Towards human-centric reconfigurable manufacturing systems

Literature review of reconfigurability enablers for reduced reconfiguration effort and classification frameworks

Napoleone, Alessia; Andersen, Ann-Louise; Brunø, Thomas Ditlev; Nielsen, Kjeld

Published in:
Journal of Manufacturing Systems

DOI (link to publication from Publisher):
10.1016/j.jmsy.2022.12.014

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Napoleone, A., Andersen, A.-L., Brunø, T. D., & Nielsen, K. (2023). Towards human-centric reconfigurable manufacturing systems: Literature review of reconfigurability enablers for reduced reconfiguration effort and classification frameworks. *Journal of Manufacturing Systems*, *67*, 23-34. https://doi.org/10.1016/j.jmsy.2022.12.014

Journal of Manufacturing Systems 67 (2023) 23–34

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Towards human-centric reconfigurable manufacturing systems: Literature review of reconfigurability enablers for reduced reconfiguration effort and classification frameworks

Alessia Napoleone *, Ann-Louise Andersen, Thomas Ditlev Brunoe, Kjeld Nielsen

Department of Materials and Production, Aalborg University, Denmark

A R T I C L E I N F O

Keywords:
Changeable manufacturing
Reconfigurable manufacturing system
Industry 4.0
Cyber-physical system
Operator 4.0

A B S T R A C T

The unpredictable market scenario in the manufacturing industry demands the adoption of reconfigurability enablers. These enablers reduce the reconfiguration effort throughout the system life cycle and allow frequent reconfigurations of the manufacturing system. Despite the relevance of the subject, examples and concepts of reconfigurability enablers are fragmented in literature. Therefore, this study systematically reviews literature in order to: (i) outline the state of the art on reconfigurability enablers in automated, mixed and manual systems; and, (ii) provides classification frameworks for reconfigurability enablers for manufacturing systems, machines, robots, material handling systems, and operators. Additionally, new reconfigurability enablers related to Industry 4.0 are outlined, which connect systems and human resources with different roles and facilitate responsive adaptation of humans to changes. Directions for future research include extending the theory on reconfigurable manufacturing with fundamentals of human-centric automation and operationalising the proposed classification framework.

1. Introduction

The manufacturing industry faces high unpredictability of market requirements and a continuous shortening of products' life cycles [1]. To secure responsiveness and competitiveness, manufacturers should develop the reconfigurability capability [2–4]. Reconfigurable Manufacturing Systems (RMSs) are capable of adopting different configurations by repeatedly changing or rearranging their components in a cost-effective way, in order to quickly respond to both predicted and unpredicted market changes [5,6]. RMSs have the capability to quickly adjust both production capacity and functionality to accommodate evolving market requirements [7,8].

RMSs have been historically considered as automated systems with minimized human presence, presupposing the presence of modular machine tools, with standard hardware and software interfaces making them integrable with each other and with new technologies' introductions [7,9]. More recently, reconfigurability has been addressed as a multi-dimensional capability, which can be designed and implemented recurring to multiple reconfigurability enablers that should be selected based on context-specific systems' features [10–13].

To this regard, the Industry 4.0 paradigm, often associated with the development of Cyber-Physical Manufacturing Systems or Smart factories, brings "cyber" or logical enablers which complement and enhance "physical" systems [14–16]. Industry 4.0 has also paved the way to the concept of "human-centricity", where the human presence and well-being in the factories of the future should be seen as prerequisite to increase competitiveness and reconfigurability [17,18]. The literature linked to the Industry 4.0 paradigm provides relevant insights regarding human operators, their relevance and interactions with other "smart" resources, such as machines, robots and material handling systems [19,20]. However, this growing research stream does not primarily focus on how these smart resources allow to develop the reconfigurability capability in manufacturing. From the RMS context, existing literature does not primarily focus on how Industry 4.0 affects the reconfiguration effort and enables frequent reconfigurations.

Thus, even though reconfigurability enablers are gaining increasing attention in literature, examples and concepts of reconfigurability enablers are fragmented. To the best of the authors' knowledge, there is no contribution that comprehensively and exhaustively outlines and classifies the enablers for systems, machines, robots, material handling

Abbreviations: RMS, Reconfigurable Manufacturing System.

* Correspondence to: Department of Materials and Production, Aalborg University, Fibigerstraede 16, Aalborg 9220, Denmark.
E-mail address: alessianapo@hotmail.it (A. Napoleone).

https://doi.org/10.1016/j.jmsy.2022.12.014
Received 27 June 2022; Received in revised form 15 November 2022; Accepted 30 December 2022
Available online 10 January 2023

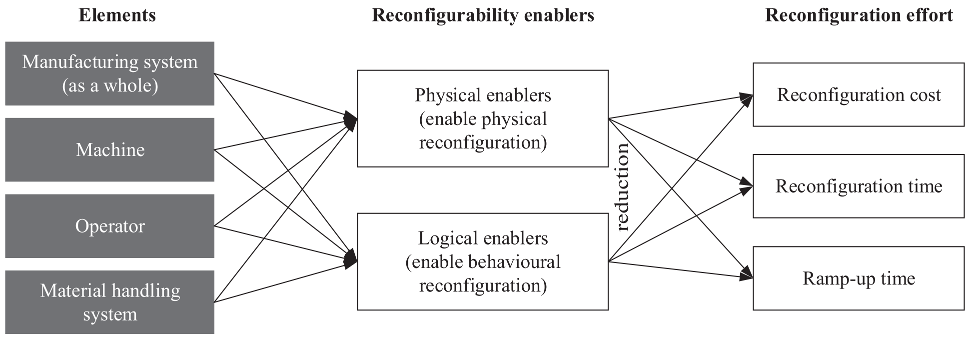

Fig. 1. Physical and logical enablers of the manufacturing system's reconfigurability.

systems and operators.

Considering both (i) the relatively recent scientific interest for reconfigurability as a multi-dimensional capability supported by different enablers, and (ii) the Industry 4.0 paradigm potentially making new reconfigurability enablers available, this study aims to: (i) investigate the state of the art on enablers for reduction of the reconfiguration effort in automated, mixed and manual manufacturing systems; and (ii) outline the reconfigurability enablers for manufacturing systems, machines, robots, material handling systems, and operators and provide classification frameworks relevant for both academics and practitioners.

Specifically, the following research questions (RQs) are addressed:

RQ1.. What is the state of the art on enablers for reduction of the reconfiguration effort in automated, mixed, and manual manufacturing systems?

RQ2.. How can reconfigurability enablers for manufacturing systems, machines, robots, material handling systems, and operators be classified in frameworks relevant for academics and practitioners?

The remainder of the paper is structured as follows. Section 2 introduces the concept of reconfigurability enablers. Section 3 describes the adopted methodology for addressing the RQs. Sections 4 and 5 present the results of this study; specifically, Section 4 answers RQ1 and provides the state of the art on enablers for reduction of the reconfiguration effort in automated, mixed and manual systems; Section 5 answers RQ2 and provides multiple classification frameworks for reconfigurability enablers for systems, machines, robots, material handling systems and operators. Section 6 details the relevance of this study for academics and practitioners. Lastly, Section 7 concludes and provides directions for further research.

2. Enablers for reduction of the reconfiguration effort

In this study, the term reconfigurability "enabler" has been used to categorize any means to reduce the reconfiguration effort during a reconfiguration of the manufacturing system throughout its life cycle [21,22]. The reconfiguration effort has three components [23,24]:

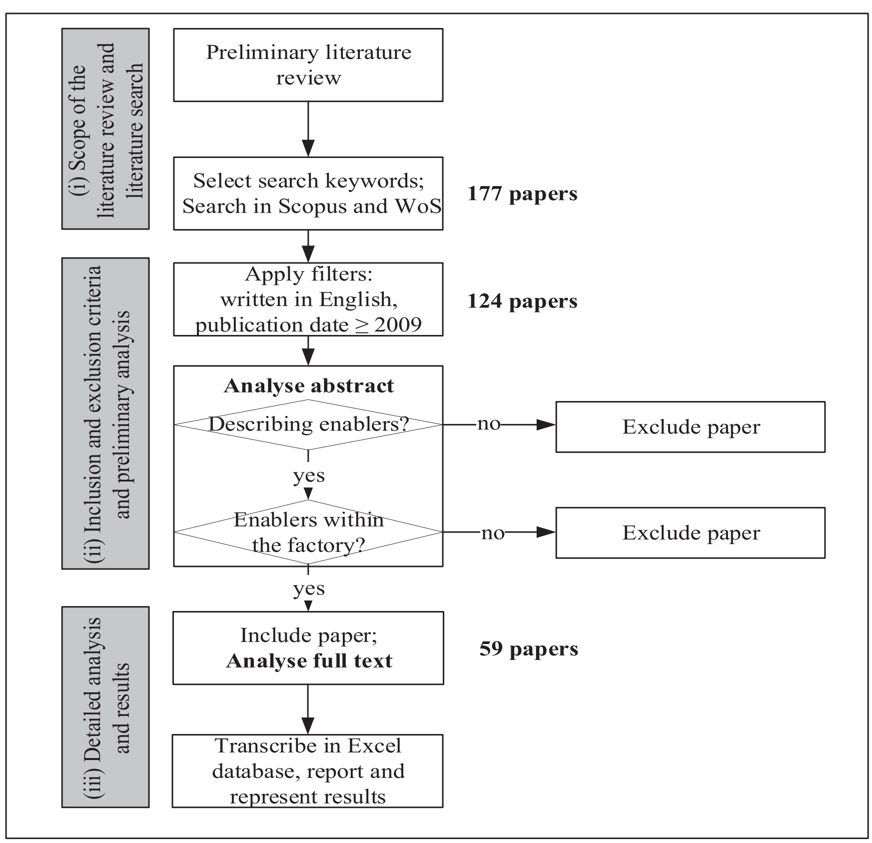

Fig. 2. Literature review process.

- the reconfiguration time, meaning the time incurred to reconfigure the system
- the reconfiguration cost, meaning the cost incurred to reconfigure the system
- the ramp-up time, meaning the time taken by the system after reconfiguration to reach a normal production state at required quality and production rate.

At the beginning of a system life cycle, reconfigurability enablers might be partially or completely absent. The latter includes the case of greenfield projects. Therefore, the effort required for a reconfiguration may be significant. Throughout the manufacturing system life cycle, the gradual acquisition of reconfigurability enablers, such as the development of modular machine tools, progressively reduces the reconfiguration effort required for subsequent reconfigurations.

Manufacturing systems encompass both physical and logical aspects [16]. Physical aspects tangibly act on the manufactured output, these are machines, robots, operators and material handling systems contributing to transform raw materials into finished products [25]. Logical aspects drive the behaviour of physical aspects, these are information flows, control systems, human-machine interfaces, and software applications [26]. Accordingly, reconfigurability enablers can be classified in: (i) physical, i.e. enabling physical reconfiguration and (ii) logical, i.e. enabling behavioural reconfiguration of the elements of the manufacturing system [27,28]. In relation to the research questions, this distinction is relevant for two reasons: first, because automated, mixed and manual manufacturing systems may need different physical and logical enablers; second, because logical enablers are particularly affected by the Industry 4.0 paradigm and are expected to affect the modes operators perform their activities. Fig. 1 provides a representation of physical and logical enablers in connection with the elements of the manufacturing system and to their effect on the reconfiguration effort.

As mentioned in Section 1, reducing the reconfiguration effort is relevant for manufacturers today, since it enables rapid, cost-effective and frequent reconfigurations when facing evolving requirements, thus securing responsiveness and competitiveness in the current context [24,29]. For this reason, the concept of enablers is gaining increasing attention in literature [13,30–32]. However, to the best of the authors' knowledge, a comprehensive overview of the reconfigurability enablers is still missing.

3. Literature review method

The literature review method was deemed appropriate for the conducted study, since a comprehensive overview of reconfigurability enablers allows consolidating and further developing knowledge about reconfigurability enablers [33].

Thus, in order to collect examples and concepts of enablers for reduction of the reconfiguration effort, a structured literature review was conducted [34]. The literature review protocol is described in the following three steps: (i) scope of the literature review and literature search; (ii) inclusion and exclusion criteria and preliminary analysis, and (iii) detailed analysis and results of the literature review.

The overall literature review process is summarized in the following Fig. 2 and detailed below.

In step one, the background theory was explored, based on a preliminary literature review, and the goal of the review was defined. To find academically relevant papers, the search databases used for the investigation were Scopus and Web of Science. To ensure the collection of any existing examples and concepts of enablers for reduction of the reconfiguration effort, the following search string was used:

'manufacturing' AND ('reconfiguration effort' OR 'reconfiguration cost' OR. 'reconfiguration time' OR 'ramp-up time').

This search string was searched in articles titles, abstracts, and keywords.

The selected string scoped the search within the manufacturing domain and ensured an adequately wide scope of investigation. Furthermore, setting this wide scope ensured the identification of reconfigurability enablers related to the Industry 4.0 paradigm.

In step two, the pertinent literature was selected by applying the following inclusion and exclusion criteria to the identified sample. To ensure the high impact of the selected articles in terms of readership, only articles written in English language were reviewed. To ensure reliability and validity of the findings, only scientific articles were considered, thus excluding trade journals and magazines. Finally, only articles published after 2009 were reviewed, because Industry 4.0 - in literature often interchangeably referred as Cyber-Physical Production or Smart Manufacturing - has gained increasing interest in literature since the beginning of the 2010 s. This was preliminarily assessed with a search of the following search string in Scopus and Web of Science:

"Industry 4.0" AND "Cyber-Physical Production" AND "Smart Manufacturing".

The search showed an exponential growth in related research articles after 2009. By applying the aforementioned inclusion and exclusion criteria, a set of 124 pertinent articles was initially identified. The search is updated to October 2022.

A preliminary analysis of the abstracts led to the selection of 59 articles describing how the reconfigurability capability reduces the reconfiguration effort. To retain the focus within the factory domain, literature focusing on enablers of reconfigurability at network and supply chain level was not considered.

In step three, a detailed analysis of the full text of the 59 articles was conducted. The identified enablers were transcribed and analysed in an Excel database and the results of the study were outlined.

During the detailed analysis, multiple classifications of enablers were made, according to: (i) the level of the enabler and referred element of the factory, (ii) the nature of the enabler, and (iii) the effect of the enabler on the reconfiguration effort, as explained below.

i. Level of the enabler and referred element of the factory. Part of the identified enablers was at system level, since these enablers included at least one interrelation between one or more individual elements of the factory, meaning machine, robot, material handling system, operator, and in fewer cases product. This information, together with the referred elements of the factory, were reported in the Excel database. For the remaining enablers (i.e., those not at system level), only the information about referred element of the factory was reported in Excel.
ii. Nature of the enablers. According to the criteria described in Section 2 and summarized in Fig. 1, all the identified enablers were additionally classified in physical and logical ones, enabling physical and behavioural reconfiguration, respectively. This information was reported in the Excel database.
iii. Effect of the enabler on the reconfiguration effort. Finally, the affected components of the reconfiguration effort – namely, the reconfiguration time, the reconfiguration cost, the ramp-up time, or any combination of these three - were specified in the Excel database as stated in literature.

Additionally, in this step, it was observed that literature referred to reconfigurability enablers with different levels of detail, meaning that some studies provided broad descriptions, some others provided specific details. These descriptions were transcribed in Excel and further analysed at a later time aiming to combine related descriptions, based on the aforementioned (i), (ii) and (iii).

The results of the conducted literature review, detailed in Sections 4

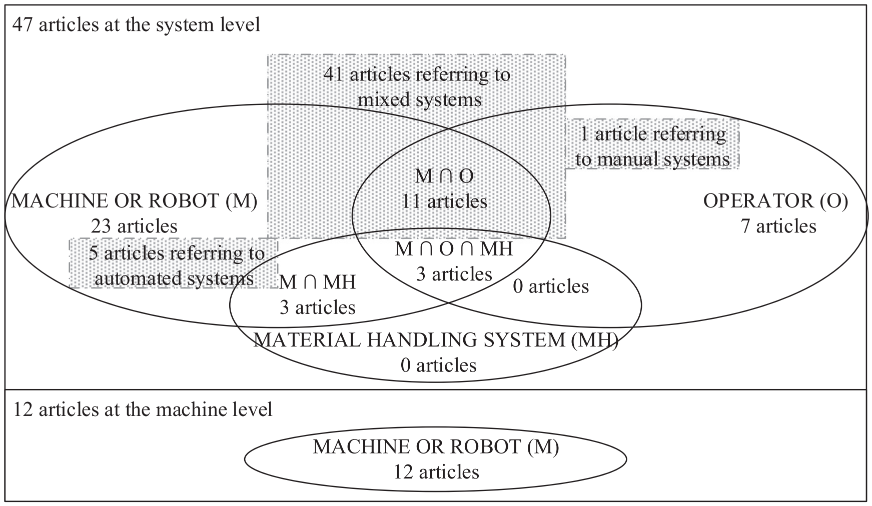

Fig. 3. The analysed sample of literature based on level of the enabler and referred element of the factory.

and 5, consist of the state of the art on reconfigurability enablers in automated, mixed, and manual manufacturing systems and of multiple classification frameworks. Specifically, Section 4 summarizes the sample of literature according to: (i) the level of the enabler and referred element of the factory; and (ii) the nature of the enablers. Section 5 describes in detail (i) and (ii), also considering (iii), i.e., the effects of the enablers on the reconfiguration effort, thus providing comprehensive classification frameworks of the physical and logical enablers for reduction of the reconfiguration effort for manufacturing systems, machines, robots, material handling systems and operators.

4. State of the art on reconfigurability enablers for automated, mixed and manual systems

When classifying the literature sample of 59 articles according to the level of the enabler and referred element of the factory, it was observed that, 47 articles addressed enablers for reduction of the reconfiguration effort at system level (79.7 % of the sample) and 12 at workstation level (20.3 % of the sample). None of the articles at workstation level referred to enablers related to operators; therefore, in the remainder the workstation level has been also indicated as machine level. A summary of the analysed sample based on level of the enabler and referred element of the factory is provided in the following Fig. 3.

Among the 47 articles at system level, the following types of manufacturing systems were considered:

- automated systems, meaning systems with minimum human intervention, in 5 articles (corresponding to the 8.5 % of the sample);
- mixed systems, meaning systems with a combination of machining, robotic and manual operations, in 41 articles (69.5 % of the sample);
- manual systems in 1 article (1.7 % of the sample).

Regarding the referred elements of the factory, the 59 articles were classified as follows:

- 35 articles (59.3 % of the sample) referred to enablers supporting the machine or the robot, in case of robotic operations; specifically, 23 analysed them also at system level, and the remaining considered them only at workstation level.
- 7 articles (11.9 % of the sample) referred to enablers supporting the operator.
- the remaining 17 articles (28.8 % of the sample) referred to enablers supporting more elements of the factory - thus at system level - as also detailed in the Fig. 3. Specifically: 3 articles addressed enablers for all types of elements of the factory, 11 articles addressed enablers for the machine and the operator, and 3 articles addressed enablers for the machine and the material handling system.

The following Table 1 completes the aforementioned information with information about the nature of the identified enablers since it reports the number and percentage of articles addressing physical and logical enablers at system and machine levels; and provides the references of the articles that were found to be relevant for the classifications.

Moreover, in alignment with the objective of the study, in case of mixed systems, Table 1 specifies whether the identified enablers mainly support: (i) the machine, (ii) both the machine and the operator or (iii) the operator. It can be observed that logical enablers are particularly relevant not only to create increasingly automated manufacturing systems, but also to support operators' adaptability to new requirements. This is further discussed in Section 5.4.

Table 1
Literature addressing physical and logical enablers in automated, mixed, and manual manufacturing systems.

	Manufacturing system level										Machine level	
	Automated		Mixed (mainly related to machine)		Mixed (mainly related to both operator and machine)		Mixed (mainly related to operator)		Manual			
	5 papers – 8.5 % of the sample		41 papers – 69.5 % of the sample						1 paper – 1.7% of the sample			
	Physical	Logical	Physical	Logical	Physical	Logical	Physical	Logical	Physical	Logical	Physical	Logical
# of papers	3	5	18	11	6	14	1	6	0	1	5	6
% in the group	60 %	100 %	85,7 %	52,4 %	42,9 %	100 %	17 %	100 %	0 %	100 %	41,7 %	50 %
References	[35–39]		[35–55]		[56–69]		[75–80]		[81]		[77–88]	
			[40–60]									
					[61–74]						[83–93]	

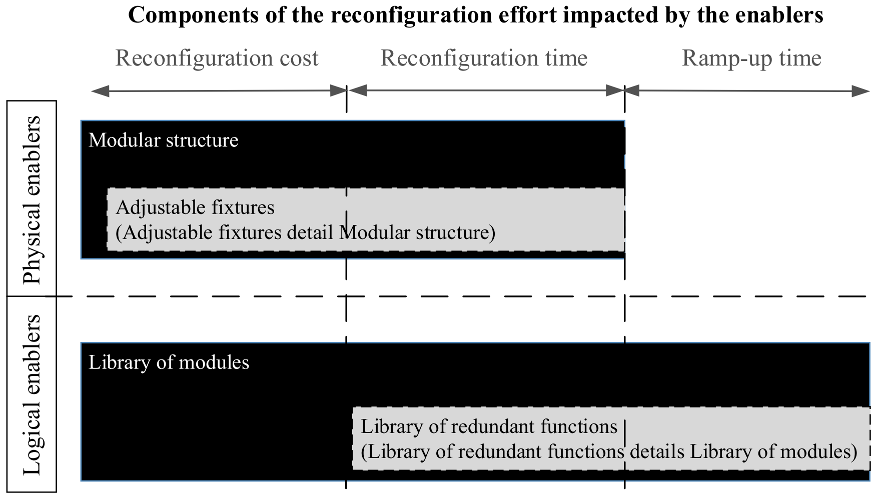

Fig. 4. Classification frameworks – mapping logic for the reconfigurability enablers.

5. Classification frameworks for reconfigurability enablers for manufacturing systems, machines, robots, material handling systems, and operators

In the following subsections, classification frameworks are provided for each element of the factory, completing, and detailing the information provided in Section 4 with the affected components of the reconfiguration effort for each physical and logical enabler. Thus, the classification frameworks refer to: (i) the manufacturing system, (ii) the machine, including the case of the robot, (iii) the operator and, (iv) the material handling system.

Fig. 4 illustrates - with an example referred to the machine - the mapping logic adopted in the classification frameworks. In each framework, physical and logical enablers were identified, and the affected components of the reconfiguration effort were indicated. For instance, in Fig. 4 the logical enabler “library of redundant functions” allows a reduction of reconfiguration time and ramp-up time.

Moreover, since the analysed literature referred to reconfigurability enablers with different levels of detail – meaning that some studies provided broad descriptions, some others provided specific details – the provided classification frameworks combine broad and detailed enablers, thus enriching the descriptions of the enablers identified in the literature review. For example, in Fig. 4 the “adjustable fixtures” detail the physical enabler “modular structure”.

5.1. Enablers for the manufacturing system

The physical and logical enablers for the manufacturing system are described in the following Sections 5.1.1 and 5.1.2, respectively. The summary of the results is provided in Section 5.1.3.

5.1.1. Physical enablers

The reusability of machines or operators’ skills reduces the reconfiguration cost [50,80,94], whenever relevant operations are standardized and modularized, these can be synergistically be reused across manufacturing systems.

The adjustable level of automation allows a reduction of all three components of the reconfiguration effort [40,95]. Whenever the system can easily increase or decrease the level of automation, it enables utilizing either manual, mixed or automated solutions depending on needed adaptability and production rates, thus reducing the reconfiguration effort.

The adjustable layout and positioning of machines [42,43,47,69] reduces all three components of the reconfiguration effort. This is also supported by the possibility to use alternative process routings, which specifically reduces the ramp-up time after reconfigurations or after unexpected reconfigurations [53,65,73]. The use of alternative process routings depends on the flexibility of processing sequences for specific products, but also on the specific adjustability of handling systems as outlined in Section 5.3.

Mobility - i.e., the ability to easily move major components [40] -, light weight [55], and low space occupation [40,68,88] of machines are all enablers for reduction of reconfiguration cost and time.

In an adjustable cellular layout, the layout and positioning of machines are designed around a specific product family, thus reducing all three components of the reconfiguration effort [45,48,52,56].

5.1.2. Logical enablers

Logical enablers for the manufacturing system connect the system with human resources with different roles and positions, including operators, operations managers, product, and production experts. This empowers human resources in their adaptation to changes.

The formation of virtual cells allows an adjustable cellular layout [63] and reduces the reconfiguration effort since this does not require physical changes to the system. Virtual cells require a capability-based view of the manufacturing system, where the capability boundaries and the operations of each machine are known, formalized and shared. These information are usually not provided or partially provided in traditional contexts, but they are part of the foundations in a digitalized manufacturing system [96].

The redundancy of functionalities within the system [58,65,97] reduces both the reconfiguration time and the ramp-up time, nonetheless this leads to the under-utilization of resources [49,55], which contributes to reduce the ramp-up time, but increases the reconfiguration cost. To avoid resources’ underutilization, redundant functionalities should be virtually available in libraries and made physically available only when required; this is detailed in Section 5.2.2.

Supporting product and production experts in ensuring the co-evolution of products and manufacturing systems is a relevant requirement to reduce the reconfiguration effort, to improve the utility of manufacturing resources and prolong the life cycle of manufacturing systems [98]. To this end, with the Internet of Things, product and production experts can work in a connected environment, based on expected market evolution, thus reducing the three components of the reconfiguration effort [36,59,64]. Specifically, the digital availability of information about market evolution [47], together with the digital twin of the product [71], the digital twin of the manufacturing system [66] and the use of human-machine interfaces [89] reduce all components of the reconfiguration effort. In digital environments, it is possible to simultaneously design product and processes with low effort [35,62].

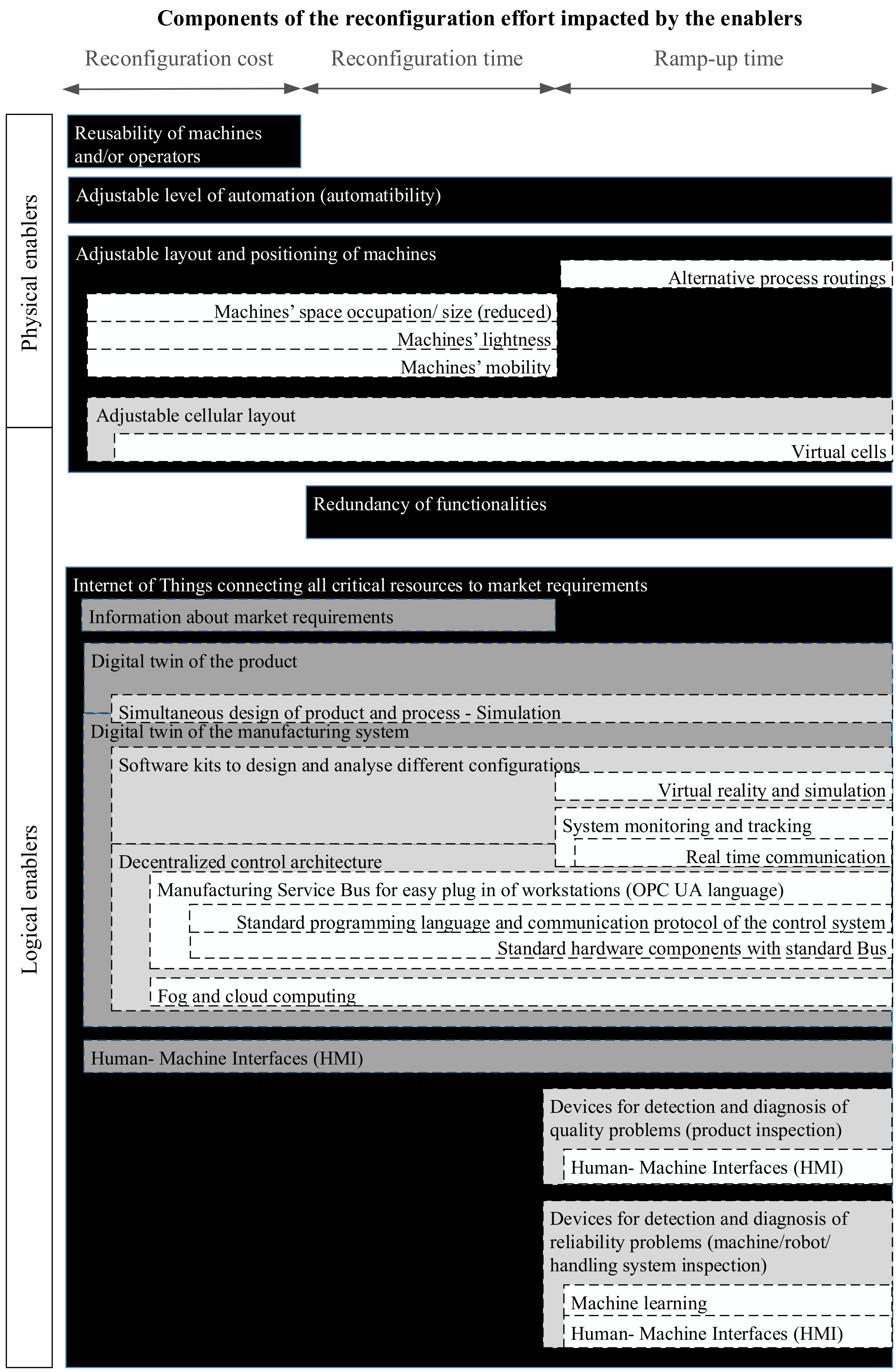

Fig. 5. Reconfigurability enablers for the manufacturing system.

Moreover, human-machine interfaces support the dynamic acquisition of context-related information [61]. The digital twin of the manufacturing system should include software kits to design and analyse different configurations [85] to reduce all components of the reconfiguration effort. When designing and analysing different configuration, virtual reality and simulation reduce the ramp-up time [78]. Moreover, monitoring and resources' tracking systems [36,66,91] allow reducing the ramp-up time, especially thanks to the possibility to exchange real-time information about the correct execution of operations in a standardized way [85].

The development of a decentralized control architecture reduces all components of the reconfiguration effort [37,90]. In this architecture, manufacturing service busses – which implement automatic discovery functionality and a common standard for skills – allow easy plug-in of workstations [38]. To this end, standard programming language and communication protocol of the control system [44], as well as standard hardware components with standard bus [85] reduce the reconfiguration effort. In addition, a decentralized control architecture can leverage on fog and cloud computing [72,90].

Relevant information about the products are collected with the

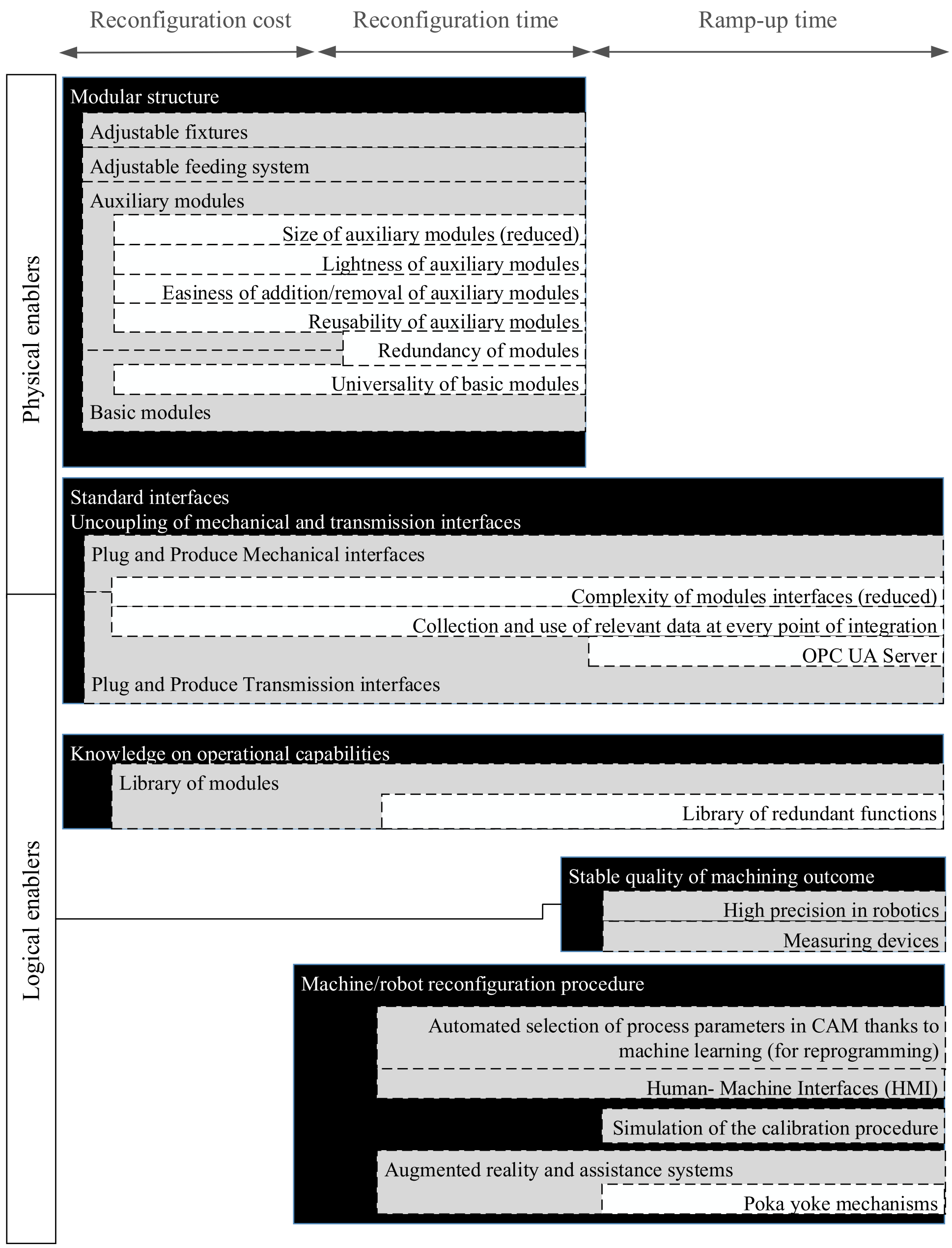

Fig. 6. Reconfigurability enablers for the machine and the robot.

inspection of products at different quality gates along the manufacturing processes [69]; the use of connected devices for detection and diagnosis of quality problems ensures the required quality of products and reduces the ramp-up time [95]. To this end, human-machine interfaces allow the exchange of feedback related to quality problems, thus empowering operators, or operations managers. The inspection may be performed by inspection machines, or operators; in these cases, related enablers are detailed in Sections 5.2 and 5.4, respectively.

To reduce the ramp-up time, relevant information about the manufacturing system can be collected with devices for detection and diagnosis of reliability problems [95]; this is facilitated by the implementation of machine learning algorithms [75], for example to automatically activate machines' reactions when a problem is detected or to identify alternative machines during the ramp-up. Human-machine interfaces can be used to report detected and diagnosed problems, allowing operations managers to take the right decisions [89].

5.1.3. *Summary*

The classification framework for the enablers for the manufacturing system is shown in Fig. 5.

5.2. *Enablers for the machine and the robot*

The same enablers were identified for both machines and robots. For the sake of simplicity, the following sections only refer to machines. Specifically, the physical and logical enablers are described in Sections 5.2.1 and 5.2.2, respectively; and the summary of the results is provided in Section 5.2.3.

5.2.1. *Physical enablers*

As traditionally pointed out by researchers, machines with a modular structure ensure a reduction of reconfiguration cost and time [51,82, 93]. To this end, the structure should be: (i) designed to ensure the right granularity of modules – meaning that the optimal decomposition of machines should be identified [57,88]; (ii) designed to reduce

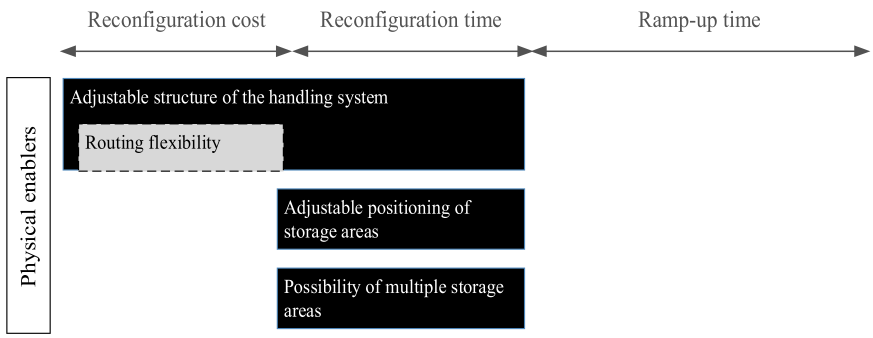

Fig. 7. Reconfigurability enablers for the material handling system.

under-utilization and space occupation of machines; and (iii) designed to allow use of the same machines in different configurations [84,85]. In general, the use of design methodologies such as the Modular Function Deployment, based on the assessment of module drivers thus considering product evolution over time, supports practitioners to develop the right extent of machine's modularity and reduces reconfiguration cost and time. For example, whenever the analysis of product evolution leads to modularity requirements at tool level – thus implying high granularity of modules -, adjustable fixtures [92], or adjustable feeding systems [39,84] can be used to accommodate different sizes of specific parts of the manufactured product.

In a modular structure, to ensure low reconfiguration cost and time, the main modules should be classified in: basic modules, which are universal [85]; and auxiliary modules, which are reusable [88]. Auxiliary modules should possibly be easy to add or remove [54], with reasonably reduced size [49] and weight [54]. Basic modules accommodate shared requirements; these are used for the most frequent operations given product variety and product evolution. Conversely, auxiliary modules accommodate variant-specific requirements.

To reduce all components of the reconfiguration effort, adequately standard interfaces between modules [41] and uncoupled mechanical and transmission interfaces [88] can be used. Plug and produce mechanical interfaces, developed with methods – such as entropy – to measure and reduce the complexity of interfaces can support the assembly and disassembly of modules in the (re)configuration processes [59].

5.2.2. Logical enablers

Plug-and-produce transmission interfaces allow a reduction of the three components of the reconfiguration effort [38,84,88]. With the Industry 4.0 paradigm, transmission interfaces can ensure the collection and use of relevant data at every point of integration [64]; moreover, the use of OPC UA Server can reduce the ramp-up after reconfigurations [38] since it allows easy plug-in of workstations at system level, as also mentioned in Section 5.1.2.

Digitally available operational capabilities can reduce the reconfiguration cost, time and ramp-up time [87,96]. A digital library of modules, recording also unavailable modules, additionally reduces the ramp-up after reconfigurations, other than the reconfiguration cost and time [87]. To this end, a library of redundant functions, reduces the ramp-up time [88] and the reconfiguration time, as also mentioned in Section 5.1.2.

Ensuring a stable quality of the machining output [84] - eventually relying on high precision in robotics [93] and the use of measuring devices [93] - reduces the ramp-up time after reconfigurations.

Machine reconfigurations procedures might be automated or require the intervention of the operator. To reduce both reconfiguration and ramp-up times, the reprogramming of machines can rely on machine learning algorithms to allow the automatic selection of process parameters [83]; alternatively, human-machine interfaces [80] support operators. The ramp-up time is also reduced with tools for the simulation of the calibration procedure [93]. Finally, the application of assistance systems reduces reconfiguration time and ramp-up time in case of reconfigurations requiring the intervention of the operator [80]; and the implementation of poka-yoke mechanisms reduces the ramp-up time [68].

5.2.3. Summary

The classification framework for the enablers for the machine and the robot is shown in the following Fig. 6.

5.3. Enablers for the material handling system

The adjustable structure of material handling systems [68,73] reduces the reconfiguration cost and time. Moreover, routing flexibility [58,73] reduces the reconfiguration cost.

The adjustable positioning of storage areas [47] and the use of multiple storage areas [47] reduce the reconfiguration time.

The classification framework for the enablers for the material handling system is shown in the following Fig. 7.

5.4. Enablers for the operator

Reconfigurability enablers related to the operator have been less investigated in previous literature compared to the enablers related to the machine. Nonetheless, recent literature outlines that operators benefit from the use of logical enablers since the application of digital technologies complements and enhances operators' skills and versatility.

Developing plug and produce skills reduces all components of the reconfiguration effort [38,80]. Additionally, the similarity of tasks [77] and the understanding of tasks [79] support this enabler. The versatility of operators specifically contributes to the reduction of the reconfiguration time [63,95], whereas the mobility of operators [50,58], which depends on their individual attitude, contributes to the reduction of both the reconfiguration cost and time.

Several logical enablers allow developing plug and produce skills and, to benefit from these enablers, the presence of human-machine interfaces - or, in the case of manual operations, interfaces with Information Systems - is required [61,80]. Digital guidance throughout tasks execution - by means of augmented reality and assistance systems - supports the adaptation to new requirements [81]. The use of poka-yoke mechanisms [79,81] and the reuse of the capitalized operators' experience [80] are additionally relevant to guide operators throughout the execution of tasks. In order to provide operators with all relevant information, logical enablers need to ensure: (i) the dynamic acquisition of context-related information [61,81], and (ii) the acquisition of operators' experience [61], these data and information need to be combined with machine learning algorithms [80].

Ensuring stable quality during the execution of tasks reduces the ramp-up time [77,84]. This enabler benefits from all aforementioned logical enablers, and from specific features of the operators' training

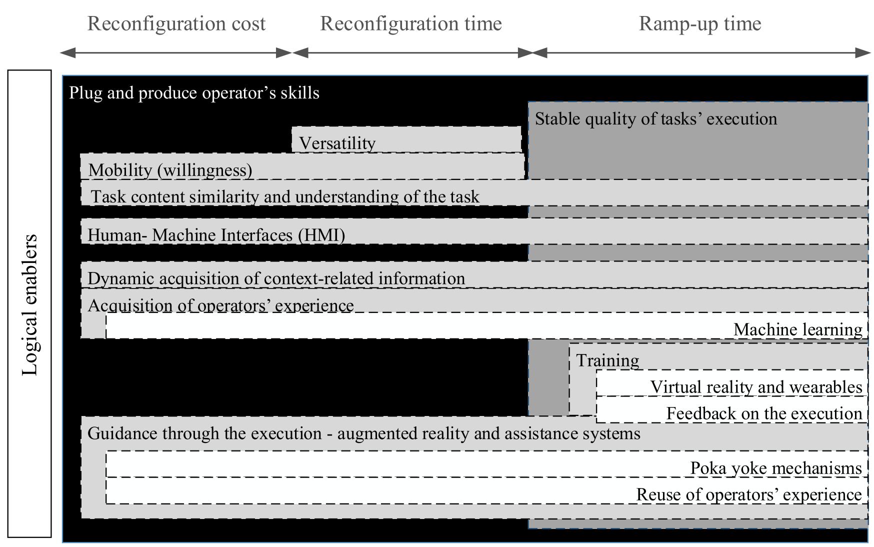

Fig. 8. Reconfigurability enablers for the operator.

process [67,73,81]. The training process allows operators to adapt to new tasks, and it can be supported by two logical enablers: virtual reality [79,81] and the provision of digital feedback during the execution of tasks [76].

The classification framework for the enablers for the operator is shown in the following Fig. 8.

6. Discussion

The scientific interest in reconfigurability as a multi-dimensional capability supported by different enablers is increasing, as well as research on the Industry 4.0 paradigm making new reconfigurability enablers available. Therefore, this study framed and combined fragmented research efforts and provided comprehensive frameworks to consolidate and further develop the knowledge about reconfigurability enablers.

The conducted literature review provided the state of the art on reconfigurability enablers for reduction of the reconfiguration effort in automated, mixed, and manual systems (RQ1) and classification frameworks for the reconfigurability enablers for systems, machines, robots, material handling systems, and operators relevant for research and industry (RQ2).

The following sections outline the relevance of this research for academics and practitioners, as well as the limitations of this study.

6.1. Relevance for academics

Addressing RQ1, the state of the art on reconfigurability enablers for reduction of the reconfiguration effort in automated, mixed, and manual manufacturing systems was provided. While enablers of reconfigurability are discussed in previous research as important elements during system design [99], this paper provides the first comprehensive overview of these. The identified enablers were then classified in physical and logical enablers, facilitating physical and behavioural reconfigurations respectively. It was observed that logical enablers are particularly relevant not only to create increasingly automated manufacturing systems, but also to support human resources' adaptability to new requirements. To this end, it was also shown that reconfigurability enablers for operators deserve further research.

Addressing RQ2, classification frameworks for the reconfigurability enablers for manufacturing systems, machines, robots, material handling systems, and operators were provided. The provided classification frameworks are deemed relevant to researchers addressing reconfigurability as a multi-dimensional capability supported by different enablers. For example, the overview of reconfigurability enablers may support academics addressing specific technical systems in the study of interactions of technical systems with the other components of complex systems, or academics interested in the managerial implications of complex systems.

The classification frameworks also outlines new reconfigurability enablers related to Industry 4.0. As detailed in Section 5, manufacturing systems, human resources in general (in Section 5.1) and operators (in Section 5.4) are particularly affected by those logical enablers related to Industry 4.0. Specifically, logical enablers for the manufacturing system connect the system with humans with different roles and positions, such as operators, operations managers, product, and production experts and

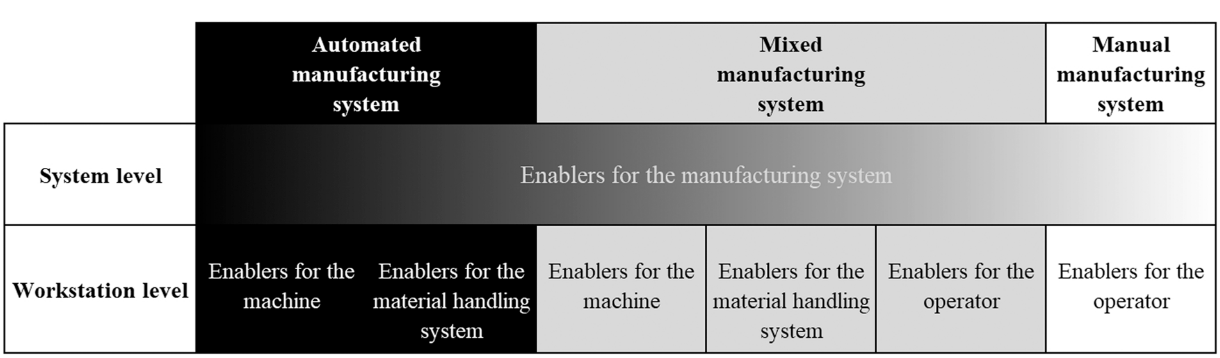

Fig. 9. Overview of reconfigurability enablers for automated, mixed and manual systems.

empower human s in their adaptation to changes. Logical enablers for the operator enable operator's responsive adaptation to changing requirements, also in case of purely manual operations. According to these findings, future research may strive to extend the theory on reconfigurable manufacturing with fundamentals of human-centric automation. This is relevant because, to date, the synergies between these two domains have not been explicitly addressed despite the potentials highlighted in this study.

6.2. Relevance for practitioners

Despite the theoretical nature, the results of this study are also relevant to practitioners. First, as detailed in Section 5, the classification frameworks illustrate the enablers in relation to affected components of the reconfiguration effort, therefore practitioners can select them based on desired effects on the effort.

Second, the classification in physical enablers, i.e., enabling physical reconfiguration; and logical ones, i.e., enabling behavioural reconfiguration may support practitioners exploring enablers based on needed reconfiguration types.

Third, as some enablers detail other enablers, the classification frameworks also clarify the definitions of the reconfigurability enablers. Therefore, depending on industry and type of manufacturing systems – ranging from automated to manual systems – manufacturers may use the proposed classification to identify preferred concepts to initiate the design of reconfigurability enablers.

Last, since each of the classification framework enablers relates to either the manufacturing system, the machine, the robot, the material handling system or the operator, an overview of different options based on the kind of manufacturing system at hand – thus, either automated, mixed, or manual system, as shown in the following Fig. 9 is provided to practitioners. In Fig. 9, the logical enablers for the manufacturing system are particularly relevant; their presence ensures the right connection of human resources with machines, material handling systems and other human resources independently of the kind of manufacturing system.

6.3. Limitations

The selection of keywords related to the reconfiguration effort allowed to reach relevant literature and ensured an adequately wide scope of investigation needed to detect the fragmented examples and concepts of enablers for reduction of the reconfiguration effort. Even though the scope of investigation was deemed necessary to develop the proposed classification frameworks and consolidate knowledge about the reconfigurability enablers, technical or specific literature may have been neglected. For this reason, future research may investigate reconfigurability enablers in technical or specific domains. As introduced in Section 6.1, research efforts may strive to support human-centric reconfigurable manufacturing systems by applying technical solutions for human-centricity to the reconfigurability capability, thus further extending the theory on RMS.

Another limitation lies in the theoretical nature of this study, but this was deemed necessary to provide theory and reference frameworks for future research. To this end, and to support practitioners in adopting reconfigurability enablers, in future research the authors aim to develop a methodology that, within the proposed classification frameworks, allows manufacturing companies to identify the most appropriate enablers given their specific features and contextual requirements, and adopt them in manufacturing system development. To this end, future research may also focus on quantitatively measuring the reduction in reconfiguration effort due to the adoption of reconfigurability enablers throughout system life cycle. Moreover, future research may also investigate the supporting relations and interactions between the enablers, pursuing these directions would enable the operationalisation of the proposed classification frameworks as tools to develop or enhance appropriate combinations of reconfigurability enablers.

7. Conclusion

To face the unpredictability of market requirements and shortening of products' life cycles, manufacturers need reconfigurability enablers, which reduce the reconfiguration effort, in terms of time, cost and ramp-up. To the best of the authors' knowledge, there is a gap of knowledge about the reconfigurability enablers as no existing study has comprehensively outlined and classified them. Therefore, this study provided a systematic analysis of literature and collection of fragmented examples and concepts of enablers for reduction of the reconfiguration effort in manufacturing, ultimately providing comprehensive classification frameworks for the reconfigurability enablers for manufacturing systems, machines, robots, material handling systems and operators. In the conducted study, the term reconfigurability "enabler" was used to categorize any means to reduce the reconfiguration effort during a reconfiguration of the manufacturing system throughout its life cycle.

Directions for future research refer both to theoretical and application-oriented contributions. Regarding theoretical contributions, this study supports research on reconfigurability as a multi-dimensional capability also enabled by Industry 4.0 and human-centric automation. To this end, future research may explore the latter research domains to support human-centric reconfigurable manufacturing systems. Regarding application-oriented contributions, future studies may operationalize the proposed frameworks, for example with details or methodologies that support practitioners in developing or enhancing appropriate combinations of enablers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author, [A.N.], upon reasonable request.

References

[1] Koren Y, Wang W, Gu X. Value creation through design for scalability of reconfigurable manufacturing systems. Int J Prod Res 2016;55:1227–42. https://doi.org/10.1080/00207543.2016.1145821.
[2] Koren Y, Shpitalni M. Design of reconfigurable manufacturing systems. J Manuf Syst 2010;29:130–41. https://doi.org/10.1016/j.jmsy.2011.01.001.
[3] Koren Y, Gu X, Guo W. Choosing the system configuration for high-volume manufacturing. Int J Prod Res 2018;56:476–90. https://doi.org/10.1080/00207543.2017.1387678.
[4] Setchi RM, Lagos N. Reconfigurability and reconfigurable manufacturing systems - state-of-the-art review. In: Proceedings of the second IEEE international conference on industrial informatics; 2004, p. 529–35. Available from: doi: 10.1109/INDIN.2004.1417401.
[5] Eldardiry OM, Alkadeem R, Sabry C. Usability of reconfigurable manufacturing systems. In: Proceedings of the forty first international conference on computers & industrial engineering created; 2012. p. 205–10.
[6] Maganha I, Silva C, Ferreira LMDF. Understanding reconfigurability of manufacturing systems: an empirical analysis. J Manuf Syst 2018;48:120–30. https://doi.org/10.1016/j.jmsy.2018.07.004.
[7] Koren Y. General RMS characteristics. Comparison with dedicated and flexible systems. Chapter 3 in reconfigurable manufacturing systems and transformable factories; 2006. p. 27–45.
[8] Abdi MR. Layout configuration selection for reconfigurable manufacturing systems using the fuzzy AHP. Int J Manuf Technol Manag 2009;17:149–65. https://doi.org/10.1504/IJMTM.2009.023783.
[9] Mehrabi MG, Ulsoy AG, Koren Y. Reconfigurable manufacturing systems and their enabling technologies. Int J Manuf Technol Manag 2000;1:1–21.
[10] Andersen A-L, Brunoe TD, Christensen B, Bejlegaard M. Tailored reconfigurability: a comparative study of eight industrial cases with reconfigurability as a key to manufacturing competitiveness. Reconfigurable Manuf Syst Des Implement 2019:209–45.
[11] Singh A, Gupta S, Asjad M, Gupta P. Reconfigurable manufacturing systems: journey and the road ahead. Int J Syst Assur Eng Manag 2017;8:1849–57. https://doi.org/10.1007/s13198-017-0610-z.

[12] Russo Spena P, Holzner P, Rauch E, Vidoni R, Matt DT. Requirements for the design of flexible and changeable manufacturing and assembly systems: a SME-survey. Procedia CIRP 2016;41:207–12. https://doi.org/10.1016/j.procir.2016.01.018.

[13] Dit Eynaud AB, Klement N, Gibaru O, Roucoules L, Durville L. Identification of reconfigurability enablers and weighting of reconfigurability characteristics based on a case study. Procedia Manuf 2019;28:96–101. https://doi.org/10.1016/j.promfg.2018.12.016.

[14] Elmaraghy H. Smart changeable manufacturing systems. Procedia Manuf 2018;28: 3–9. https://doi.org/10.1016/j.promfg.2018.12.002.

[15] Koren Y, Gu X, Guo W. Reconfigurable manufacturing systems: principles, design, and future trends. Front Mech Eng 2018;13:121–36.

[16] ElMaraghy H, Monostori L, Schuh G, ElMaraghy W. Evolution and future of manufacturing systems. CIRP Ann 2021;70:635–58. https://doi.org/10.1016/j.cirp.2021.05.008.

[17] Romero D, Noran O, Stahre J, Bernus P, Fast-Berglund Å. Towards a human-centred reference architecture for next generation balanced automation systems: human-automation symbiosis. IFIP Adv Inf Commun Technol 2015;460:556–66. https://doi.org/10.1007/978-3-319-22759-7_64.

[18] Lu Y, Zheng H, Chand S, Xia W, Liu Z, Xu X, et al. Outlook on human-centric manufacturing towards Industry 5.0. J Manuf Syst 2022;62:612–27. https://doi.org/10.1016/j.jmsy.2022.02.001.

[19] Cimino C, Negri E, Fumagalli L. Computers in Industry Review of digital twin applications in manufacturing. Comput Ind 2019;113:1–13. https://doi.org/10.1016/j.compind.2019.103130.

[20] Ji Z, Yanhong Z, Baicun W, Jiyuan Z. Human – cyber – physical systems (HCPSs) in the context of new-generation intelligent manufacturing. Engineering 2019;5: 624–36. https://doi.org/10.1016/j.eng.2019.07.015.

[21] Andersen A-L, Larsen JK, Brunoe TD, Nielsen K, Ketelsen C. Critical enablers of changeable and reconfigurable manufacturing and their industrial implementation. J Manuf Technol Manag 2018;29:983–1002. https://doi.org/10.1108/MRR-09-2015-0216.

[22] Goyal KK, Jain PKK, Jain M. Optimal configuration selection for reconfigurable manufacturing system using NSGA II and TOPSIS. Int J Prod Res 2012;50:4175–91. https://doi.org/10.1080/00207543.2011.599345.

[23] Zhang G, Liu R, Gong L, Huang Q. An analytical comparison on cost and performance among DMS, AMS, FMS and RMS. Reconfigurable manufacturing systems and transformable factories. 2006. p. 659–73. https://doi.org/10.1007/3-540-29397-3_33.

[24] Koren Y. The rapid responsiveness of RMS. Int J Prod Res 2013;51:6817–27. https://doi.org/10.1080/00207543.2013.856528.

[25] Carrus B.J. The design and implementation of material and information flow for manufacturing systems. Massachusetts Insititute of Technology; 2000.

[26] Wang G, Li D, Tu Y, Zhang C, Li F, Wang S. A product-process-resource based formal modelling framework for customized manufacturing in cyber-physical production systems. Int J Comput Integr Manuf 2022. https://doi.org/10.1080/0951192X.2021.1992662.

[27] Azab A, ElMaraghy H. Sequential process planning: a hybrid optimal macro-level approach. J Manuf Syst 2007;26:147–60. https://doi.org/10.1016/j.jmsy.2008.03.003.

[28] Urbanic RJ, Hedrick RW. A matrix-based framework for assessing machine tool reconfiguration alternatives. Int J Adv Manuf Technol 2015;81:1893–919. https://doi.org/10.1007/s00170-015-7287-8.

[29] Ayman M, Youssef A, ElMaraghy HA. Assessment of manufacturing systems reconfiguration smoothness. Int J Adv Manuf Technol 2006;30:174–93. https://doi.org/10.1007/s00170-005-0034-9.

[30] Andersen A-L, ElMaraghy H, ElMaraghy W, Brunoe TD, Nielsen K. A participatory systems design methodology for changeable manufacturing systems. Int J Prod Res 2018;56:2769–87. https://doi.org/10.1080/00207543.2017.1394594.

[31] Maganha I, Silva C, Ferreira LMDF, Thurer M, Frazzon EM, Silvestri M. Proposal of a reconfigurability index using analytic network process. IEEE Int Conf Ind Eng Eng Manag 2019:1310–3. https://doi.org/10.1109/IEEM44572.2019.8978532.

[32] Napoleone A, Andersen AL, Brunoe TD, Nielsen K. An industry-applicable screening tool for the clarification of changeability requirements. IFIP 2021;631. https://doi.org/10.1007/978-3-030-85902-2_50.

[33] Durach CF, Kembro JH, Wieland A. How to advance theory through literature reviews in logistics and supply chain management. Int J Phys Distrib Logist Manag 2021;51:1090–107. https://doi.org/10.1108/IJPDLM-11-2020-0381.

[34] Durach CF, Kembro J, Wieland A. A new paradigm for systematic literature reviews in supply chain management. J Supply Chain Manag 2017;53:67–85. https://doi.org/10.1111/jscm.12145.

[35] Abellán-nebot JV, Romero F, Julio S, Mira S. Manufacturing variation models in multi-station machining systems; 2013. p. 63–83. Available from: doi: 10.1007/s00170-012-4016-4.

[36] Kurniadi KA, Ryu K. Development of IOT-based reconfigurable manufacturing system to solve reconfiguration planning problem. Procedia Manuf 2017;11: 965–72. https://doi.org/10.1016/j.promfg.2017.07.201.

[37] Lesi V, Jakovljevic Z, Pajic M. Towards plug-n-play numerical control for reconfigurable manufacturing systems. IEEE Int Conf Emerg Technol Fact Autom, ETFA 2016. https://doi.org/10.1109/ETFA.2016.7733524.

[38] Profanter S, Dorofeev K, Zoitl A, Knoll A. OPC UA for plug & produce : automatic device discovery using LDS-ME. In: Proceedings of the twenty second IEEE international conference on emerging technologies and factory automation (ETFA); 2017.

[39] Saliba MA, Zarb AV, Borg JC. A modular, reconfigurable end effector for the plastics industry. Assem Autom 2010;30:147–54. https://doi.org/10.1108/01445151011029781.

[40] Andersen A-L, Nielsen K, Brunoe TD. Understanding changeability enablers and their impact on performance in manufacturing companies. In: Proceedings of the IFIP WG 5.7 international conference, APMS, 536; 2018. p. 297–304. Available from: doi: 10.1007/978-3-319-99707-0.

[41] Bech S, Brunoe TD, Larsen JK. Changeability of the manufacturing systems in the food industry – a case study. Procedia CIRP 2018;72:641–6. https://doi.org/10.1016/j.procir.2018.03.014.

[42] Bensmaine A, Dahane M, Benyoucef L. A non dominated sorting genetic algorithm based approach for optimal machines selection in reconfigurable manufacturing environment. Comput Ind Eng 2013;66:519–24. https://doi.org/10.1016/j.cie.2012.09.008.

[43] Dou J, Li J, Su C. Bi-objective optimization of integrating configuration generation and scheduling for reconfigurable flow lines using NSGA-II. Int J Adv Manuf Technol 2016;86:1945–62. https://doi.org/10.1007/s00170-015-8291-8.

[44] Fallah SM, Wolny S, Wimmer M. Towards model-integrated service-oriented manufacturing execution system. In: Proceedings of the first international workshop on cyber-physical production systems (CPPS), IEEE; 2016. p. 1–5. Available from: doi: 10.1109/CPPS.2016.7483917.

[45] Fan JJ, Feng DZ, Cao M. Modeling and application for cellular formation under dynamic environment. In: Proceedings of the IEEE seventeenth international conference on industrial engineering and engineering management, IE and EM2010; 2010. p. 542–6. Available from: doi: 10.1109/ICIEEM.2010.5646555.

[46] Imseitif J, Nezamoddini N. Macro and micro-production planning for reconfigurable manufacturing systems. In: Cromarty L, Shirwaiker R, Wang E P, editors. n: Proceedings of the 2020 IISE Annual Conference L; 2020.

[47] Kurniadi KA, Ryu K. Development of a framework for selecting the best collaboration path between machines for reconfigurable manufacturing systems. Procedia Manuf 2020;51:1267–74. https://doi.org/10.1016/j.promfg.2020.10.177.

[48] Mehdizadeh E, Shamoradifar M. A genetic algorithm for solving a dynamic cellular manufacturing system. service orientation in holonic and multi-agent manufacturing. SOHOMA 2018. Stud Comput Intell 2019:384–95. https://doi.org/10.1007/978-3-030-03003-2_30.

[49] Mittal KK, Jain PK. An overview of performance measures in reconfigurable manufacturing system. Procedia Eng 2014;69:1125–9. https://doi.org/10.1016/j.proeng.2014.03.100.

[50] Moghaddam SK, Houshmand M, Saitou K. Configuration design of scalable reconfigurable manufacturing systems for part family. Int J Prod Res 2019;0:1–23. https://doi.org/10.1080/00207543.2019.1620365.

[51] Napoleone A, Macchi M, Pozzetti A. Planning the reconfiguration of manufacturing systems: a literature review. Proc Summer Sch Fr Turc 2016:13–5.

[52] Padayachee J, Bright G. A multi-period group technology method for dynamic cellular manufacturing systems. South Afr J Od Ind Eng 2016;27:90–100.

[53] Prasad D, Jayswal SC. Scheduling in reconfigurable manufacturing system for uncertainty in decision variables. Mater Today Proc 2018;5:18451–8. https://doi.org/10.1016/j.matpr.2018.06.186.

[54] Prasad D, Jayswal SC. Scheduling of products for reconfiguration effort in reconfigurable manufacturing system. Mater Today Proc 2018;5:4167–74. https://doi.org/10.1016/j.matpr.2017.11.679.

[55] Prasad D, Jayswal SC. Levels of reconfiguration in a reconfigurable manufacturing industry. J Manuf Technol Res 2018;10:89–102.

[56] Saxena LK, Jain PK. Dynamic cellular manufacturing systems design - a comprehensive model. Int J Adv Manuf Technol 2011;53:11–34. https://doi.org/10.1007/s00170-010-2842-9.

[57] Singh PP, Madan J, Singh H. A systematic approach for responsiveness assessment for product and material flow in reconfigurable manufacturing system (RMS. Mater Today Proc 2020;28:1643–8. https://doi.org/10.1016/j.matpr.2020.04.890.

[58] Tavakkoli-Moghaddam R, Sakhaii M, Vatani B. A robust model for a dynamic cellular manufacturing system with production planning. Int J Eng, Trans A Basics 2014;27:587–98. https://doi.org/10.5829/idosi.ije.2014.27.04a.09.

[59] Yi G, Wang Y, Zhao X. Evaluation and optimization of the design schemes of reconfigurable machine tools based on multiple-attribute decision-making. Adv Mech Eng 2018;10:1–9. https://doi.org/10.1177/1687814018813054.

[60] Zeng P, Wang Z, Jia Z, Kong L, Li D, Jin X. Time-slotted software-defined Industrial Ethernet for real-time Quality of Service in Industry 4.0. Future Gener Comput Syst 2019;99:1–10. https://doi.org/10.1016/j.future.2019.04.009.

[61] Almeida F, Dias P, Gonçalves G, Peschl M, Hoffmeister M. A proposition of a manufactronic network approach for intelligent and flexible manufacturing systems. Int J Ind Eng Comput 2011;2:873–90. https://doi.org/10.5267/j.ijiec.2011.05.006.

[62] Hashemi-Petroodi SE, Gonnermann C, Paul M, Thevenin S, Dolgui A, Reinhart G. Decision support system for joint product design and reconfiguration of production systems. IFIP Int Conf Adv Prod Manag Syst 2019:231–8. https://doi.org/10.1007/978-3-030-30000-5_30.

[63] Liu C, Wang J, Zhou M. Reconfiguration of virtual cellular manufacturing systems via improved imperialist competitive approach. IEEE Trans Autom Sci Eng 2019; 16:1301–14. https://doi.org/10.1109/TASE.2018.2878653.

[64] Lowenstein D, Slater C. Management of test utilization, optimization, and health through real-time data. In: Proceedings of the 2018 IEEE AUTOTESTCON. IEEE; 2018. p. 1–6. https://doi.org/10.1109/AUTEST.2018.8532554.

[65] Mehdizadeh E, Daei Niaki SV, Rahimi V. A vibration damping optimization algorithm for solving a new multi-objective dynamic cell formation problem with workers training. Comput Ind Eng 2016;101:35–52. https://doi.org/10.1016/j.cie.2016.08.012.

[66] Morariu O, Borangiu T, Raileanu S, Morariu C. Redundancy and scalability for virtualized MES systems with programmable infrastructure. Comput Ind 2016;81: 26–35. https://doi.org/10.1016/j.compind.2015.08.011.
[67] Niroomand I, Kuzgunkaya O, Bulgak AA. The effect of system configuration and ramp-up time on manufacturing system acquisition under uncertain demand. Comput Ind Eng 2014;73:61–74. https://doi.org/10.1016/j.cie.2014.04.017.
[68] Prasad D, Jayswal SC. Assessment of a reconfigurable manufacturing system. Benchmarking 2019. https://doi.org/10.1108/BIJ-06-2018-0147.
[69] Prasad D, Jayswal SC. Reconfigurability consideration and scheduling of products in a manufacturing industry. Int J Prod Res 2018;56:6430–49. https://doi.org/10.1080/00207543.2017.1334979.
[70] Schamp M, Hoedt S, Claeys A, Aghezzaf EH, Cottyn J. Impact of a virtual twin on commissioning time and quality. IFAC-Pap 2018;51:1047–52. https://doi.org/10.1016/j.ifacol.2018.08.469.
[71] Sierla S, Kyrki V, Aarnio P, Vyatkin V. Automatic assembly planning based on digital product descriptions. Comput Ind 2018;97:34–46. https://doi.org/10.1016/j.compind.2018.01.013.
[72] Verba N, Chao KM, James A, Lewandowski J, Fei X, Tsai CF. Graph analysis of fog computing systems for industry 4.0. In: Proceedings of the fourteenth IEEE international conference on E-business engineering, ICEBE 2017 - including thirteenth workshop on service-oriented applications, integration and collaboration, SOAIC 207; 2017. p. 46–53. Available from: doi: 10.1109/ICEBE.2017.17.
[73] Yilmaz E, Erol R. A mathematical programming model for reconfiguration of flexible manufacturing cells. Eng Optim 2015;47:184–203. https://doi.org/10.1080/0305215X.2014.881808.
[74] Peschl M, Link N, Hoffmeister M, Gonçalves G, Fernando LF. Designing and implementation of an intelligent manufacturing system. J Ind Eng Manag 2013;4: 718–45.
[75] Doltsinis S, Ferreira P, Lohse N. Reinforcement learning for production Ramp-up - a Q-batch learning approach. In: Proceedings of the eleventh international conference on machine learning and applications. 1. IEEE; 2012. p. 610–5. https://doi.org/10.1109/ICMLA.2012.113.
[76] Doltsinis SC, Ratchev S, Lohse N. A framework for performance measurement during production ramp-up of assembly stations. Eur J Oper Res 2013;229:85–94. https://doi.org/10.1016/j.ejor.2013.02.051.
[77] Fan J, Cao M, Zhang L, Jiang S. Study on the reconfiguration of dual resource cellular manufacturing system. Open Autom Control Syst J 2015;7:42–8.
[78] Laseinde OT, Mouchou R, Kuti O. Evaluation of virtual reality concepts for rapid prototyping of gears using additive layer technology. Advances in intelligent systems and computing. AISC. Springer International Publishing,; 2020. p. 756–61. https://doi.org/10.1007/978-3-030-51828-8_100.
[79] Ordaz N, Romero D, Gorecky D, Siller HR. Serious games and virtual simulator for automotive manufacturing education & training. Procedia Comput Sci 2015;75: 267–74. https://doi.org/10.1016/j.procs.2015.12.247.
[80] Zimmer M, Ferreira P, Danny P, Al-Yacoub A, Lohse N. Towards a decision-support framework for reducing ramp-up effort in plug-and-produce systems. In: Procedings of the IEEE international conference on industrial cyber physical systems (ICPS). IEEE; 2019. p. 478–83.
[81] Rodriguez L, Quint F, Gorecky D, Romero D, Siller HR. Developing a mixed reality assistance system based on projection mapping technology for manual operations at assembly workstations. Procedia Comput Sci 2015;75:327–33. https://doi.org/10.1016/j.procs.2015.12.254.
[82] Cui F, Geng N, Jiang Z, Zhou X. A stochastic programming approach for configuration optimization of reconfigurable manufacturing systems. IEEE Int Conf Ind Eng Eng Manag 2020:1152–6. https://doi.org/10.1109/IEEM45057.2020.9309813.
[83] Denkena B, Dittrich MA, Nguyen HN, Bild K. Self-optimizing process planning of multi-step polishing processes. Prod Eng 2021;15:563–71. https://doi.org/10.1007/s11740-021-01042-6.
[84] Farhan UH, Tolouei-Rad M, Osseiran A. Enhancing the reconfigurability of special purpose machine tools using mechanical module interfaces. J Achiev Mater Manuf Eng 2017;85:56–66.
[85] Gadalla M, Xue D. Recent advances in research on reconfigurable machine tools: a literature review. Int J Prod Res 2017;55:1440–54. https://doi.org/10.1080/00207543.2016.1237795.
[86] Goyal KK, Jain PK. Design of reconfigurable flow lines using MOPSO and maximum deviation theory. Int J Adv Manuf Technol 2016;84:1587–600. https://doi.org/10.1007/s00170-015-7760-4.
[87] Goyal KK, Jain PK, Jain M. A novel methodology to measure the responsiveness of RMTs in reconfigurable manufacturing system. J Manuf Syst 2013;32:724–30. https://doi.org/10.1016/j.jmsy.2013.05.002.
[88] Huang S, Xu Z, Wang G, Zeng C, Yan Y. Reconfigurable machine tools design for multi-part families. Int J Adv Manuf Technol 2019;105:813–29.
[89] Schlechtendahl J, Kretschmer F, Lechler A, Verl A. Communication mechanisms for cloud based machine controls. Procedia CIRP 2014;17:830–4. https://doi.org/10.1016/j.procir.2014.01.074.
[90] Schlechtendahl J, Kretschmer F, Sang Z, Lechler A, Xu X. Extended study of network capability for cloud based control systems. Robot Comput-Integr Manuf 2017;43:89–95. https://doi.org/10.1016/j.rcim.2015.10.012.
[91] Harrison WS, Tilbury DM. A formal characterization and analysis for hardware-in-the-loop and hybrid process simulation during manufacturing system deployment; 2011. p. 151–69. Available from: doi: 10.1007/s12008-011-0127-7.
[92] Leonardo L De, Zoppi M, Xiong L, Zlatanov D, Molfino RM. SwarmItFIX : a multi-robot-based reconfigurable fixture; 2013. Available from: doi: 10.1108/01439911311320822.
[93] Pini F, Leali F, Ansaloni M. Offline workpiece calibration method for robotic reconfigurable machining platform. In: Procedings of the ninteenth IEEE international conference on emerging technologies and factory automation. ETFA; 2014 2014. https://doi.org/10.1109/ETFA.2014.7005246.
[94] Abdi MR, Labib AW. Performance evaluation of reconfigurable manufacturing systems via holonic architecture and the analytic network process. Int J Prod Res 2011;49:1319–35. https://doi.org/10.1080/00207543.2010.520989.
[95] Napoleone A, Andersen A-L, Pozzetti A, Macchi M. Reconfigurable manufacturing: a classification of elements enabling convertibility and scalability, 566; 2019. Available from: doi: 10.1007/978-3-030-30000-5_44.
[96] Baykasoglu A, Göçken M. Capability-based distributed layout and its simulation based analyses. J Intell Manuf 2010;21:471–85. https://doi.org/10.1007/s10845-008-0202-5.
[97] Huang S, Wang G, Yan Y. Delayed reconfigurable manufacturing system. Int J Prod Res 2019;57:2372–91. https://doi.org/10.1080/00207543.2018.1518605.
[98] AlGeddawy T, ElMaraghy H. A model for co-evolution in manufacturing based on biological analogy. Int J Prod Res 2011;49:4415–35. https://doi.org/10.1080/00207543.2010.497780.
[99] ElMaraghy HA, Wiendahl H-P. Changeability – an introduction. Chang Reconfigurable Manuf Syst 2008:3–24. https://doi.org/10.1007/978-1-84882-067-8_1.