibilities were included.

To conclude, only a limited number of papers clearly link reconfigurability and social sustainability. One of these was Bortolini et al. (2021), who included ergonomic principles in the development of reconfigurable manufacturing systems. By proposing an optimisation model which included the occupational repetitive actions (OCRA) method and, thus, performs a risks assessment in the evaluation of repetitive movements of operators who frequently perform tasks with low loads (Bortolini et al., 2021).

3.1.3 Economic sustainability

In total, 33 of the reviewed papers included economic sustainability in the research. The majority of these included cost minimisation, primarily through adding this as an objective when designing and proposing novel models and methods. These papers seem to have reconfigurability as a basis when developing the models and methods, whereas reconfigurability has been included as a production paradigm without any clear separation of its core characteristics. Hence, in these models it has seldom been explicitly clarified which characteristics of reconfigurability lead to economic sustainability, nor how they are connected.

The cost reduction has been specified to certain areas, including *general cost reduction* (Dahmani et al., 2022; Kumar et al., 2022; Lee and Ryu, 2022; Kurniadi and Ryu, 2020; Paul et al., 2020; Koren et al., 2018a; Lee et al., 2017), *maintenance* (Singh et al., 2021; Olabanji and Mpofu, 2020; Huang and Badurdeen, 2018), *transportation* (Ghanei and AlGeddawy, 2016, 2020; Huang et al., 2018; Badurdeen and Jawahir, 2017), *water and energy* (Singh et al., 2021; Ghanei and AlGeddawy, 2016, 2020; Paul et al., 2020; Huang et al., 2018; Bi, 2011), *production equipment investment cost* (Olabanji and Mpofu, 2020; Huang et al., 2018), and reconfiguration cost (Singh et al., 2021; Ghanei and AlGeddawy, 2016, 2020; Touzout and Benyoucef, 2018, 2019; Touzout et al., 2018). The latter can be recognised as a fairly exclusive cost for reconfigurable manufacturing, as this type of manufacturing system leads to more frequent system – machine – and tool changes. Hence, costs related to the relocation, replacement, transfer and setup of systems, machines and tools have been recognised as important factors to include and reduce to achieve economic sustainability in reconfigurability. Furthermore, the focus area *manufacturing* cost was also used as a general objective in several models and methods. For instance in terms of minimising the operating cost when design and development of reconfigurable machines (Olabanji and Mpofu, 2020), minimising the production cost through process and production planning optimisation model (Yazdani et al., 2021, 2022), and reduction of processing cost in multi-objective models for generating the optimal process plan (Touzout and Benyoucef, 2018, 2019; Touzout et al., 2018).

Apart from cost reductions, the economic sustainability was expressed as increased *manufacturing flexibility* (Kumar et al., 2022; Koren et al., 2018b), as well as the need and improved *utilisation of resources*, capacity *and production equipment* (Kumar et al., 2022; Napoleone et al., 2022; Abdi et al., 2018; Huang et al., 2018; Badurdeen and Jawahir, 2017; Garbie, 2013). Furthermore, a few papers included the economic sustainability perspective on a more general level, whereas increased *customer satisfaction* (Kumar et al., 2022; Huang et al., 2018; Koren, Xi Gu, et al., 2018), *market presence* (Lee and Ryu, 2022; Lee et al., 2017), finding the *ideal location* (Badurdeen and Jawahir, 2017), and the ability to meet *future stricter regulations* (Paul et al., 2020) were mentioned in the conducted research on reconfigurability and economic sustainability. For instance, Lee et al. (2017) developed a novel simulation model used to include sustainability factors in a self-reconfigurable manufacturing systems. In their research, market presence and economic performance in terms of cost reduction were used as factors related to economic sustainability. Badurdeen and Jawahir (2017) argued that future manufacturing systems must be flexible and scalable, while being beneficially located and having an optimal resource, method, and tool utilisation in order to achieve substantial cost reduction. In Abdi et al. (2018), the possible optimisation of capacity usage in reconfigurable manufacturing systems based on the idea of linking manufacturing, supplier, and market demands is discussed. Koren et al. (2018) found reconfigurability as capable of enhancing economic sustainability performance in terms of, e.g., cost reduction and improved product quality.

3.1.4 Circular production

Based on the 10R framework (Potting et al., 2017), the reconfigurability research focusing on circularity has been broken down further (see Table 2). The Rs in the framework are described in descending order based on their level of alignment with circularity. For instance, reduce and reuse are considered to have a larger impact on circularity as they enable a high resource efficiency with lower effort in comparison to, e.g., recycle and recover which might require high effort and be the last opportunity to, salvage any value from the resource. The results from using the 10R framework to analyse the reconfigurability research indicate that redesign involves materials and tool. redesign was used in this paper instead of rethink which is used the 10R framework (Potting et al., 2017). This due to the references (Badurdeen and Jawahir, 2017; Bi, 2011) used redesign, and since both terms were deemed to be on a similar level of alignment with circularity it was deemed an appropriate alteration. Reduce has in this literature review solely been included when specifically mentioning reduce in combination with the R methodology. Reduce was found clearly connected to emissions, energy consumption, amount of inventory, generated waste, used materials, natural resources, and tools. Reconfigurability has also been clearly linked to the ability of reusing manufacturing resources, specifically mentioned are production machines, transfer lines, and used tools. Also connections to reusing water has been mentioned (Huang et al., 2018). The ability of easy repair of machines was involved in several research papers (Pansare et al., 2022; Bockholt et al., 2020; Olabanji and Mpofu, 2020; Brunoe et al., 2019). Recycling was mentioned in terms of materials, unwanted parts/products, tools, wasted energy, water, and products. The latter was discussed by Barwood et al. (2015) who converted the traditional setting where reconfigurability works into an application in a recycling system. In their research, Barwood et al. (2015) explored how a flexible robotic disassembly cell fits into the reconfigurable recycling system (RSS), and, thus, leads to environmental sustainability. Furthermore, some research has adapted reconfigurability to aid in realising remanufacturing practices from a systems perspective (e.g. (Brunoe et al., 2019; Aljuneidi and Bulgak, 2016, 2017)). Similarly, Bockholt et al. (2020) provided empirical insight through a case study on how changeability and reconfigurability can be applied in a manufacturing system to deal with the challenges in closed-loop manufacturing systems, particularly for product take-backs. In the last R, namely Recover, focus has been on used tools and materials.

Table 2 Circularity practice types

R		*Circularity practice type*	*References*
R0	Refuse	No further explanation	
R1	Redesign	Materials, tools	Badurdeen and Jawahir (2017), Bi (2011)
R2	Reduce	Emissions, energy, inventory, generated wastes, materials, natural resources, tools	Abdi et al. (2018), Koren et al. (2018a), Dubey et al. (2017), Bi (2011)
R3	Reuse	Water, manufacturing resources, parts, products, production machines, transfer lines, used materials, used tools	Napoleone et al. (2022), Kurniadi and Ryu (2020, 2021), Paul et al. (2020), Abdi et al. (2018), Huang et al. (2018), Koren et al. (2018a), Bi (2011)
R4	Repair	Machines	Olabanji and Mpofu (2020)
R5	Refurbish	No further explanation	
R6	Reman.	Materials, products, tools	Abdi et al. (2018), Bi (2011)
R7	Repurpose	No further explanation	
R8	Recycle	Materials, unwanted parts/products, tools, wasted energy, water products	Abdi et al. (2018), Huang et al. (2018), Koren et al. (2018b), Bi (2011)
R9	Recover	Used materials, used tools	Pansare et al. (2022), Badurdeen and Jawahir (2017), Bi (2011)

3.2 Category 3 – structural level of the factory

Dependent on within which structural level of the factory the research was carried out, different statements about the results can be made. As illustrated in Figure 5 and Figure 6, the majority of the research studies were applied on a *system level*, i.e., a total of 44 papers. Thus, these papers have concentrated on studying reconfigurable manufacturing systems (RMS) from different sustainability perspectives. A single paper focused on *machine level*, which involved the design and development of reconfigurable machines (Olabanji and Mpofu, 2020). Two papers covered the *tool level*, including papers on reconfigurable tools based on modular and scalable axis drivers (Bruzzone, 2022), and development of smart modular machine tool frames (Peukert et al., 2015). Lastly, three papers covered a *network level*, these focused on reusing manufacturing resources and viability modelling in supply chains (Kumar et al., 2022; Napoleone et al., 2022), and design sustainability for global manufacturing enterprises (Garbie, 2013).

3.3 Category 4 – connection between sustainability and reconfigurability

The papers were also divided into either including a sustainability perspective through assumptions, or validation in the results. The area *Via assumptions* (38 papers in total) primarily includes papers wherein sustainability has been added in mathematical models. These handled the areas of reduction of hazardous wastes, GhG emissions and energy consumption, as included in, e.g. (Khettabi et al., 2022; Gao et al., 2021; Khettabi et al., 2021b; Khezri et al., 2019, 2020, 2021; Massimi, Benderbal, et al., 2020). Most of these papers tested a single optimisation of a production system constellation without any comparative analysis of different options. AlGeddawy and ElMaraghy (2016) conducted a comparison between four different reconfigurability scenarios and concluded that through reconfigurability it is possible to minimise the energy consumption. However, as only different solutions of reconfigurability were tested, not different levels of reconfigurability or comparison with other systems, the paper was categorised as connection *via assumptions*. Furthermore, papers which used reconfigurability as contextual foundation was also categorised as *via assumptions* (Bruzzone, 2022; Kurniadi and Ryu, 2021; Olabanji and Mpofu, 2020; Kurniadi and Ryu, 2020; Copani et al., 2019). Likewise has reconfigurability been recognised as one of several core components in a sustainable manufacturing enterprise, alongside, e.g., innovative products and flexible organisation management (Garbie, 2013).

Validation through results was foremost included in conceptual papers and in papers which used real cases. The former was categorised as supported through the results as they through logical arguments end up with results which supports the connection between sustainability and reconfigurability (Badurdeen and Jawahir, 2017; Bi, 2011). Previously conducted literature reviews were categorised in the same way, for instance Dahmani et al. (2022). Apart from purely conceptual research, some papers strengthened the validation through survey (Dubey et al., 2017), simulations (Andersen et al., 2022), and interviews (Paul et al., 2020). Paul et al (2020) conducted interviews and important factors were mentioned by the respondents, hence, the validation were categorised as supported in the results. Moreover, Andersen et al. (2022) conducted simulations to test if reconfigurability increases manufacturing systems robustness in product take-back programs.

3.4. Category 5 – study type

The study type was categorised according to how the connection between reconfigurability and sustainability was verified. Out of the 50 papers which focused both on sustainability and reconfigurability, 11 were purely conceptual research, 24 were identified as including fictional examples, and 15 were able to include real cases as a means to validate the results.

The *conceptual research* mostly involved making logical conclusions that sustainability is positively impacted through reconfigurability. These involve, e.g., development of design procedures (Garbie, 2013), optimisation methods influencing both economic goals and sustainability (Lee and Ryu, 2022) and simulation model for self-reconfigurable manufacturing systems with an emphasis on sustainability factors (Lee et al., 2017). The area *conceptual research* also included research which involved an explanatory approach to combine sustainability and reconfigurability. Examples of such research include Koren et al. (2018) and Badurdeen and Jawahir (2017), who through sheer logic argued for the existence of a positive impact which reconfigurability has on sustainability.

Using *fictional examples* was commonly used in research wherein mathematical models and optimisation models were developed. This was to display the functionality of the model, wherein *fictional examples* including illustrative numbers were frequently used. However, although using *fictional examples* might prove to be effective as an illustrative example, it is seldom possible to draw the conclusion that, e.g., reconfigurability leads to improved sustainability through such a way. For instance, Mejia-Moncayo et al. (2021) developed a hybrid architecture for a reconfigurable cellular remanufacturing system where a mixed integer non-linear optimisation model was used to, e.g., balance the workloads and quantify reconfigurability cost. Reconfigurability was identified as an enabler for a quick change, and remanufacturing seen as leading to, e.g., savings in labour, materials, energy cost and so on (Mejía-Moncayo et al., 2021). Similarly has research focusing on optimising process planning, scheduling, configurations and layout been using *fictional examples* as a means to test the proposed optimisation models, e.g., by Ghanei and AlGeddawy (2016), Gao et al. (2021), Jamiri et al. (2021), Touzout and Benyoucef (2019).

Several papers include real cases as a support to validate the results. Developing and testing prototypes of reconfigurable machines and tools, as in the research by Copani et al. (2019), Olabanji and Mpofu (2020), and Bruzzone (2022) was found to be the research with tangible results. Although the majority of hitherto conducted research on sustainability and reconfigurability has focused on the system level, developing, and testing an entire reconfigurable manufacturing system is yet to be described in research. The most elaborately developed and described reconfigurable manufacturing system is perhaps the iFactory, which was used by AlGeddawy and ElMaraghy (2016) and represents such a system. *Real cases* in terms of conducting interviews were also realised by Paul et al. (2020) and Andersen et al. (2022). The latter also used a fictional simulation as support of their findings related to the concept that reconfigurability might be economically viable disassembly, and thus for circularity practices such as remanufacturing and recycling (Andersen et al., 2022). Lastly, in research focusing on modelling methods, *real cases* have been tested for products including cooling fans (Kurniadi and Ryu, 2020), hairdryers (Kurniadi and Ryu, 2021) and automotive pistons (Singh et al., 2021).

4 Discussion

4.1 Comparison between the sustainability pillars

There is a clear difference both in terms of frequency and discrepancy amongst the three pillars of sustainability in the reviewed literature on reconfigurable manufacturing. Regarding environmental sustainability, the most frequently recurring focus areas were; *circularity, emissions (to land, water and air), energy consumption, GhG emissions, resource efficiency, and waste (hazardous and non-hazardous)*. Identifying and describing these focus areas was possible primarily since the environmental sustainability is based on common factors frequently used in research and easily quantifiable. This might also derive a common preconceived notion that sustainability is primarily an environmental matter, which might be the reason why the development towards a unified understanding of which environmental sustainability factors currently exists. Many of these papers are related to the decrease of energy consumption, primarily regarding suggestions of models which have been adapted for sustainability by adding the objective of lowering energy consumption, e.g., Ghani et al. (2011), Massimi et al. (2020) Singh et al. (2021). A similar logic for adapting models for sustainability includes adding the objective of minimising emissions of GhGs, apart from the common optimisation objectives concerning cost and time, e.g., Touzout and Benyoucef (2018) and Touzout et al. (2018). Recently, models with predetermined objectives, e.g., Khettabi et al.

(2021a), are presented as a solution for including a sustainability perspective in reconfigurability research.

Economic sustainability was found to be a more circumlocutional term compared to environmental sustainability. This forced a somewhat subjective analysis of whether these papers are discussing reconfigurability and economic sustainability, or simply taking different costs into consideration. Regardless, as stated previously, only papers explicitly discussing economic sustainability were included in this literature review, and, thus, this should not be recognised as an issue. Nevertheless, the findings from this literature review indicate that most authors are focusing on cost reduction when discussing reconfigurability and sustainability, with the argumentation that reducing costs leads to an economically sustainable enterprise, e.g., Kurniadi and Ryu (2020). Amongst these papers, authors seem to simply include factors found to be relevant and supporting of the focal case. On the contrary, some authors use a terminology based on a general definition, which might not be completely relevant when studying manufacturing systems, e.g., *location and market presence* as economic sustainability focus areas. As a means to display full transparency in the analysis, these were included regardless of relevance.

Lastly, identifying and describing a common connection of how reconfigurability lead to social sustainability was proven to be a far more challenging task compared to environmental sustainability. Most often, researchers have not clearly established a connection between social sustainability and reconfigurability. For instance, many authors have solely described general sustainability factors based on descriptions made by instances such as the global reporting initiative, e.g., Lee et al. (2017). These factors are often difficult to quantify, in comparison to the environmental and economic sustainability focus areas. Thus, social sustainability has seldom been included in novel models specifically designed for reconfigurable manufacturing, which many of the papers included in this literature review have developed.

4.2 Relation between sustainability and reconfigurability

Sustainability in reconfigurable manufacturing research is evidently an increasingly significant subject amongst researchers. In this literature review, a peak in the most common year of publication was in 2021, followed by 2022 and 2020, as seen in Figure 3. However, even though there is an apparent increase in research interest, there is still little empirical data or insight supporting the claims that reconfigurability lead to sustainable manufacturing, even though the logical answer might indicate so. This correlates with one of the findings from this literature review, that a significant amount of the research on sustainability and reconfigurability has added the perspective of sustainability through the inclusion of certain sustainability factors in novel models specifically designed for reconfigurable manufacturing. These papers are not concluding that reconfigurability lead to sustainable manufacturing, but rather that it is possible to include a sustainability perspective when designing, planning, and controlling reconfigurable manufacturing. On the contrary, few authors are indeed arguing for the fact that sustainability and reconfigurability have an inherent relationship (Khezri et al., 2020; Koren et al., 2018b; Dubey et al., 2017). Some authors (Singh et al., 2017) are even stressing that sustainability should be recognised as a core characteristic of reconfigurability, alongside the traditional characteristics such as modularity, integrability and changeability, as means to merge the two.

Furthermore, describing economic, environmental, and social sustainability in a reconfigurable manufacturing context has proven to be a challenging task. Seldom are researchers agreeing on a unified definition of the triple bottom line of sustainability. The lack of a common terminology might have caused researchers to elaborate on their own definition of sustainability in reconfigurable research. This discrepancy has caused issues when trying to collectively describe the hitherto conducted research on reconfigurability and sustainability. The lack of a common terminology might also cause further challenges in establishing the relationship between sustainability and reconfigurability. This also leads to the problematic of quantifying sustainability in reconfigurable manufacturing remaining a difficult task, as highlighted by Paul et al. (2020, 37, p.505);

> "… the interviews highlighted the importance of developing metrics for measuring the sustainability of RMS. A return-on-investment indicator considering the possibilities posed by reconfigurability, a measure of costs and benefits from an ecological standpoint and a metric for reconfigurability potential could help decision-makers to adopt RMS".

In terms of the structuring level in focus, the results from this literature review are similar to the findings from Andersen et al. (2015), i.e., that most research about reconfigurability have been on a system level. In the majority of reconfigurability research, assumptions have been made regarding the increase of sustainability through reconfigurability. However, comparisons between different reconfigurable solutions have rarely been accomplished. Similarly, there is a clear absence of real cases to support this connection, as the majority of papers included in this literature have been limited to using fictional examples. This might be explained through the difficulties in making comparisons between different alternatives are hugely affected by the uniqueness in the solutions. Nevertheless, the question of whether reconfigurability aids in achieving sustainable manufacturing remains without empirical support from real cases.

Additionally, the results of this literature review suggests that reconfigurability can have a positive impact on the ability to achieve circularity. Both reconfigurability and circularity in manufacturing share a very similar purpose, i.e., to extend the lifetime of the manufacturing resources and production equipment. Hence, the findings of identified circularity practice categories (Table 2) related to reconfigurability might serve as complement to previously conducted research on circularity practices in manufacturing. Because, previous research have not managed to clearly connect reconfigurability to circularity practises, as seen in, e.g., Skärin et al. (2022b, 2022a). Thus, a further strengthening of the connection between reconfigurability and circularity has been realised in this paper.

Lastly, while research clearly fails at making obvious connections between reconfigurability and sustainability, it is necessary to highlight that the oldest paper included in this literature review brings an interesting statement to the table. Because, Bi (2011, p.1335) concluded that "*Without a doubt, the enhancement of reconfigurability of an RMS will improve sustainability*". This statement is not supported by the findings of this literature review which implies that there still is limited empirical evidence supporting the conclusion that reconfigurability has a positive impact sustainability, although almost a decade of research has passed since.

4.3 Triple bottom line papers

In order to achieve sustainable manufacturing, companies must take all three pillars of sustainability into consideration (Elkington, 1994). However, when focusing on a limited research area, such as reconfigurability, a clear connection to all three pillars simultaneously seldom exists. As indicated by the findings in these papers, only 12 out of 50 papers covered all three pillars. Although these papers involve all three pillars of sustainability, it is possible to argue that an issue also involves which specific focus areas within each pillar must be included in order for research to actually be sustainable. Neglecting significant sustainability focus areas might also be an indicator of an incorrectly labelled sustainability. This raises the debate whether including the three pillars of sustainability by addressing issues in a few sustainability focus areas is sufficient to recognise the research as supporting sustainability. Or if all applicable and relevant focus areas in all three sustainability pillars are required to be addressed in the same research. If the latter is a more profound idea, all papers included in this literature review which focus on, e.g., developing optimisation models which solely includes a few sustainability focus areas would be irrelevant. This since they are so limited that their results cannot be used to determine whether reconfigurability is linked to sustainability or not. However, through this logic, only those papers which inherits a complete systems perspective or compares the result to absolute sustainability could be labelled as completely adapting a sustainability pillar. This would reduce the amount of eligible research papers which could be labelled as actually focusing sustainability to a bare minimum. By this reason, adding only the relevant sustainability categories should, as argued in this paper, be sufficient for the results to be explicitly connected and rooted in sustainability. Nevertheless, previous research has been tackling this issue quite differently, as it is apparent that in some research the strategy involved focusing on a very limited amount of sustainability categories, thus, reenforcing the debate whether these are sufficient and relevant. Others have addressed the issue by adding a selection of sustainability focus areas to the research, and, thus, faced the necessity to also manage the argumentation why these are relevant.

5 Conclusions and future research

Reconfigurability has previously been identified as the solution to simultaneously achieve high responsiveness and cost efficiency. However, today's manufacturing systems also need to be sustainable. In order to clarify how reconfigurable manufacturing specifically can support companies in achieving sustainable manufacturing, a literature review was carried out. This review aimed at categorising, describing, and summarising the previously conducted research on reconfigurable manufacturing in relation to sustainability. Two research questions were addressed in the study:

1 How has sustainability been considered in previously conducted reconfigurability research?

2 What future research directions exist based on the identified research gaps?

As an answer to the first research question, it is evident that a large amount of research primarily focused on reconfigurability has been adapted or developed to incorporating some aspect of sustainability. For example, reconfigurability research focusing on optimising design or operational aspects of the manufacturing system simply have added certain sustainability focus areas to the models and equations. However, these papers rarely conclude that reconfigurability lead to sustainable manufacturing, nor do they draw any distinct connections between the areas. Hence, the connection between sustainability and reconfigurability is generally emphasised but quite vague in past research, however, if emphasising circularity in particular, the connection to reconfigurability is stronger. This is primarily due to the fact that reconfigurable manufacturing and circularity in manufacturing largely share the same purpose, i.e., to prolong the lifetimes of the manufacturing equipment and resources. As identified in this literature review, previously conducted research has connected reconfigurable manufacturing to several stages within the 10R framework, while focusing on a vast range of manufacturing resources as well as manufacturing equipment.

Furthermore, there seems to be a general lack of common terminology when discussing economic, environmental, and social sustainability in relation to reconfigurability. Few researchers clearly define sustainability, even more rarely directly defining connections and establishing how reconfigurability leads to sustainable manufacturing. Moreover, researchers are seldom establishing a triple bottom line approach when discussing sustainability in reconfigurability. The lack of a triple bottom line approach is foremost caused by a missing focus on social sustainability. This might derive from challenges in quantifying the social sustainability, which is strengthened by the fact that many researchers are proposing novel models/methods/tools which solely focus on economic and environmental sustainability.

As a result of the literature review, some apparent research gaps have been identified, opening up for potential future research directions which answers the second research question. The directions include:

- Circular and long term management of manufacturing resources and equipment – although it is evident that reconfigurable manufacturing share the same purpose as circularity, further research is needed in order to elaborate on how to manage manufacturing resources and equipment over time, in order align it with circularity. For instance, in terms of how they can be reused, repaired and refurbished. Although this research has clarified which circularity practice categories which previously conducted reconfigurability research has focused on, the connections need further investigation.
- Exploring the role of reconfigurability on a network level – as most research has focused on reconfigurability on a system level, there is an evident lack of research on other levels which need further investigation. The machine and tool level might be recognised as similar to the system level, as these are constituent parts of a system. However, the network level might be studied rather differently, primarily as reconfigurability might have the potential to aid in beneficial distribution of manufacturing equipment between manufacturing facilities, as well as between companies, in order to further address circularity. Further research on how the relocation and redistribution of manufacturing resources and production equipment is therefore needed.

- Emphasising social sustainability – further research on how social sustainability is supported by reconfigurability is necessary, as a means to clarify how reconfigurability leads to sustainability. This can, for instance, be achieved by including the ergonomic consequences of having changeable and adjustable modules in the manufacturing.
- Empirical studies – further research investigating if and how reconfigurability leads to sustainability and circularity is needed. Foremost is the lack of empirical studies causing the inability to relate the areas. Few studies have been conducted with real empirical data, as well as few studies which compares different alternatives of manufacturing solutions. Hence, research aiming at filling these gaps might be of interest.

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