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Considering Sustainability in Reconfigurable Manufacturing Systems Research – A Literature Review

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Abstract. Reconfigurable manufacturing systems (RMS) have since the introduction almost two decades ago been recognized as the future of manufacturing. In line with a rapidly increasing customer demand for mass customization, RMS have been found to be a solution for managing frequent product introductions whilst keeping a high production efficiency. However, in recent years the focus has partly shifted from producing solely from an economic standpoint towards establishing a triple bottom line of sustainability, i.e., taking economic, social and environmental perspectives into consideration. Some authors have found RMS as an enabler for sustainable manufacturing, however, this needs further investigation. This paper aims through a literature review at describing and summarizing the hitherto conducted research on RMS and sustainability. A literature review in the database Scopus was carried out and a total of 265 papers were initially reviewed. Two categorizations of prominent papers were carried out: an initial categorization and a categorization according to the triple bottom line of sustainability. Based on these categorizations, the hitherto conducted research on RMS and sustainability was described. Several frequently discussed sustainability factors were identified, as well as suggestions of future research.

Keywords. Reconfigurable manufacturing systems, Changeable manufacturing systems, Sustainability, Circularity, Literature review

1. Introduction

Reconfigurable manufacturing systems (RMS) have since the introduction almost two decades ago been recognized as the future of manufacturing systems [1]. In line with a rapidly increasing customer demand for mass customization, the characteristics of an RMS have been found to be a solution for managing frequent product introductions and fluctuating capacity requirements, whilst having a prolonged system lifetime. Characteristics including modularity, integrability, scalability, diagnosability, convertibility and customization have been described as underlying factors enabling this capability [2]. However, in recent years, companies' attention has shifted from solely focusing on economic performance towards establishing a triple bottom line approach, i.e. taking economic, societal, and environmental sustainability into consideration in manufacturing. The RMS was previously solely introduced for reaching goals of cost-

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efficiency and responsiveness. However, RMS is able to accomplish more than this and is obviously a step towards sustainability [3]. This has been found to be necessary in order to achieve sustainable manufacturing. RMSs have been expressed as capable of being the foundation for achieving sustainable manufacturing [4], whilst also as an enabler for establishing circular supply chains and re-manufacturing [5]. Still, further clarifications of how RMS lead to sustainable manufacturing are necessary. One way to achieve this is to describe and summarize the hitherto conducted research on RMS and sustainability, and thus enable the possibility of identifying how sustainability has been addressed in RMS research. By doing this, it will also be possible to highlight gaps in this research. Thereby, the identification and suggestions of future research trends is also achievable. In order to achieve this, the following research question was formulated: *How has sustainability been considered in hitherto conducted RMS research?*

2. Reconfigurable manufacturing systems and sustainable manufacturing

2.1. Reconfigurable manufacturing systems

As a response to increasing demands for mass customization, the concept of the RMS was proposed in the 1990s by professor Yoram Koren [6]. In contrast to the other two major manufacturing systems, i.e. flexible and dedicated manufacturing systems, the RMS is based on an inherent ability to be reconfigured into fitting current needs, which is enabled through its six core characteristics [2,7]:

- *Modularity* – the ability to adjust production equipment and operations by utilizing an inherent modular structure.
- *Scalability* – the ability to scale up or down production capacity by removing or adding machines, tools, fixtures, etc.
- *Integrability* – the ability to use standardized interfaces in order to achieve quick changes in production equipment.
- *Diagnosability* – the ability to instantly identify root causes of product and operational defects.
- *Convertibility* – the ability to convert system functionality to match new production requirements.
- *Customization* – the ability to customize system flexibility according to changing product family requirements.

2.2. Sustainable manufacturing

The sustainable performance in manufacturing has grown to become a significant area of importance. Primarily since it plays a major part in reducing negative environmental impacts, developing social welfare and contributing to sustainable economic growth [8]. As a way of conceptualizing the notion of sustainability in the manufacturing industry, the idea of sustainable manufacturing has emerged [8]. This is based on the Brundtland commission's definition of sustainable development, who describe it as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" [9]. The tripartite focus within the definition by Brundtland sets the foundation for a concept called triple bottom line of sustainability, which was coined by Elkington in 1994 [10]. The concept is based on the idea that a company's success and well-being should not solely be evaluated as a financial performance, but also as a matter of social and environmental performance as well [11]. Thus, sustainable manufacturing can be recognized as one of the key components for achieving a global sustainable development [8].

3. Research methodology

A literature review was systematically carried out with the objective of identifying and describing how sustainability previously has been addressed in RMS research. 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 literature review initially included a total of 265 papers. After the search, a filter excluding papers not written in English was added, thus removing 14 papers. The abstracts of the remaining papers were read, and papers considered relevant were included for the next step. In total 103 papers remained after reading the abstract. The majority of the removed papers were identified as non-relevant due to irrelevant subject or area. Many of these 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, 46 papers remained after finalizing this step. Hence were 57 papers excluded from the literature review. Many of the removed papers did not include sustainability or RMS in the full text, solely in the abstract, hence they were removed from the literature review. However, an additional 6 papers were added through applying backwards snowballing based on a few prominent papers. The next step in the literature review included categorizing the contents of the remaining papers. This was achieved in two parts: an initial categorization and a sustainability categorization according to the triple bottom line of sustainability. The initial categorization was inspired by Boldt et al. [12] 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 sustainability and reconfigurability, the papers included in the literature review must have focused on both areas in order to be included in the next categorization. Hence, only papers found to be belonging to the matrix category of having both sustainability and reconfigurability in focus were used in the second categorization, i.e. according to the triple bottom line of sustainability. During the second categorization, the papers were also analyzed according to how these were connected to certain sustainability perspectives, in order to enable the possibility of further describing each perspective.

4. Classification of literature

The initial categorization comprised of 52 papers in 4 matrix fields. Out of these papers, 1 paper was found to have mentioned both sustainability and reconfigurability, 3 papers focused on sustainability but only mentioned reconfigurability, 15 papers focused on reconfigurability but only mentioned sustainability, and 33 papers focused on both sustainability and reconfigurability (see Figure 1). As an example, Azab et al. [13] developed a framework for planning, evaluating and restructuring RMS. Hence a clear focus on reconfigurability was present. The suggested framework was proposed to be synchronized with sustainable methods, otherwise sustainability was not discussed any further, hence the paper was found to be solely mentioning sustainability.

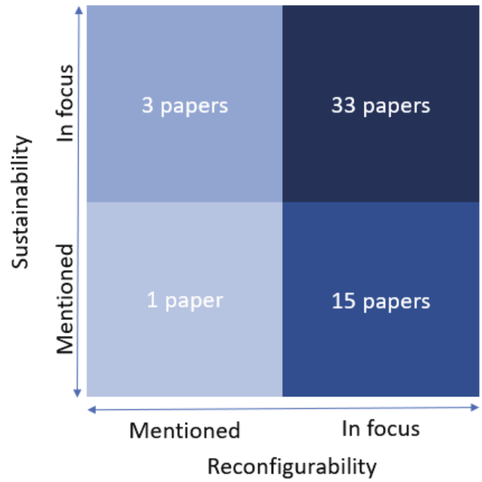

Figure 1. Sustainability and RMS matrix

The papers identified as belonging to the category of having both reconfigurability and sustainability in focus were included for the second categorization. A total of 33 papers were included for this stage. These papers were published between 2011-2021, whereas the majority was published in 2018 or later, as illustrated in Figure 2.

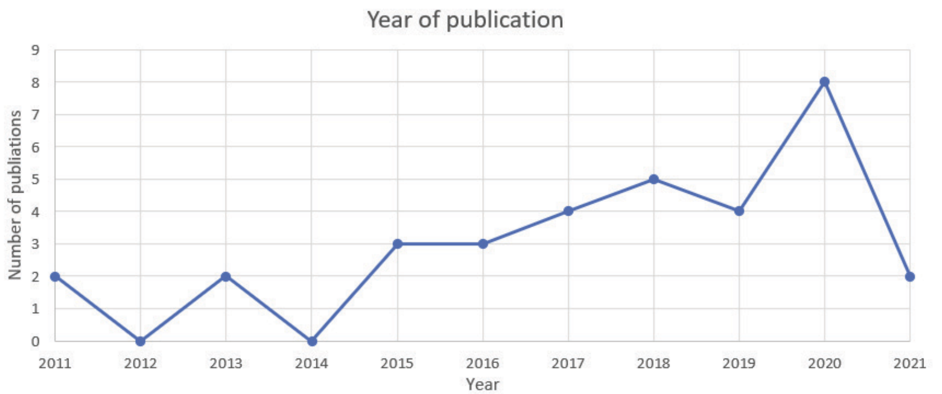

Figure 2. Year of publication summary

The 33 papers were categorized according to the three perspectives of the triple bottom line of sustainability, and specified which of the three categories they include, i.e. economic, environmental and social sustainability, see Table 1. The categorization was based on the papers having a clear connection to certain sustainability perspectives, either through an explicit statement or a clear focus in the full text.

Table 1. Sustainability breakdown

Author(s)	Year	Reference	Eco. sust.	Env. sust.	Soc. sust.
Bi	2011	[14]	✓	✓	
Ghani et al.	2011	[15]		✓	
Garbie	2013	[16]	✓		
Fasth-Berglund & Stahre	2013	[17]			✓
Copani & Rosa	2015	[18]	✓		
Peukert et al.	2015	[19]	✓	✓	✓
Barwood et al.	2015	[20]		✓	
Aljuneidi & Bulgak	2016	[21]	✓		
Ghanei & AlGeddawy	2016	[22]	✓	✓	
AlGeddawy & ElMaraghy	2016	[23]		✓	
Dubey et al.	2017	[24]		✓	
Badurdeen & Jawahir	2017	[25]	✓	✓	
Aljuneidi & Bulgak	2017	[26]		✓	
Lee et al.	2017	[27]	✓	✓	✓
Koren et al.	2018	[3]	✓	✓	✓
Huang et al.	2018	[28]	✓	✓	
Touzout & Benyoucef	2018	[29]	✓	✓	
Abdi et al.	2018	[30]	✓	✓	
Touzout et al.	2018	[31]	✓	✓	
Touzout & Benyoucef	2019	[32]	✓	✓	
Khezri et al.	2019	[33]		✓	
Tolio et al.	2019	[34]		✓	
Brunoe et al.	2019	[5]		✓	
Ghanei & AlGeddawy	2020	[35]	✓	✓	
Massimi et al.	2020	[36]		✓	
Paul et al.	2020	[37]	✓	✓	✓
Kurniadi & Ryu	2020	[38]	✓	✓	✓
Olabanji & Mpofu	2020	[39]	✓	✓	✓
Bockholt et al.	2020	[40]		✓	
Khezri et al.	2020	[4]		✓	
Massimi et al.	2020	[41]		✓	
Khettabi et al.	2021	[42]		✓	
Singh et al.	2021	[43]	✓	✓	

In total, 19 papers were found to have an economic sustainability perspective, 29 papers an environmental sustainability perspective and 7 papers a social sustainability perspective. Out of these papers, 6 papers were identified as taking all three sustainability perspectives into consideration. Below follows a further breakdown and explanation of each sustainability perspective.

4.1. Economic sustainability

In total, 19 of the reviewed papers included economic sustainability in their research. The majority of those papers are focusing on cost minimization, primarily through including it as an objective when designing and proposing novel models. These papers seem to have reconfigurability as a basis when developing the models, whereas the typical core characteristics of RMS are taken into consideration as a general concept. Hence, in these models it is seldom explicitly clarified which characteristics of RMS lead to economic sustainability, nor how they are connected. The common aim of the models proposed in these papers is to reduce costs, whereas it is found that if achieving this aim, an economic sustainability is fulfilled. The cost reduction is specified to certain areas, for instance maintenance [26,28,39,43], inventory [38,39], transportation [22,25,35], investment [21,43], manufacturing [19,29,31,38,39], and reconfiguration cost [22,26,29,31,32,35,39]. The latter can be recognized as a fairly exclusive cost for RMS, on the basis that this type of manufacturing system leads to more frequent system-, machine- and tool changes. Hence, costs related to the relocation, replacement, transfer and set-up of systems, machines and tools are recognized as important factors to include and reduce in order to achieve economic sustainability in RMS.

A few papers include the economic sustainability perspective on a more overarching level, whereas market presence [27], finding the ideal location [25], capacity usage [30], optimizing resource utilization [14,25] and ensuring high quality [3,18] are connected to conducted research on RMS and economic sustainability. For instance, Lee et al. [27] 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 & Jawahir [25] argued that future manufacturing systems must be flexible and scalable, whilst being beneficially located and having an optimal resource, method and tool utilization in order to achieve substantial cost reduction. In Abdi et al. [30], the possible optimization of capacity usage in RMS based on the idea of linking market, supplier and market perspectives is discussed. Koren et al. [3] found RMS as capable of enhancing economic sustainability performance in terms of e.g. cost reduction and improved product quality.

4.2. Environmental sustainability

In total, 29 of the reviewed papers included environmental sustainability in their research. A few areas were found to be prominent in several of these papers, for instance, circularity, water usage, greenhouse gases (GhGs), energy consumption, resource efficiency and hazardous waste.

Circularity in RMS has thus far primarily on adapting the RMS to fit in a remanufacturing practice (e.g. [5,26]). Likewise, Bockholt et al. [40] provided empirical insight through a case study 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. Moreover, Barwood et al. [20] converted the traditional setting where RMS works into an application in a recycling system. In their research, Barwood et al. [20] explored how a flexible robotic disassembly cell fits into the reconfigurable recycling system (RSS), and thus leads to environmental sustainability.

Water usage was foremost found to be included in novel models specifically designed for RMS. For instance, Lee et al. [27] developed a novel simulation model used to include sustainability factors in a self-reconfigurable manufacturing systems. In their research, water usage was used as a sustainability factor [27]. Huang et al. [28] developed a performance assessment model for sustainable reconfigurable manufacturing systems. The model consisted of several economic and environmental clusters, whereas water use and efficiency was one of these. In contrast, Koren et al. [3], found RMS as being capable of improving environmental sustainability by its ability to reduce water usage.

Emissions of greenhouse gases (GhGs) in relation to RMS were discussed in several papers. In some of these, GhGs were touched upon as a factor aimed at minimizing in the manufacturing system. One of these include Touzout et al. [31] who presented a hybrid multi-objective approach for creating a sustainable process plan. This approach was specifically designed for RMS, given its ability to quickly adapt to changes in the production. In their research, sustainability is taken into consideration in the shape of GhGs through having it set as one of the criterion alongside time and cost [31]. Similar works were conducted by [29,32].

Energy consumption, similar to GhGs, energy consumption was found to be a frequent topic in sustainability and RMS research. Several authors are including energy consumption as an important factor to reduce when developing models (e.g. [35,41,43]). For example, Ghani et al. [15] developed a conceptual approach used to minimize energy consumption through integrated monitoring systems in reconfigurable manufacturing systems. AlGeddawy & ElMaraghy [23] developed a design synthesis to enhance the energy sustainability in manufacturing systems. In their case study, a changeable assembly system was used in order to demonstrate and validate the synthesis. The authors found that by enhancing system design, the minimization of energy consumption is possible [23]. Khezri et al. [4] proposed a model used to integrate diagnosability, i.e. a core characteristic of RMS, into the system design in order to achieve sustainability. In their model, one of the objectives involves to minimize energy consumption and energy losses [4].

Resource efficiency was found by several researches to be achieved through the typical structure and characteristics of RMS. Regarding this, Bi et al. [14] found that in terms of sustainability, one of the key objective in RMS is to reduce waste, which is accomplished by reusing manufacturing resources and thus optimizing the resource efficiency. Similarly, Koren et al. [3] argued for the idea that modularity in a manufacturing system leads to an optimal resource efficiency by reducing the frequency of underutilizing resources. Dubey et al. [24] conducted empirical research on RMS and sustainability from a top management perspective. They concluded, for instance, 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 organization the higher their environmental performance is.*" [24, p.63], 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 RMS [24].

The hazardous waste is regarded similarly to the sustainability factors greenhouse gases and energy consumption, i.e. that it is foremost related to research aiming at minimization through adding it as a factor in models and programs (e.g. [41,42]). For instance, Khettabi et al. [42] developed a non-linear multi-objective program where four objective were minimized; 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 RMS design.

4.3. Social sustainability

In total, 7 of the reviewed papers included social sustainability in their research. Factors such as employee health and safety [3,17,27,39], training and education [25,27,39], and ethical and legal following [19,27,39] are recurrently discussed in multiple papers as having a connection to RMS. Some authors are describing social sustainability in an imprecise term and focus on the general factors which a production system can lead to, as for instance in Kurniadi & Ryu [38] where the ability to reconfigure a manufacturing system leads to the possibility to match requirements in terms of quantity and products to changing demands. Thereby they recognize that the ability to satisfy a societal need is achieved [38]. Koren et al. [3] found the merging of RMS and sustainable manufacturing to be necessary in order to achieve social sustainability. In their research, social sustainability in RMS regards employee health and safety. However, a detailed description how this is achieved is not provided.

Other authors, primarily those who develop novel models, seem to have a more detailed description of which social sustainability factors to include in order to achieve social sustainability in RMS. Nevertheless, amongst those authors there is no apparent commonality in what social sustainability includes, instead these definitions differ quite drastically. For instance, Peukert et al. [19] developed a model where social sustainability is included through adding the factor of performing a fair wage assessment. Olabanji & Mpofu [39] on the other hand, developed a novel sustainability assessment model for reconfigurable machines. In their model, a social indicator is taken into consideration where, for instance, operator training, required level of maintenance, patenting and usage regulation, ethical issues/responsibilities are included.

Direct connections between the core characteristics of RMS and social sustainability are seldom confirmed. One of the few authors studied in this literature who make a connection are Fasth-Berglund & Stahre [17] who in one of their case studies found that through mobility in a production system is it possible to reduce walking distance and head movements, leading to a socially sustainable workplace.

5. Discussion

Sustainability in RMS research is evidently an increasingly significant subject amongst researchers. In this literature review, the most common year of publication was 2020, followed by 2017/2018 and then 2019, as seen in Figure 2. However, even though there is an apparent increase in research interest, there is still little empirical data or insight supporting the claims that RMS are leading to sustainable manufacturing, even though the logical answer might indicate so. This correlates with one of the findings from this literature review which regards that a significant amount of the research on sustainability and RMS have added the perspective of sustainability through the inclusion of certain sustainability factors in novel models specifically designed for RMS. These papers are not coming to the conclusion that RMS lead to sustainable manufacturing, but rather that it is possible to include a sustainability perspective when designing, planning and controlling RMS. On the contrary, few authors are indeed arguing for the fact that sustainability and RMS have an inherent relationship [3,4,24]. Some authors ([44]) are even stressing that sustainability should be recognized as a core characteristic of RMS, 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 RMS 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 RMS research. This discrepancy has caused issues when trying to collectively describe the hitherto conducted research on RMS and sustainability. The lack of a common terminology might also cause further challenges in establishing the relationship between sustainability and RMS. This also leads to the problematic of quantifying sustainability in RMS remaining a difficult task, as highlighted by Paul et al. [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*".

Nevertheless, some frequently recurring areas within the environmental sustainability was found to be possible to identify and describe, these include; circularity, water usage, GhG emissions, energy consumption, resource efficiency and hazardous waste (see Figure 3). Identifying and describing these factors was possible primarily since the environmental sustainability is based on common factors frequently used in research and that are easily quantifiable. This might also derive from authors' preconceived notion that sustainability is solely an environmental matter, which might be the reason why the development towards a unified understanding of which environmental sustainability factors currently exists.

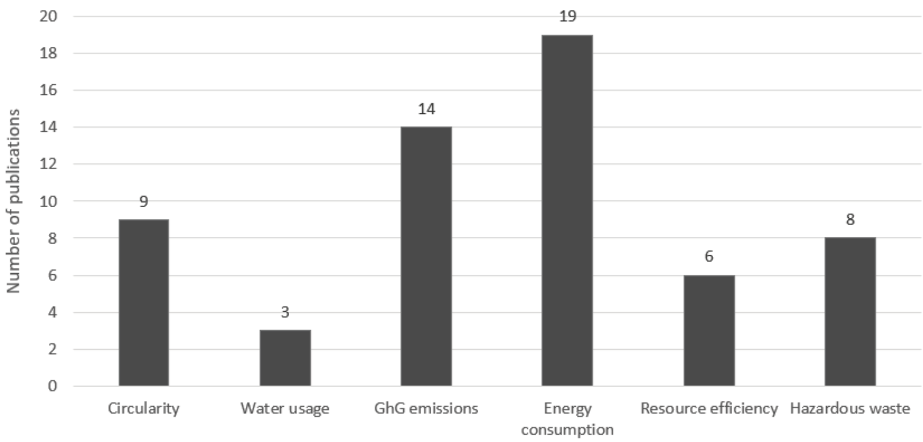

Figure 3. Environmental sustainability perspective breakdown

The majority of these papers are related to the decrease of energy consumption, primarily in terms of suggestions of models which have been adapted for sustainability by adding the objective of lowering energy consumption (e.g. [15,41,43]). A similar logic for adapting models for sustainability includes adding the objective of minimizing emissions of GhGs, apart from the tradition optimization objectives concerning cost and time (e.g. [29,31]). Frequently, models with predetermined objectives, e.g. Khettabi et al. [42], are presented as a solution for including a sustainability perspective in RMS research.

However, economic sustainability was found to be a term used without any clear definition connected to the usage of it. This forces a somewhat subjective analysis on whether these papers are actually discussing RMS and economic sustainability, or simply taking different costs into consideration and thus reckon economic sustainability as included. Regardless, as stated previously, only papers explicitly discussing economic sustainability were included in this literature review, and thus this should not be recognized as an issue. Nevertheless, the findings from this literature review indicate that most authors are focusing on cost reduction when discussing RMS and sustainability, with the argumentation that reducing costs leads to an economically sustainable enterprise. 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 factors.

Lastly, identifying and describing a common connection of how RMS lead to social sustainability has proven to be a far more challenging task compared to environmental sustainability. Most often, researchers are not clearly establishing a connection between social sustainability and RMS. For instance, many authors are solely describing general sustainability factors based on descriptions made by instances such as the global reporting initiative (e.g. [27]). These factors are often difficult to quantify, in comparison to the environmental and economic sustainability factors. Thus social sustainability is seldom included in novel models specifically designed for RMS, which many of the papers included in this literature review aim at developing. This might be one of the reasons why few researchers are focusing on this particular sustainability perspective.

6. Conclusions and future research

Even though there is an apparent increase in research interest, there is still few papers discussing how RMS lead to sustainable manufacturing. Reconfigurability has previously been identified as the solution to simultaneously being able to achieve high responsiveness and cost efficiency. However, today's manufacturing systems also need to be sustainable. This research was conducted in order to answer a research question regarding how sustainability has been considered in hitherto conducted RMS research. Thus far, a lot of the research on RMS and sustainability focus on adapting or developing models for RMS, as a means to achieve sustainable manufacturing. However, these do not conclude that RMS lead to sustainable manufacturing, nor do they draw any distinct connections between the areas.

Seldom are researchers establishing a triple bottom line approach when discussing sustainability in RMS. The lack of a triple bottom line approach is foremost caused by a missing focus on social sustainability. This might be deriving from challenges in quantifying the social sustainability, which is strengthened by the fact that many researchers are proposing novel models/tools which solely focus on economic and environmental sustainability. Therefore, further research on how social sustainability is supported by RMS is necessary, as a means to clarify how RMS leads to sustainability. This can, for instance, be achieved in terms of including the ergonomic consequences of having changeable and adjustable modules in the production system.

Moreover, there seems to be a general lack of common terminology when discussing economic, environmental, and social sustainability in relation to RMS. Few researchers are clearly defining sustainability, even more rarely do they draw direct connections and establish how RMS leads to sustainable manufacturing. Hence, according to the findings of this literature review, further research on investigating how RMS leads to sustainable manufacturing is needed. A possible way to achieve this might be to study the characteristics, i.e. the parts unique for RMS, and how they affect the possibility to achieve sustainable manufacturing. This has been tested to some degree in a few papers, but not to any greater extents. Further research is also needed on how RMS lead to the possible adaptation to a circular economy. Researchers have thus far primarily focused on the possibility of remanufacturing products in RMS, however, the adaptation of the RMS to a circular economy should also comprise of studying circularity in terms of how the systems themselves can e.g. be reused, refurbished and repaired in order to prolong their lifetimes and maximize resource utilization, thus aid in achieving sustainable manufacturing.

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