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## Survey

Timo Müller\*, Birte Caesar, Matthias Weiß, Selma Ferhat, Nada Sahlab, Alexander Fay, Raphaël Oger, Nasser Jazdi and Michael Weyrich

# Reconfiguration management in manufacturing

Rekonfigurationsmanagement in der Produktion

## A systematic literature review

Eine systematische Literaturrecherche

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**Abstract:** Driven by shorter innovation and product life cycles as well as economic volatility, the demand for reconfiguration of production systems is increasing. Thus, a systematic literature review on reconfiguration management in manufacturing is conducted within this work in order to determine by which degree this is addressed by the literature. To approach this, a definition of reconfiguration management is provided and key aspects of reconfigurable manufacturing systems as well as shortcomings of today's manufacturing systems reconfiguration are depicted. These provide the basis to derive the requirements for answering the formulated research question. Consequently, the methodical procedure of the literature review is outlined, which is based on the assessment of the derived requirements.

Timo Müller, Birte Caesar and Matthias Weiß contributed equally to this work.

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Finally, the obtained results are provided and noteworthy insights are given.

**Keywords:** adaption; configuration selection; cyber-physical production systems; manufacturing; reconfiguration management; systematic literature review.

**Zusammenfassung:** Aufgrund kürzerer Innovations- und Produktlebenszyklen sowie wirtschaftlicher Volatilität steigt der Rekonfigurationsbedarf von Produktionssystemen. Daher wird im Rahmen dieser Arbeit eine systematische Literaturrecherche zum Rekonfigurationsmanagement in der Produktion durchgeführt, um zu ermitteln, inwieweit dies in der Literatur adressiert wird. Dazu wird zunächst eine Definition des Rekonfigurationsmanagements gegeben und zentrale Aspekte rekonfigurierbarer Fertigungssysteme sowie die Defizite der heutigen Rekonfiguration von Fertigungssystemen dargestellt. Aus diesen werden die Anforderungen zur Beantwortung der formulierten Forschungsfrage abgeleitet. Anschließend wird das methodische Vorgehen der Literaturrecherche skizziert, welches auf der Bewertung der abgeleiteten Anforderungen basiert. Abschließend werden die erzielten Ergebnisse dargestellt und weitergehende Erkenntnisse erläutert.

**Schlagwörter:** Adaption; Konfigurationsauswahl; Cyber-Physische Produktionssysteme; Fertigung; Rekonfigurationsmanagement; Systematische Literaturrecherche.

## 1 Introduction

Today, industrial production faces an unstable market. On one hand, there's the customer need, which increases the importance and demand for individualized and customized products [1]. On the other hand, shorter innovation and product life cycles [2, 3] result in frequently changing production requirements. Thus, production goals are becoming ever more unpredictable during the design phase of these

systems. Consequently, adaptations of production systems by means of reconfigurations (i.e. adaptations during the operational phase) become the rule rather than the exception [4].

Besides, environmental awareness and the demand for resource-friendly production are increasing. Indeed, one-third of the energy consumption in the world is emitted by the manufacturing domain [5]. Additionally, operators aim to achieve a high availability, and thus possible machine failures have to be handled. With the expansion of product variety, volatility and variation of volume, dedicated manufacturing lines (DMLs) are no longer sufficient to satisfy the required responsiveness in an adequate time since manufacturing systems need more degrees of freedom to adapt to these changing dynamics. Currently, most existing production systems are designed for single purpose usage with limited or no reconfigurability [6–8].

One solution to address this need is given through Reconfigurable Manufacturing Systems (RMSs), which can be composed of diverse machines from different vendors providing varying manufacturing capabilities [9]. During the past 20 years, the concept of RMSs has been exploited from a technical point of view presenting several design solutions for hardware and software modularity within the same product family in order to respond to unexpected market changes or internal system changes. But for industrial applications there are still several barriers to overcome [8–10]. In particular, reconfiguration management during operation remains mostly a manual task and individually triggered [9, 11]. Reconfiguration management includes the identification of reconfiguration needs, reconfiguration planning, and finally reconfiguration execution [12]. Without a systematic and methodical support for reconfiguration management, the configuration selection process during reconfiguration planning remains subjective. Based on incomplete knowledge of individual employees, the manual creation of new configurations will be error-prone [11, 13].

To underline the need for reconfiguration management, Haddou Benderbal et al. [13] state that configuration selection is a complex task, with complexity increasing if both system and machine level reconfigurations are considered, as the number of configurations increases exponentially with the number of machines in an RMS [13]. Furthermore, to support reconfiguration management, economic criteria are important as reconfiguration decision support can also be used as economical reconfiguration triggers [14]. It should be noted, however, that the relevant economic criteria can differ greatly depending on the organizational level and must be taken into account [7, 15, 16].

Moreover, the future of industrial automation will be characterized by the concept of Cyber-Physical System (CPS) [17–22]. Core aspects of CPSs are their connectivity and their ability to process information in addition to their physical components [23]. These enable CPSs to possess a degree of intelligence that can vary greatly in its manifestations. Manufacturing systems based on CPS are also referred to as cyber-physical production systems (CPPSs) [24, 25]. CPPSs have several roots within the manufacturing domain, such as RMSs [26]. Consequently, the concept of CPPSs is not intended to contradict these developments, but rather to merge and enhance them.

In recent years, a large number of surveys have been performed on the subject of reconfiguration already. Publications such as [27, 28] describe the different phases of reconfiguration and look into technological solutions for common challenges like system complexity. Yelles-Chaouche et al. [29] provide a focused survey on RMS types and their optimization in design and operation. The authors of [30] present a literature review on RMS and related topics such as reconfigurable transport systems including publications from 1999 to 2017. They point out that until 2017 rather few publications consider the integration of industry 4.0 technologies and RMS which is expected to provide advantages in achieving agility and changeability. Surveys like [31, 32] address the integration of reconfiguration in digital twins and CPPSs, but do not provide a holistic view on reconfiguration management. Consequently, the authors of this survey aim to provide a comprehensive view on reconfiguration management and put a special emphasis on the utilization of CPPS capabilities by answering the research question: *How can CPPSs be enriched with the capability of self-organized reconfiguration management such that the solution space is fully exploited and various economic factors, as well as reconfiguration triggers, can be considered appropriately?*

By conducting a systematic literature review, we explore how comprehensive the stated research question is answered by the literature of the past five years. With this, we give insights about what reconfiguration management aspects in manufacturing are covered by existing approaches and which are barely researched.

The remainder of this paper is structured as follows. Section 2 introduces the term reconfiguration management, as well as basics concerning RMSs and shortcomings concerning the reconfiguration of manufacturing systems. Section 3 is dedicated to the applied methodology to conduct this systematic literature review. The results of the conducted literature analysis are presented in Section 4. The article concludes highlighting the obtained key insights,

as well as an outlook concerning future research activities and expected trends, Section 5.

## 2 Reconfiguration management

Matevska-Meyer [33] defines a reconfiguration as the technical process of changing a finished, developed and in use system, in order to meet new requirements, extend functionality, eliminate errors or improve quality characteristics. As stated in the introduction, in a nutshell, a reconfiguration describes the adaptation of a system during operation. A reconfiguration can comprise structural changes of software and/or hardware. However, in order to highlight the fact that the topic of reconfiguration encompasses more than just the execution of reconfiguration measures, the term reconfiguration management (see Figure 1) was introduced. Based on [34], it is explained in [12, 35, 36] that reconfiguration management also includes the steps of identification of reconfiguration demand and reconfiguration planning. Thereby, reconfiguration planning can be further subdivided into the steps of generation of alternative configurations, evaluation of configurations, and selection of a new configuration. The execution of reconfiguration measures is depicted transparently, since it is considered an optional extension that is classically performed manually. Nevertheless, it is important that the implied reconfiguration effort of this step should not be neglected within the reconfiguration management, as this effort is needed to shift from the current into a future configuration.

RMSs have five key aspects that should be reconfigurable and consequently need to be considered by reconfiguration management. These reconfiguration aspects are as follows [38–40]:

- *System*: This aspect concerns the selection and arrangement of the modules, i.e. the positioning of

machines, within the layout, as well as the selection of a module to manufacture a certain product feature.

- *Software*: The software architecture should be modular, modifiable, expandable, reusable, and able to contain different configurations. This enables the addition or modification of components, allowing to adapt the provided functionality.
- *Control*: The control structure should not need to be adapted. This means that the control concept should still be valid after any reconfiguration, on both module and system level.
- *Process*: It should be possible to adapt the manufacturing process to achieve optimum performance in order to be able to manufacture the required quantity in the required quality (e.g. adjustment of the process parameters).
- *Machine*: The hardware structure of a machine should be reconfigurable, e.g. to offer alternative functions or to adjust the production rate, further allowing to produce the required quantity in a given period of time.

Although the economic and ecological necessity for the reconfiguration of production systems is undisputed, it is seldom realized so far [41, 42]. This is due to the fact that the reconfiguration of manufacturing systems currently has the following shortcomings [6, 34]: (i) it is time-consuming since it is triggered, planned and executed manually and individually. Second, (ii) it is error-prone because there is no systematic or methodological support. Third, (iii) there is no guarantee for near optimal solutions, as it is based on limited human knowledge, which only covers a subset of the solution space. Lastly, (iv) evaluation and selection are not based on objective criteria, but on human experience.

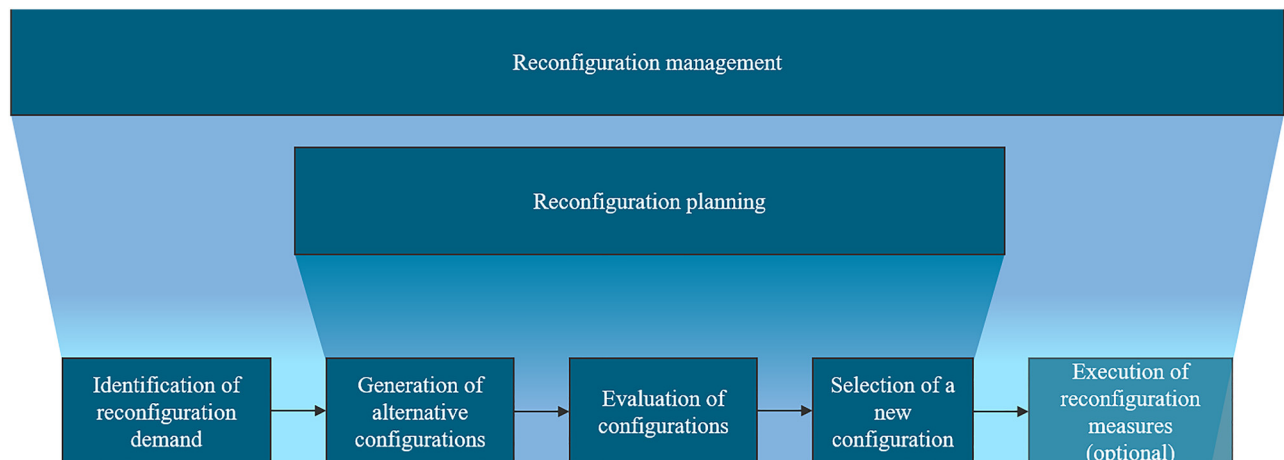


Figure 1: Scope of reconfiguration activities [37].

These shortcomings can be addressed with the help of reconfiguration management. Furthermore, according to [6, 42], the success and acceptance of RMSs depend primarily on the effort required to reconfigure the system and the resulting benefits. In order to do so, different information from different knowledge sources, e.g. manufacturing orders, system status, machine knowledge, manufacturing process knowledge, quality measures, etc., have to be integrated for an appropriate reconfiguration management. At this point CPPSs come into play as they represent the “vision of adaptive, self-configuring and partially self-organizing, flexible production plants” [43] and can lead to reduced setup times and optimized energy and resource usage [43]. This is due to the high level of interconnectivity and data exchange CPPSs provide [43]. However, to be able to exploit the full potentials of CPPSs, such as self-organized reconfiguration management, semantic models of the CPPS and its components are required [44]. Based on semantic models and on the knowledge they contain, appropriate concepts that adopt existing algorithms from domains such as artificial intelligence or mathematical optimization can be developed and transferred to the application. Further, semantic models help to provide unambiguity in dynamic environments that CPPSs often face. Consequently, CPPSs offer promising potentials to realize reconfiguration management, especially since they possess models, provide intelligence and are (internally) connected.

### 3 Methodical procedure of the review

In general, a systematic literature review (SLR) is defined as a structured strategy for assessing previous literature findings. There are various methods for conducting an SLR, depending on the research domain as well as the intended outcome. Xiao and Watson [45] conducted a study on methodologies for SLRs to derive a generalized framework and an abstract sequence of steps for SLRs. Another popular guideline for SLRs is the PRISMA statement [46], which provides authors with a set of methods and a comprehensive checklist in order to help authors to develop their own methodology. As such, this survey uses the sequence of [45] as a baseline and derives a distinct methodology by following the PRISMA guidelines. An overview of the resulting process is shown in Figure 2 and the sequence of steps is as follows:

1. **Formulate the problem:** Identification of research questions to answer by the SLR and derivation of requirements that, if fulfilled, solve the related

challenges. Section 3.1 lists the questions and requirements for this SLR.

2. **Develop and validate the review protocol:** Definition of the methodology that will be used in the SLR, including data extraction strategies and evaluation criteria. This section presents a condensed version of the review protocol for this survey. Additional documentation of the procedure, such as the records of each publication screening, can be found in the Appendix.
3. **Search the literature:** Definition of one or more suitable search strings to scan scientific databases for publications, followed by the actual publication retrieval. To enable a context-based analysis and the retrieval of hidden insights and patterns in the literature, it was decided to merge the publications into a knowledge graph structure. This is achieved by using the SLR support tool described in [47] which is also able to automate the database search. Section 3.2 describes the details of the process.
4. **Screen for inclusion:** Deciding if a publication should be included into the literature review based on the abstract. In this SLR, each abstract was read by two authors, who independently gave their judgement on this matter. In the case of contradicting opinions, a third author reviewed the conflict and made the final decision. Details on the inclusion criteria are given in Section 3.3.
5. **Extract data:** Performing full-text reviews on each publication in order to extract relevant information for the survey. In the case of this SLR, each publication was read by one author, who summarized its contents and gave a rating for each requirement defined in step 1.

As shown in Figure 2, a total of 404 publications were retrieved from scientific databases and screened for inclusion. Of these, 67 publications were included into the detailed literature analysis. In the following the steps regarding problem formulation (Section 3.1), literature search (Section 3.2) and publication screening for inclusion (Section 3.3) will be described in more detail. Section 4 shows the synthesized results of the review process.

#### 3.1 Problem formulation and requirements

As derived in Section 1 the research question considered in this SLR reads as: *How can CPPSs be enriched with the capability of self-organized reconfiguration management such that the solution space is fully exploited and various economic factors, as well as reconfiguration triggers, can be considered appropriately?*

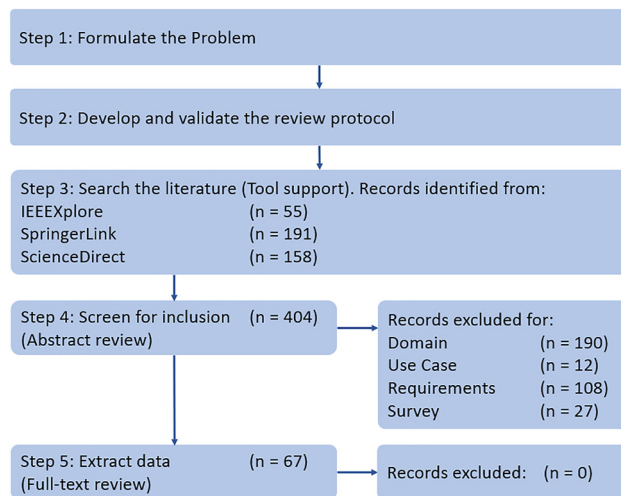


Figure 2: Overview of SLR methodology.

Thus, this section presents and describes the requirements concerning the formulated research question. The requirements ( $R$ ) are derived from Section 2 and are the foundation of the literature review.

*(R1) Appropriate realization of reconfiguration management steps within the CPPS:* In accordance with the introduced steps of reconfiguration management in Section 2, a suitable consideration of these steps is required. This results in the requirements *identification of reconfiguration demand (R1.1)*, *generation of alternative configurations (R1.2)*, *evaluation of configurations (R1.3)*, and *selection of a new configuration (R1.4)*. These requirements allow to evaluate in more detail the relevant aspects and to identify the shortcomings of the state of research for each reconfiguration management step.

*(R1.1) Identification of reconfiguration demand:* A reconfiguration can be required due to manifold reasons. The most common one is the change of the product to be manufactured, but also unplanned reasons, i.e. machine failure or a decrease in manufacturing quality, have to be taken into account. To determine the reconfiguration requirements, the current manufacturing requirements must be compared with the current configuration and state of the manufacturing system. Therefore, suitable triggers must be defined so that the reconfiguration planning is initiated.

*(R1.2) Generation of alternative configurations:* The possibilities to cope with the respective current manufacturing requirements are manifold. As a reconfiguration can take place at the machine or the system level, several alternative configurations should be considered. On the machine level (*R1.2.1*) this should cover the hardware and software and on the system level (*R1.2.2*) the selection of

machines, their positioning within the layout, as well as the adaptation of the production process (i.e. its allocation, sequence and parameterization). In contrast to allocation, scheduling refers to a time-wise decision about which product feature is created on a certain machine and is thus also considered. To avoid that only a subset of the solution space for alternative configurations is considered, an intelligent exploration of the solution space for configuration alternatives should be taken into account (*R1.2.3*). Further, this way solution space explosion can be taken into account as well.

*(R1.3) Evaluation of configurations:* In order to compare the alternative configurations, both the reconfiguration effort (*R1.3.1*) and the production effort (*R1.3.2*) should be considered. This enables the cost-benefit ratio consideration, which is essential for an economic reconfiguration management strategy, see Section 2. Furthermore, the evaluation of the alternative configurations should be multi-criteria and based on objective criteria (*R1.3.3*) in order to avoid that the evaluation is only based on human experience.

*(R1.4) Selection of a configuration:* To complete the steps of reconfiguration planning, the selection of a suitable configuration of the manufacturing system is conducted. A suitable description of the selected configuration should be provided so that its subsequent application is possible.

*(R2) Automated execution of reconfiguration management:* To minimize the error-proneness as well as the implied time expenditure, an automated execution of the reconfiguration management is desirable.

*(R3) Exploiting the potentials of cyber-physical production systems:* Based on the description of CPPSs and the concept of CPSs in general (see Section 1 and Section 2), the hypothesis that CPPSs offer promising potential for reconfiguration management will be examined. Thus, the potentials of CPPSs should be utilized accordingly.

*(R4) Methodological support for reconfiguration management model creation:* Models to describe the reconfiguration space on the machine level and on the system level are complex and require domain as well as model expert knowledge. Therefore, methodological support is desirable in order to reduce the barriers for introduction of reconfiguration management.

*(R5) Interoperability management:* The interoperability management considers the constraints a module of a manufacturing system has regarding the fulfillment of its tasks, i.e. processing a product feature. These constraints could be the requirement of a module for a separate loading and unloading system or a connection to a transportation unit. In general this requirement addresses the point of

interaction between a module and its environment and thus has to take hardware and software aspects into account.

### 3.2 Automated literature search

After the identification of suitable research questions and requirements, the next step of the SLR is to search for matching literature in scientific databases. To facilitate this process, the tool described in [47] is being used to enable an automated search based on a search string. Figure 3 shows the sequence of the tool's search process. The first step involves the definition of the scope of the search by criteria such as the publication type, year, and language. In this survey, conference and journal publications in English and dating from 01/01/2018 to 06/08/2022 (the day on which the search was conducted) were considered. Subsequently, a list of keywords that match the research question needed to be created. In this survey, the authors accomplished this by performing a preview mapping, i.e., reviewing publications from the targeted domain and extracting common keywords and keyword variations. The result can be split into roughly two categories:

- **Reconfiguration management** and related concepts. These include: reconfiguration management, reconfiguration, adaption, self-adaption, self-adapting, self-configuration, self-configuring, adaptation, self-adaptiveness
- **Domains** in which reconfiguration is predominant. These include: cyber-physical system/s, cyber-physical production system/s, manufacturing system/s, reconfigurable manufacturing system/s, flexible manufacturing system/s, adaptable manufacturing system/s, cpps, cps, rms, rmt

After providing the keywords, the search string has been derived by combining each topic keyword with each domain keyword via logical operators (AND, OR, ...). The search process began by inserting the search string into the SLR tool, which relays both the string and search criteria to the digital libraries via their public interfaces. For this survey, three libraries of peer-reviewed research publications were chosen, namely IEEEExplore, ScienceDirect and SpringerLink. The tool collects publication data and processes the findings by collecting each publication's title, author names, year of publication, keywords, abstract as well as its DOI. In total, the tool found 55 publications from IEEEExplore, 158 from ScienceDirect and 191 from SpringerLink.

The results from different scientific databases are uniformly represented in CSV files by using defined CSV headers. In the next step, a labeled property graph is created

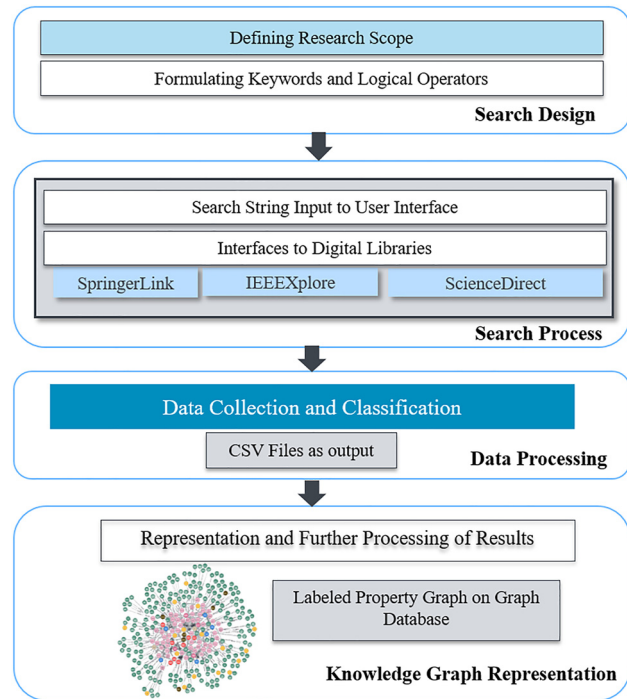


Figure 3: Steps of the automated literature search.

based on the generated CSV files and a metamodel defining nodes and relations. In this metamodel, a publication node is defined with node properties to reflect its collected information, such as author name, title, abstract and DOI. Each publication node is then connected to a year-node and a database node. Furthermore, each keyword is mapped into a node. Using this metamodel for generating a knowledge graph, publications are represented in a connected manner and with variable views so that they can be grouped and further processed based on similarities or databases. This approach enables the derivation of new insights and their representation by including further properties to nodes and relations.

### 3.3 Screening for inclusion

After the database search, the abstract of each publication is screened by two authors to decide whether it should be included in the full-text analysis or not. In the case of contradicting judgements, a third author reviews the conflict and makes the final decision. If the third author is also indecisive about the eligibility of a publication, following the recommendation of [45] it is included for full-text review to determine its suitability for the survey in the final step. In the case of this survey, a publication was included if it considers at least one of the above stated requirements

and one of the following domains: Discrete Manufacturing, Cyber-Physical Systems or Reconfigurable Manufacturing Systems. Further, publications were excluded if they were surveys themselves or if the provided use case did not concern the reconfiguration on the machine/shop floor level (e.g. reconfiguration of FPGAs).

From all included 67 publications, all of them had at least one intersection with reconfiguration management and thus none was excluded during the full text analysis.

## 4 Literature analysis

In this section detailed insights of the conducted SLR are presented, structured in sections based on the requirements of Section 3.1. Overall, Figure 4 shows a world map with the author's countries of origin for all included publications. It can be seen that the most active research communities on reconfiguration management are situated in Germany, France and China. The fulfillment of each requirement is rated based on levels. Which level each requirement can have is explained in the following subsections. The explicit results for each publication can be found in the table of Appendix, representing only the numbers of the levels.

### 4.1 Findings regarding R1

In order to evaluate the fulfillment of R1, the results from the sub-requirements R1.1, R1.2, R1.3 and R1.4 are summarized in such a way that a rather rough overview is given. For this purpose, the achieved scores for each of the mentioned sub-requirements of the respective work

were normalized to represent a percentage degree of fulfillment. Afterwards, a second normalization (i.e., a division by 4) was then calculated after summarizing the percentages determined for each sub-requirement (R1.1–R1.4) of a publication. The overview provided in Figure 5 shows that only 5% of the publications achieve a score between 75% and 100%, thus do consider most of the reconfiguration management steps as described in Section 2. In contrast, 28% of the contributions achieved between 50% and 75% fulfillment. The biggest share, with 37%, achieved a score between 25% and 50%, indicating that many publications only address specific reconfiguration management steps. Moreover, 30% reached a fulfillment between only 0% and 25%, which includes mostly publications with a specific scope that is distantly related to reconfiguration management. More detailed results on the fulfillment degree of the sub-requirements can be found in the respective subsections.

#### 4.1.1 Findings regarding R1.1

The assessment scheme for the identification of reconfiguration demand (R1.1) is based on the consideration of operational as well as strategic reconfiguration triggers. If the identification of reconfiguration demand covers either operational (system internal) or strategic (system external) triggers, the requirement is considered as partially fulfilled (level 1). If both trigger types are concerned this requirement is fulfilled (level 2).

Figure 6 shows that most publications do not consider the identification of reconfiguration demand. Instead they assume that a reconfiguration is needed and neglect the

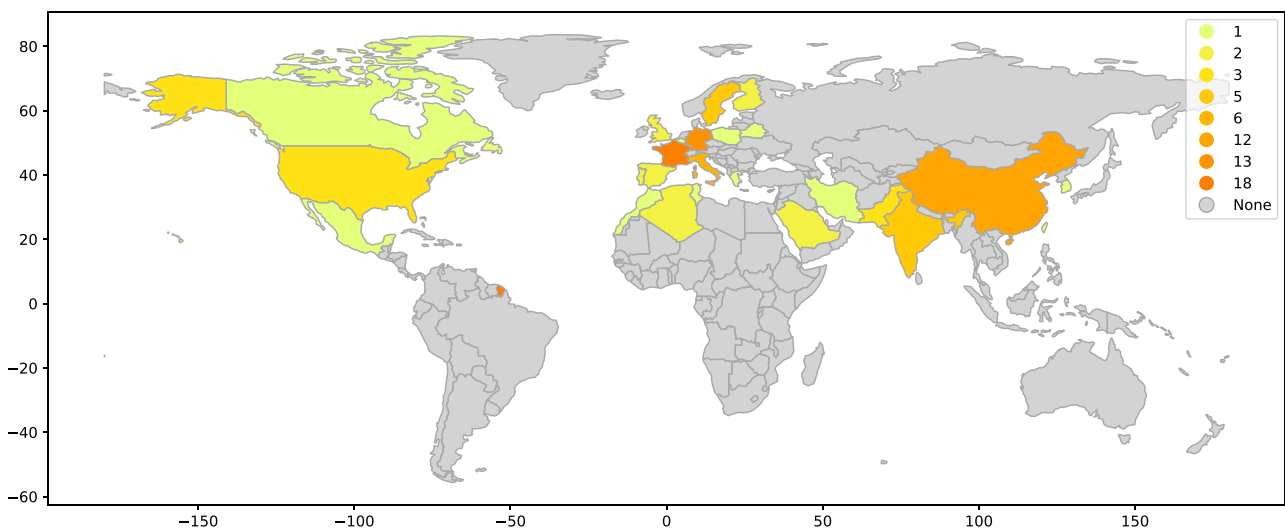


Figure 4: Most contributing countries towards reconfiguration management.



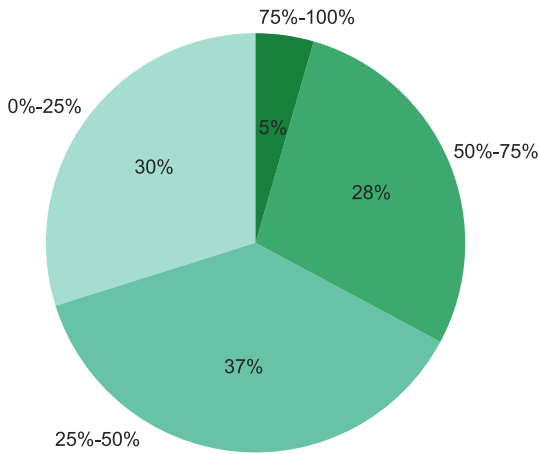


Figure 5: Requirement 1: summary of the fulfillment of requirement R1.

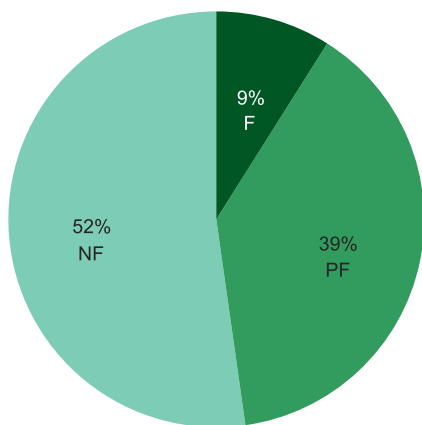


Figure 6: Requirement 1.1: identification of reconfiguration demand – F = fulfilled, PF = partially fulfilled, NF = not fulfilled.

challenge of identifying changes that request for a reconfiguration. If they do consider the identification of reconfiguration demand, they use strategic triggers, i.e. new products, changed demand, new orders [48–52]. Slightly fewer include operational triggers, e.g. machine failures [53–55]. Only a modest percentage considers both types, e.g. [56–58]. Additional insights are that, for operational triggers, scheduling, process allocation, machine selection, as well as software reconfigurability are of particular interest. From this, the hypothesis can be derived that taking these aspects at least partially into account could be beneficial for existing approaches that want to include operational triggers as well.

### 4.1.2 Findings regarding R1.2

The following pie charts visualize by how many approaches and to what extend the subrequirements R1.2.1, R1.2.2 and R1.2.3 are taken into account. Overall, many approaches focus on conducting a (mere) production planning and scheduling from scratch rather than on concerning an existing production system and the reconfiguration of it such as [49, 59–61]. The respective following subsections will provide further detailed insights.

#### 4.1.2.1 Findings regarding R1.2.1

The resulting machine level coverage is depicted by a nested pie chart, see Figure 7. The inner circle assesses how far the reconfiguration at machine level includes hardware (HW) and/or software (SW). If only HW or SW is mentioned, but it is not sufficiently explained how this is modeled, the requirement is rated as partially fulfilled (level 1), blue segment of Figure 7. If either HW or SW is categorised as fulfilled (level 2) and the other is partially fulfilled (level 1) or not at all (level 0), then the requirement is rated as advanced fulfillment (level 2), green segment of Figure 7. Approaches are rated as fulfilled if the HW/SW configuration alternatives are modeled, purple segment of Figure 7. In summary the requirement is rated as fulfilled (level 3) if both, HW and SW are rated as fulfilled. The outer circle gives insights about the percentage of approaches considering HW and/or SW. Thus it shows that 62% of the approaches more likely consider HW reconfiguration, in contrast to 26% which consider the SW reconfiguration.

#### 4.1.2.2 Findings regarding R1.2.2

Requirement R1.2.2 assesses on the one hand side to what extend the system level reconfiguration is considered by

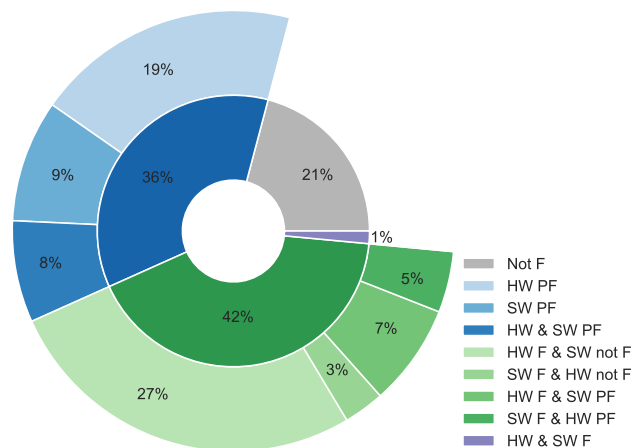


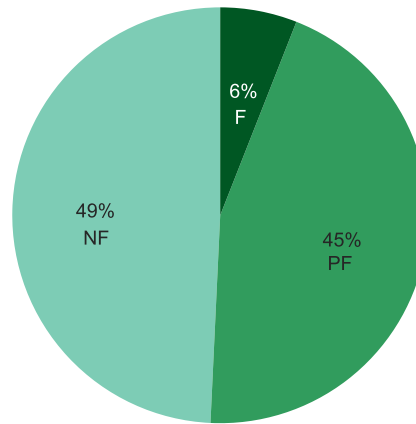
Figure 7: Requirement 1.2.1: machine level reconfiguration – F = fulfilled, PF = partially fulfilled.

the approaches and on the other hand which of the system level reconfiguration tasks are more often considered. The inner circle of Figure 8 shows that 12% of the approached do not consider reconfiguration on system level. 22% of the approaches only consider one of machine selection (MS), production sequence adaptation (PSA) or scheduling (S). 31% do combine two of these, and further include machine positioning (MP). Three of these are combined by 27% of the approaches and only 7% do consider all four system level reconfiguration tasks. Machine positioning is the less common considered task (23%). In contrast to that machine selection and production sequence adaptation are the most covered tasks each by 68% of the approaches. However, production sequence adaptation regarding parameterization is barely covered (e.g. [12, 57, 59, 62]). But the allocation and determination of production sequences are realized more regularly [35, 55–58, 61]. Interdependencies, especially the preceding-order of tasks are sometimes covered, e.g. [63, 64]. In general, the vast majority of the publications did not address this aspect.

**4.1.2.3 Findings regarding R1.2.3**

Regarding the intelligent exploration of the solution space for alternative configurations, it is assessed as follows. Level 1 is attended either by dividing the solution space into several smaller problems or by an intelligent reduction of the solution space. If so, the requirement is considered as partially fulfilled. Level 2, in turn, covers both of these aspects and the requirement is considered completely fulfilled.

The intelligent solution space exploration was barely rated to be fulfilled (see Figure 9), e.g. by [7, 35, 57]. To that end, even if rated as fulfilled, in detail it was (often) very specific. Rodrigues et al. [57] for example, did not aim for a global optimization but rather for a global management at



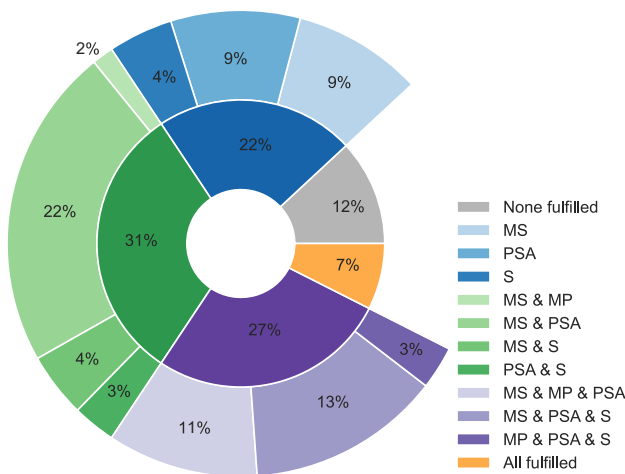
**Figure 9:** Requirement 1.2.3: intelligent solution space exploration – F = fulfilled, PF = partially fulfilled, NF = not fulfilled.

the system level. However, they reduce the solution space by discarding non-feasible, non-reasonable and non-beneficial solution in order to assure that the system is able to carry out the production order. Furthermore, they also fulfilled the division aspect, as the overall solution space is divided since resource agents are responsible for the generation of their own optimal reconfiguration alternatives.

Overall, about half of the examined publications partially fulfilled this requirements. This was far more often approached by a reduction of the solution space [65–68] rather than by a division [52] of it. Additionally, the reduction of the solution space was mostly realized by the application of constraints on a mathematical model. However, in seldom cases such as [68] lower bounds are determined and applied. Some further approaches, such as [57] discarded unfeasible or non-promising solutions early on.

**4.1.3 Findings regarding R1.3**

The inner circle of Figure 10 summarizes the consideration of evaluation criteria of configurations. A great part (33%) does not consider an evaluation of the generated configurations at all. However, Figure 10 shows that the majority of approaches (67%) considers objective criteria to evaluate a configuration. 20% of these approaches do not consider the impact of the reconfiguration effort (RE), see in the outer circle of Figure 10 the sum of PE & MCO and PE. 24% of the approaches either consider the reconfiguration or the production effort (PE) as single-objective optimization evaluation. 30% of the examined approaches cover single-objective as well as multi-objective optimization (MCO) approaches. About 20% include either reconfiguration or production effort criteria for multi-objective optimization, sometimes combined with criteria, e.g. carbon footprint. 13% however



**Figure 8:** Requirement 1.2.2: system level reconfiguration.

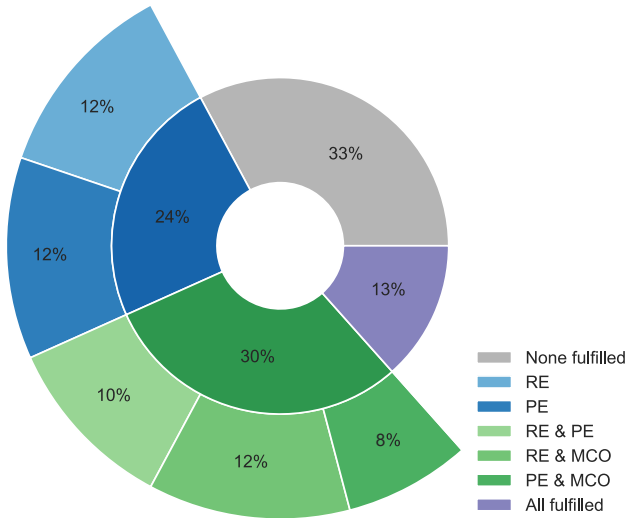


Figure 10: Requirement 1.3: new configuration selection.

consider both for multi-objective optimization. The most prominent objectives are by far time and (monetary) cost both concerned with diverse sub-aspects such as makespan or mean time for operation, which underlines the authors' previous work [14]. Another prominent objective is the manufacturing quality, also occurring in diverse variants. Furthermore, an increase of the consideration of energy aspects can be noted. This is since the carbon footprint (sometimes even considered directly) [63–65, 69] is getting more attention nowadays.

#### 4.1.4 Findings regarding R1.4

The selection of a new configuration is assessed as partially fulfilled (level 1) if one of several alternative configurations has to be selected by the operator himself. Whenever one alternative configuration is expected to be the best for the respective formulated goals and is selected, the requirement is fulfilled (level 2).

As Figure 11 shows, the selection of a new configuration from a pool of multiple alternatives is not even considered in most of the approaches (43%). However, if it is considered, the approaches are more likely to derive one, best fitting, configuration (36%), e.g. [65, 66, 70, 71], instead of a mere provision of a set of configuration to an operator (21%), e.g. [50, 72–74].

#### 4.2 Findings regarding R2

In order to assess to which degree the reconfiguration management is automated, the Level of Automation (LoA) according to [75] is used. Hereby, the LoA is ascending,

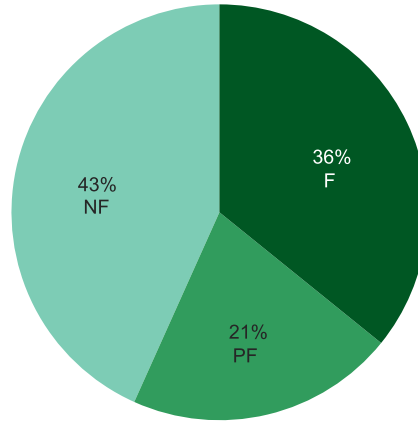


Figure 11: Requirement 1.4: new configuration selection – F = fulfilled, PF = partially fulfilled, NF = not fulfilled.

starting from LoA = 1, i.e. the computer offers no assistance, all the way up to LoA = 10, i.e. the computer decides everything autonomously. Note that the step with the lowest assigned LoA defines the overall LoA. Whenever the respective publication did not cover all reconfiguration management steps, only the considered steps are taken into account.

Regarding Figure 12, one can see that a broad spectrum of LoAs are realized by the examined approaches. However, LoA = 1, LoA = 3, LoA = 4 and LoA = 10 are achieved the most. Since LoA = 3 refers to *the computer narrows the selection down to a few*, whilst LoA = 4 refers to *the computer suggests one alternative*, those LoAs refer to assistance systems. In Figure 12, LoA = 6 is missing because this value was assigned to none of the publications.

#### 4.3 Findings regarding R3

The exploitation of the potentials of CPPSs is evaluated as partially fulfilled (level 1) as soon as either models or the

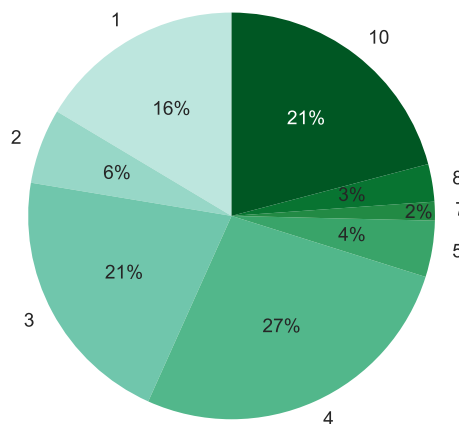


Figure 12: Requirement 2: reached level of automation 1–10 (LoA).

interconnectivity are utilized. If both of the aforementioned are used, the requirement is fulfilled (level 2).

It has to be noticed that Figure 13 reveals that the vast majority of approaches (64%) do not exploit the potentials of CPPSs at all. Furthermore, most approaches such as [68] have their scope on the planning phase where no current system is considered. They do neither use a networking aspect, nor a model, instead they use a table depicting, mostly exemplary, global information. However, the authors of [68] mention as an outlook, that it would be useful to have a real-world consideration at this end. Thus, they could greatly benefit from utilizing models and a CPS-based approach. It seems that many publications, such as [73], even if they follow a CPS-based approach and utilize models, rather have one global model with all the information concerning the resources rather than module specific decentralized models. Also, many approaches, even if mentioned to be CPS-based [68], do not concern the networking, i.e. communication, aspect or do at least not mention it explicit. One can conclude that [68, 76] depict some of many examples where the authors describe an approach *for* a CPPS rather than *by means of* a CPPS.

The aforementioned also applies to the overall usage of models, since the more *classical* approaches tend to utilize, often simplified and/or generated, information that are either given in global tables or even not at all. Especially for the *classical* approaches the models, if utilized, are often only concerned with the functional capabilities of production resources and the description of necessary operations to transform a product rather than on behavior aspects, non-functional properties or material flow/transportation aspects. Thus, many *classical* approaches tend to derive mathematical models, often for rather specific defined problems but in elegant ways, and try to solve them either

exactly (see [77, 78]) or with the help of applied heuristics (see [79, 80]). On the other hand, simulation-based approaches (such as [35, 81, 82]) for CPPS are currently used less frequently.

#### 4.4 Findings regarding R4

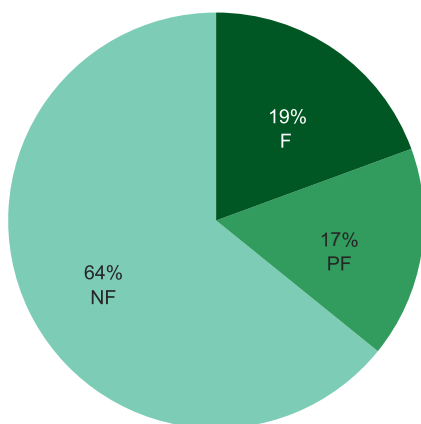
The model creation as basis for reconfiguration management is considered as partially fulfilled if it is either systematically conducted manually (level 1) or with tool support (level 2). It is fulfilled (level 3) if an automated model creation process without human intervention is provided. “Tool support” refers to the support of the user with e.g. dedicated input via a user interface. On the contrary, an “automatic creation” refers to an extraction from existing artifacts.

Our SLR unveiled that a methodological support for reconfiguration management model creation is not addressed in most of the examined publications (81%), see Figure 14. In some cases, such as [48, 62, 83, 84], support for a manual creation is described (12%). In rare cases, such as [81, 85], respective tool support is described (3%). Also, only few publications were rated to cover an automated model creation without human intervention (4%). e.g. [35, 86].

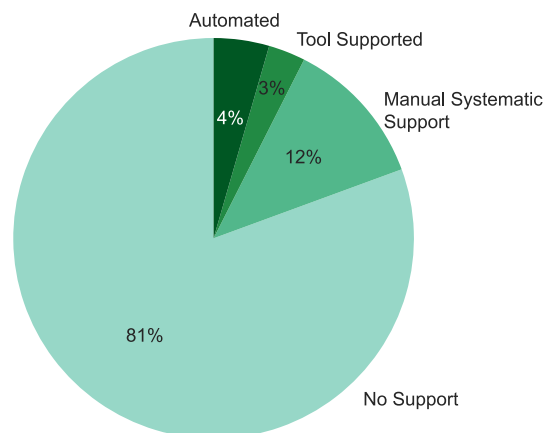
#### 4.5 Findings regarding R5

The consideration of interoperability aspects is partially fulfilled (level 1) if either the HW or SW interoperability is regarded. If both, HW and SW interoperability aspects, are considered, it is fulfilled (level 2).

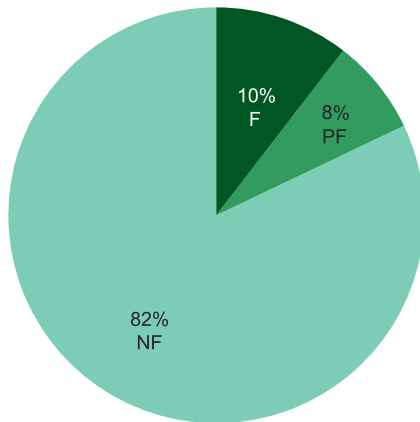
This requirement is barely addressed at all (18%), see Figure 15. One of the few examples that partially fulfill this requirement (8%) is given in [73] as they integrate the collaboration of groups of resources into production planning



**Figure 13:** Requirement 3: CPPS potential exploitation – F = fulfilled, PF = partially fulfilled, NF = not fulfilled.



**Figure 14:** Requirement R4: model creation support.



**Figure 15:** Requirement R5: interoperability consideration – F = fulfilled, PF = partially fulfilled, NF = not fulfilled.

in order to fulfill tasks. However, they do not specifically address the SW aspect of this requirement. R5 was fulfilled by 10% of the examined publications, some examples are [7, 48, 62, 86]. This shows that there is a need for methodological support, especially if reconfiguration management is addressed as a comprehensive approach.

#### 4.6 Further findings from full text reading

Most approaches neglect to cover the behavior of the real production system by means of its control approach. This is even true for approaches based on the CPS concept, which however cover this aspect more often than the more *classical* approaches. Some of the exceptions here are [35, 69], whereby [69] considers the behavior and models it in automata for each machine and transport system.

The SLR revealed further interesting aspects, which are tackled within the literature but were not within the specified scope of the applied assessment scheme. The setup time by means of a needed ramp up phase is seldom considered (e.g. in [65]). However, this is most likely based on the fact that most approaches focus on reconfiguration of a single product family portfolio, where the ramp up phase is not considered, as mainly the same machines are used. Consequently, many approaches are not covering this aspect, since the scope of classic RMSs are on one product family. Moreover, the tool orientation with respect to product orientation is also rarely addressed. However, it is covered by [65, 66]. In turn, the SLR also revealed that the six established RMS characteristics (see [38, 87, 88]): Modularity, Integrability, Convertibility, Customization, Scalability and Diagnosability, whilst being often mentioned, are barely utilized by

means of assessment metrics. Some approaches which are at least to a certain degree concerned with a subset of these characteristics are [7, 76, 89] and [90].

Overall, the SLR reveals that there is no approach that answers the research question under investigation in total.

#### 4.7 Limitation of this SLR

Ending this section, the authors want to state the following: Some approaches tend to receive a better rating when it comes to the fulfillment of requirements (a.) compared to other approaches and (b.) even if they have a rather specific scope just because they fit better into our defined assessment scheme. The authors also want to point out that we tried our best to derive a fitting assessment scheme, which takes into account an appropriate level of detail. The assessment scheme is rather detailed, but still provides a good overview without being too complex. Nevertheless, with other schemes it would be possible that some approaches would tend to receive a better rating – this SLR does by no means intend to discredit or diminish the value of the work of any cited author. Adding to this: The examined approaches hugely differ in terms of the level of details they provide, especially when it comes to *how* things are implemented (algorithm/logic) or described (information and/or their modeling). This made it difficult to assess the publications.

Another noteworthy aspect to the methodological approach for conducting the SLR is regarding the application of the proposed tool. To that end, insights, e.g. by clustering publications in terms of common authors or institutions to find similarities could be formulated by a dedicated query set. This would provide the possibility to regard associated whole research efforts instead of single publications. This is especially relevant for authors that present their work in multiple consecutive publications.

### 5 Conclusion and outlook

In order to examine how comprehensive the stated research question of *how CPPSs can be enriched with the capability of self-organized reconfiguration management such that the solution space is fully exploited and various economic factors, as well as reconfiguration triggers, can be considered appropriately?* is answered by the literature of the past five years, a systematic literature review was conducted. The following **key insights** are a summary of Section 4.6 and have been derived within the course of our literature review:

- The formulated research question was not sufficiently answered by any single investigated approach.
- The aspects of reconfiguration management are subject of numerous ongoing research activities. Thus, the importance of reconfiguration management is evident.
- A trend towards the consideration of the CPS concept for reconfiguration has been recognized within the screened literature.
- However, most of the reviewed CPPS-based approaches involve reconfiguration *for* CPPSs rather than *by means of* CPPSs.
- Reconfiguration management is a research area where several aspects, which are mainly considered disjunctive, need to be combined, e.g. process planning and production planning.
- Further, reconfiguration management requires dedicated models to describe the reconfiguration space, but methodological support for the model generation is mainly not considered.
- Additionally, since the energy cost is getting more and more expensive and unstable, a higher amount of approaches covering energy aspects is expected.

This SLR revealed that there is still significant research need concerning reconfiguration management. For this survey, we assessed the reconfiguration management in manufacturing, taking into account the operational requirements and standard reconfiguration metrics like production and reconfiguration effort.

Moreover, few articles discussed the characteristics of RMS (Modularity, Integrability, Convertibility, Customization, Scalability, Diagnosability, Mobility, Automation) as quantitative metrics to assess reconfigurability and addressed them independently. Further research would be required to combine RMS metrics with other production metrics as cost and time so as to obtain reliable configurations.

In general we distinguished three challenges, which offer great potential to improve the reconfiguration management.

**Challenge 1 – Production behavior consideration.**

In order to consider the behavior of real production systems by means of their control approach, the rise of the concept of digital twins with the implied availability of simulation models depicts a possibility and a challenge at the same time. This leads to a better representation of reality by

considering the control behavior deterministic instead of stochastic. Thus, the results of the reconfiguration management are more reliable. Research has to be conducted on how to combine the simulation models with intelligent algorithms for a reconfiguration management.

**Challenge 2 – Model creation support.** To increase the reliability of reconfiguration management and reduce the implied effort not only during operation but also while developing the needed models for reconfiguration, systematic support is needed. This requires for methodologies, which ease the model creation either semi-automatic or automated. Hence, not only interoperability of different models, but also of different machines need to be considered. Especially for existing and in use systems this presents a particular challenge as engineering artefacts and further information are often missing.

**Challenge 3 – Supply chain reconfiguration.** Future research activities could consider a whole supply chain, expanding the reconfiguration management scope to comprise both operational requirements and organizational ones and attend a common objective that fits all concerned stakeholders along the supply chain. The supply chain reconfiguration was not within the scope of this literature review. However, more comprehensive approaches covering the whole supply chain could lead to an early detection of dynamic changes. Furthermore, when considering such an expanded scope, it is possible to aim for a global optimum of this expanded scope consequently.

To conclude, addressing the three challenges mentioned above, even partially, is a demanding task. An effective reconfiguration management which satisfies these challenges can help a CPPS to adapt to changing conditions and maintain optimal performance. It can also improve the reliability of the system by enabling it to react to unexpected events. Overall, this can involve considering a range of factors, including economic considerations, technical capabilities, and the specific triggers that may prompt the need for reconfiguration. Because of these benefits, the authors are convinced that in the upcoming years, more research should, and will, address the mentioned challenges, towards a more comprehensive reconfiguration management.

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**Conflict of interest statement:** The authors declare no conflicts of interest regarding this article.

Appendix: Analysis results

#	R1	R1.1	R1.2	R1.2.1	R1.2.1.1	R1.2.1.2	R1.2.2	R1.2.2.1	R1.2.2.2	R1.2.2.3	R1.2.2.4	R1.2.3	R1.3	R1.3.1	R1.3.2	R1.3.3	R1.4	R2	R3	R4	R5
[58]	57.50%	2	3	2	0	2	2	1	0	2	0	0	0	0	0	0	2	10	2	0	0
[62]	17.50%	1	2	1	1	1	1	0	0	1	0	0	0	0	0	0	0	3	0	1	2
[86]	22.50%	0	4	1	0	1	2	0	0	1	2	1	0	0	0	0	1	5	1	3	2
[80]	5.00%	0	2	0	0	0	2	1	0	0	2	0	0	0	0	0	0	10	0	0	0
[56]	55.00%	2	2	0	0	0	2	0	0	2	1	0	0	0	0	0	2	10	2	0	0
[69]	67.50%	1	2	0	0	0	1	0	0	0	0	1	3	1	1	1	2	4	2	0	0
[91]	15.00%	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
[78]	15.83%	0	3	1	1	0	1	0	0	1	0	1	1	1	0	0	0	10	0	0	0
[92]	50.83%	1	2	1	1	1	1	1	0	0	0	0	1	1	0	0	2	10	1	1	0
[93]	15.00%	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0
[60]	39.17%	0	4	2	2	0	2	1	0	1	0	1	2	1	0	1	1	1	0	0	0
[79]	31.67%	0	6	2	2	0	3	1	1	2	0	1	2	1	0	1	0	3	0	0	0
[89]	51.67%	0	4	2	2	0	2	1	0	1	0	1	2	1	0	1	2	10	0	0	0
[94]	62.50%	0	5	1	1	1	1	0	0	0	1	2	3	1	1	1	2	4	0	0	0
[95]	55.83%	1	4	2	2	0	2	1	0	2	0	0	1	1	0	0	2	3	0	0	0
[96]	26.67%	0	4	1	1	0	2	1	1	0	0	1	2	1	0	1	0	4	0	0	0
[67]	44.17%	0	6	2	2	0	4	1	1	1	1	1	2	1	1	0	1	3	0	0	0
[64]	45.83%	0	5	3	2	2	2	1	0	2	0	0	1	1	0	0	2	4	0	0	0
[59]	47.50%	1	4	1	1	0	3	1	1	1	0	0	0	0	0	0	2	4	0	0	0
[97]	23.33%	0	6	2	2	0	3	1	1	1	0	1	1	1	1	0	0	4	0	0	0
[90]	47.50%	0	4	2	2	0	3	1	0	2	0	1	3	1	1	1	1	3	0	0	0
[63]	62.50%	0	5	2	2	1	2	1	0	2	0	1	3	1	1	1	2	4	0	0	0
[49]	37.50%	1	5	2	2	1	3	0	1	1	1	0	0	0	0	0	1	1	0	0	0
[98]	56.67%	0	6	2	2	0	3	1	0	1	1	1	2	0	1	1	2	4	0	0	0
[65]	51.67%	0	4	2	2	0	2	1	0	1	0	1	2	1	1	0	2	10	0	1	0
[85]	8.33%	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	1	1	2	0
[61]	54.17%	0	5	2	2	0	2	1	0	1	0	1	2	1	0	1	2	3	0	0	0
[83]	37.50%	2	5	1	1	0	3	1	1	1	0	1	0	0	0	0	0	1	0	1	0
[99]	12.50%	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
[100]	17.50%	1	2	1	0	1	1	1	0	0	0	0	0	0	0	0	0	2	0	0	0
[71]	35.00%	0	4	1	1	0	3	1	0	2	1	0	0	0	0	0	2	3	0	0	0
[101]	26.67%	0	4	1	1	0	4	1	1	1	1	0	2	1	1	0	0	4	0	0	0
[66]	40.83%	0	3	2	2	0	1	0	0	1	0	1	1	1	1	0	2	10	0	0	0
[48]	77.50%	1	6	2	2	1	4	1	1	2	2	0	3	1	1	1	2	4	0	1	1
[102]	40.83%	1	3	0	0	0	2	1	0	0	1	1	1	1	0	0	1	3	0	0	0
[54]	28.33%	1	3	2	1	2	1	0	0	0	2	0	1	0	1	0	0	10	0	0	0
[103]	19.17%	0	1	0	0	0	1	0	0	0	1	0	2	1	0	1	0	3	0	0	0

Appendix: (continued)

#	R1	R1.1	R1.2	R1.2.1	R1.2.1.1	R1.2.1.1.1	R1.2.1.1.2	R1.2.2	R1.2.2.1	R1.2.2.2	R1.2.2.3	R1.2.2.4	R1.2.3	R1.3	R1.3.1	R1.3.2	R1.3.3	R1.4	R2	R3	R4	R5
[104]	24.17%	0	3	1	1	1	0	2	1	0	2	0	0	2	1	1	0	0	4	0	0	0
[105]	15.00%	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
[82]	0.00%	0	0	0	0	0	1	2	1	1	2	0	0	0	0	0	0	0	4	2	1	1
[57]	87.50%	2	5	2	0	0	2	1	0	0	2	0	2	3	1	1	1	2	10	2	0	0
[106]	26.67%	0	4	0	0	0	0	3	1	0	2	2	1	2	0	1	1	0	4	2	0	0
[70]	54.17%	0	5	2	1	1	2	2	1	0	2	0	1	2	1	0	1	2	5	1	3	2
[107]	30.83%	1	4	2	2	2	0	2	1	0	2	0	1	1	0	1	0	0	4	0	0	0
[52]	69.17%	1	6	2	2	2	0	3	1	0	1	1	1	2	1	1	0	2	10	1	0	0
[108]	34.17%	1	2	1	0	1	1	1	1	0	0	0	0	2	1	1	0	0	8	2	0	0
[50]	37.50%	1	5	2	2	1	1	3	1	0	2	1	0	0	0	0	0	1	3	0	0	0
[84]	25.83%	1	2	1	1	0	0	1	0	0	3	0	0	1	0	1	0	0	4	1	1	0
[55]	53.33%	1	3	1	1	0	1	1	0	0	2	0	1	1	0	1	0	2	10	1	0	0
[7]	80.00%	1	7	2	1	1	2	3	1	1	3	0	2	3	1	1	1	2	7	2	0	2
[109]	48.33%	0	6	2	2	1	1	4	1	1	2	2	1	1	1	0	0	2	4	0	0	2
[51]	30.83%	1	4	1	1	1	0	3	1	0	1	2	0	1	0	1	0	0	10	0	0	0
[68]	56.67%	0	6	2	2	0	2	0	1	0	2	1	1	2	1	1	0	2	10	0	0	0
[76]	29.17%	0	5	1	0	1	1	3	1	0	3	2	1	2	0	1	1	0	3	2	0	1
[110]	20.00%	0	3	1	0	0	1	1	1	0	0	0	1	0	0	0	0	1	1	0	0	2
[72]	65.00%	1	6	1	1	1	0	4	1	1	1	2	1	3	1	1	1	1	4	0	0	0
[73]	34.17%	0	2	0	0	0	0	2	1	0	1	0	0	2	0	1	1	1	3	1	0	1
[12]	66.67%	2	5	1	1	1	1	3	1	1	2	0	1	2	1	0	1	1	2	2	0	0
[35]	80.00%	1	7	2	2	0	0	3	0	1	1	1	2	3	1	1	1	2	5	1	3	0
[81]	0.00%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	0
[111]	15.83%	0	3	0	0	0	0	2	1	0	2	0	1	1	1	0	0	0	1	1	0	0
[112]	2.50%	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
[74]	27.50%	0	6	2	2	2	0	2	1	0	2	0	0	0	0	0	0	1	3	0	0	0
[77]	20.00%	1	3	2	2	0	0	1	1	0	0	0	0	0	0	0	0	0	4	2	1	2
[113]	12.50%	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0
[114]	46.67%	2	2	0	0	0	0	2	1	0	0	1	0	2	0	1	1	0	2	2	0	0
[53]	45.83%	1	5	2	2	0	0	3	1	0	1	1	1	1	1	0	0	1	3	0	0	0



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