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Technical Paper

A systematic methodology for changeable and reconfigurable manufacturing systems development

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ABSTRACT

Pursuing manufacturing competitiveness in the dynamic industrial landscape necessitates implementing changeable and reconfigurable manufacturing systems (RMS) capable of rapid adaptation to varying functionalities and capacities. However, current manufacturing system development methods often overlook product-driven changes during the system's life cycle, hindering companies from effectively responding to shifting demands and technological advancements. Consequently, this research paper proposes a systematic methodology for designing and developing changeable and reconfigurable manufacturing systems to address this gap. The proposed methodology is derived from a synthesis of design theory, reconfigurability theory, and practical insights to guide the development process from conception to implementation. The four-step development method adopts a system life cycle-wide perspective, encompassing (i) identification and clarification of the need for reconfigurability, (ii) formulation of reconfigurable concepts, (iii) detailed design of the reconfigurable system, and (iv) successful implementation and utilization of reconfigurability. Crucially, the development method blends existing RMS development tools and novel tools co-created with industry partners, ensuring its pragmatic and holistic applicability. Each step incorporates specific activities and supporting tools, rendering the methodology flexible and adaptable to diverse manufacturing environments. The proposed methodology was validated through case studies in seven diverse manufacturing companies. The primary contributions of this research lie in integrating new and existing development tools into a comprehensive and practical development method, facilitating a system life cycle-wide approach to RMS design, and promoting industry-specific adaptability. The validation across multiple manufacturing companies ensures the effectiveness and broad applicability of the proposed methodology. Consequently, this paper is a valuable resource for manufacturing companies aiming to enhance competitiveness by adopting changeable and reconfigurable manufacturing systems.

1. Introduction

Unpredictable market changes are a constant concern for manufacturing companies, which must frequently change manufacturing systems to produce the expected variety, volumes, and generations of products responsively and cost-effectively. Developing new manufacturing systems to accommodate these changes requires explicit consideration of expected future requirements and how the changes might affect existing production processes. However, the uncertainty related to future requirements is increasing drastically due to global challenges such as natural disasters, geopolitical conflicts, and the transition to an environmentally sustainable economy. These circumstances present both challenges and opportunities for manufacturing companies. Challenges relate to the feasibility of relying on traditional development approaches for manufacturing systems, as these are ill-equipped to accommodate uncertainties [1], potentially resulting in higher costs, insufficient process capabilities, and reduced competitiveness of the manufacturing system. Opportunities relate to adopting new manufacturing paradigms, specifically changeable and reconfigurable manufacturing systems, as these are conceived to accommodate uncertainties in variants, volume, or products [2] at competitive costs.

Reconfigurable [3] and changeable [4] manufacturing systems have gained widespread attention [5,6]. Enabled by modularity,

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integrability, customization, convertibility, scalability, and diagnosability [7], these systems implement the concept of reconfigurability, which allows cost-effective reuse of manufacturing assets and responsive adaption to market changes. In the context of these systems, reusable manufacturing assets are also referred to as modules, which are typically standardized system elements implementing one or more functions and with defined interfaces to other modules facilitating easy interchangeability.

The development of reconfigurable and changeable manufacturing systems is complex. These systems need to consider changes encountered across varying time horizons to define the right level of reconfigurability for the system, as illustrated in Fig. 1. Three different types of change drivers are variant changes (in the short-term), volume changes (in the mid-term), and product changes (in the long-term), each requiring progressively larger adaptations of a production system, thereby adding to the complexity of developing these systems. While some system changes can occur as frequently as multiple times per day (e.g., product variant changeovers), others may happen only a few times per year (adjusting manufacturing capacity) or once every few years (introducing new product generations). The different scopes of change in the production system and their changeability classification are illustrated by analogy on the right-hand side of Fig. 1.

Relying on traditional manufacturing development methods devised to create manufacturing systems for only one or a few products in a fixed volume presents challenges for the longevity of the resulting manufacturing systems. However, despite interest from the industry towards changeable and reconfigurable manufacturing, studies demonstrating the potential of these systems [9,10], and cases of implementation of RMSs in companies [11,12], the adoption of reconfigurable manufacturing in the industry is still limited [13–16]. There is, therefore, a clear need to support companies in their endeavor to increase the changeability of their production through a tool-based and practitioner-oriented systems development methodology for changeable and reconfigurable manufacturing systems. For the purposes of the present study, "tool" is used as an umbrella term that comprises different procedures, approaches, or techniques, whether quantitative or qualitative, to solve specific sub-problems related to manufacturing system development.

The contribution of this paper is the presentation of a tool-based, practitioner-oriented, systematic methodology for the development of changeable and reconfigurable manufacturing systems. The specific research objectives of the systematic development methodology are presented in Section 2.4.

Fig. 2 illustrates the research design and the corresponding sections of this paper. The research design comprises three main phases with

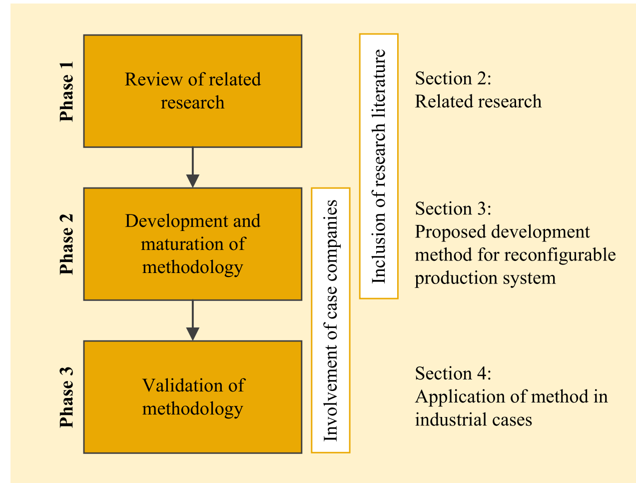

Fig. 2. Overview of research method and corresponding sections of this paper.

some overlapping, as described in the following.

In phase 1, related literature has been reviewed. Research on reconfigurable and changeable manufacturing is plentiful. Thus, a review of available literature on methods and tools for developing reconfigurable manufacturing systems initiated the research process. Highlights of this phase are included in Section 2, and the section concludes by summarizing identified research gaps.

Section 3 then introduces the results of the development and maturation phase. This second phase first took outset in the thorough literature review followed by mapping available RMS development methods and tools which provided most of the "building blocks" of the proposed methodology. Next, the development of the proposed methodology was primarily concerned with structuring the selected tools within specific activities of the proposed methodology to form a coherent and logical development process. Phase 2 additionally involved the maturation of individual tools in collaboration with case companies and the development of additional tools needed to support the proposed development methodology.

Phase 3 of the research design involved validation of the method in different industrial settings. The process and results hereof are described in Section 4, where seven case companies involved in this research are presented along with key findings from applying the methodology across these cases. Next, Section 5 discusses the results, implications, and limitations of the present study. Lastly, Section 6 concludes the findings of this study and provides suggestions for further research.

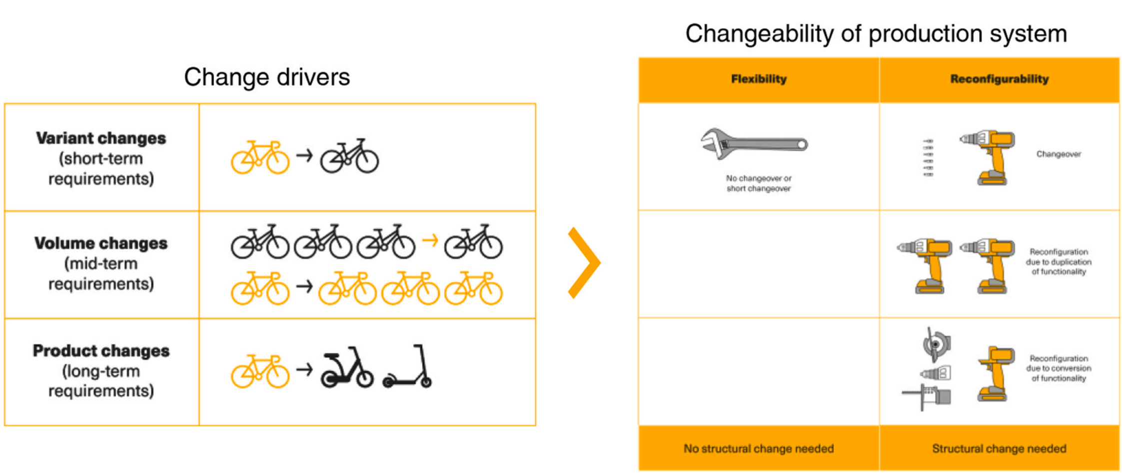

Fig. 1. The relation between change drivers over different time horizons and their impact on the manufacturing system's changeability.
Adapted from Andersen et al. [8].

2. Related research

Research on the development of changeable and reconfigurable manufacturing systems has significant analogies with traditional manufacturing system design; therefore, studies focusing on conventional manufacturing system design have been first reviewed, as detailed in Section 2.1. Additionally, studies on the development of changeable and reconfigurable manufacturing systems have been analyzed and classified as either (i) studies focusing on the system level and proposing corresponding solutions, as covered in Section 2.2, or (ii) studies proposing solutions for the many partial issues, as covered in Section 2.3. Based on the findings from reviewing related literature, Section 2.4 presents the research objective and requirements for the proposed methodology.

2.1. Traditional manufacturing system design and development

Manufacturing systems are traditionally designed to produce specific products. In this sense, manufacturing development can be viewed as similar to the problem-solving activity of engineering design, and elements of manufacturing systems design can be traced back to product design theory [17]. However, while research on product design and development methodologies is abundant and industrially mature (notable examples include [18–20]), similar research focusing on manufacturing systems development to accommodate changing product requirements is relatively scarce. The similarities between product design and manufacturing system design mean that most manufacturing design methodologies involve the same basic activities of (i) problem analysis, (ii) solution proposal, and (iii) evaluation. Specific to manufacturing systems, Wu [21] presented a design methodology to accommodate both greenfield and brownfield manufacturing design. Accommodating the often iterative nature of design processes, Wu [21] integrates multiple iterative loops to earlier design stages, thus implementing reactive rather than proactive adaptation to changes. To proactively adapt systems to changes, and thus for manufacturing design to become manufacturing development, a broader life cycle perspective, including system implementation, must be adopted [17]. Johansson and Nord [22] extend the manufacturing design methodology to include equipment installation and ramp-up. An even broader perspective on the system life cycle is demonstrated by the inclusion of system performance monitoring activities in the development methodology by Bellgran and Säfsten [17]. Even so, traditional manufacturing design and development methodologies lack focus on system design that enables adaptation to the three change drivers (see Fig. 1). Moreover, these often overlook the impact of change drivers on manufacturing systems' life cycle, which, on the other hand, should significantly affect design choices during the development of a reconfigurable or changeable manufacturing system [23].

2.2. Changeable and reconfigurable manufacturing system design and development methods

Changeability is about responding to change impulses, as described in Section 1, proactively and economically [4]. The change drivers reflect product-related changes on different time horizons and for other objectives. Changeability is an umbrella term that covers changes to production [2], both physically and logically and across factory levels [2,4]. In the context of changeability, factory levels span from the most disaggregate level of individual production stations across production systems and factories to the most aggregate perspective of a production network [4]. Different types of changeability can be implemented across different factory levels. While changeability can be implemented in various ways, only reconfigurability as a changeability class will be described here (for detailed descriptions of all change classes, see [4]). Fundamentally, reconfigurability is the capability to change the functionality and capacity of production in response to change drivers [23] by making structural changes to the production system [3]. As described in Section 1, production systems accomplish this through the core characteristics of an RMS, of which the reuse of production assets through modular architectures is archetypical [24].

An essential aspect of changeable and reconfigurable manufacturing systems is the necessity to consider both products and processes and their dynamic relations due to changes. While traditional manufacturing systems must also ensure a fit between the product and manufacturing processes, the relation is static rather than dynamic over time. The concept of change drivers as representations of future products' needs of the production processes is central to several methods [1,23,25,26]. In contrast, others take outset in, e.g., submitted engineering changes [11], processes of defined product range [27], or requirements for an initial product [28]. The most explicit consideration of product-process interactions is provided by Heisel and Meitzner [14], who consider workpiece dimensions and materials' impact on required process capabilities. Common to the reviewed methods is consideration of product-process interactions, although to varying degrees.

The shortcomings of traditional manufacturing development methods, as outlined in Section 2.1, sparked research interest regarding design and development methods for RMSs. Abdi and Labib [29–31] propose a generic design method and demonstrate its applicability through a case study in the automotive industry. Focusing on object-oriented design principles, Schuh et al. [25] present a design method for changeable manufacturing systems and show application through two automotive industry cases. Andersen et al. [26] propose another design method for reconfigurable manufacturing systems applied in two industrial cases. While Heisel and Meitzner [14] present a design method that focuses more on machine design than systems design, Bryan et al. [32] offer a method for designing system reconfigurations through mathematical optimization. However, judging their practical applicability is challenging as both studies lack a demonstration of the relevance of their methods in industrial cases.

Besides these numerous design methods for reconfigurable and changeable manufacturing systems, several manufacturing development methods (i.e., methods adopting a broader life cycle perspective compared to manufacturing system design, including system implementation) have also been proposed. A method covering all development phases is proposed by Deif and ElMaraghy [33], yet does not include a cyclic perspective (i.e., lacks iterative loops) on development. Furthermore, the application of the method is only demonstrated through a numerical example of electronics manufacturing equipment. Several development methods acknowledge the often-iterative nature of systems development and are consequently designed as cyclic methods to various extents [11,23,27,28,34]. Only Al-Zaher [11] demonstrates the application of their development method in an industrial case. The remaining development methods present numerical examples [27,34] or no application examples [23].

Common to most of the methods reviewed is their use of multiple levels of abstraction in relation to the systems development process. In this context, abstraction levels are considered as different degrees of aggregation of the activities and sequences involved in systems development, ranging from methods with only a high-level description of the steps involved, omitting specification of the comprising development activities [25,32], to methods that present subdivisions of these steps into comprising activities [1,11,14,23,26,27,29–31,35] or sub-activities [33,34]. Despite the generally higher degree of instruction for users among the reviewed methods, activities are not described to the same level of detail in all instances, as demonstrated by Francalanza et al. [27], where only the synthesis and criteria steps are elaborated on in their proposed development process.

A method may suggest specific tools to support the user in carrying out development activities. Most reviewed methods are supported by one or more specific tools to carry out the comprising activities, although the number and scope of tools suggested differ significantly. Most common are methods that suggest a single tool to support RMS design or development [14,25,26,29,30], while some methods offer several tools typically associated with different development activities [11,28,32,33]. However, only Andersen et al. [1,23] and Napoleone et al. [35] provide comprehensive collections of tools spanning all system life cycle phases.

Seeking to integrate previous research and practical experience, Andersen et al. [1] propose a holistic and practitioner-oriented development method emphasizing adaptability to various contexts. Despite a focus on industry, neither Napoleone et al. [35] nor Andersen et al. [1] present validation of their proposed methods in industrial cases. Table 1 summarizes the characteristics of the reviewed RMS design and development methods.

Table 1 shows that most reviewed methods are categorized as development methods, thereby adopting a broader perspective on manufacturing system development in line with the life cycle-wide considerations required by practitioners. Furthermore, a few methods restrict themselves to a more abstract perspective on realizing new manufacturing systems by specifying only the high-level steps involved. However, most methods subdivide development tasks into specific activities. For practitioners with limited knowledge of RMS, instructional methods are considered conducive for application in industry. Some proposed methods further increase their instructional value by suggesting specific tools for development activities. However, a recurring issue is poor or lack of instruction on the practical application of these tools. The overview of reviewed methods further illustrates that while some studies seek to validate their proposed methods, this is done through single cases relating primarily to automotive industries. Several studies without validation rely on analytical generalization. Both factors limit the proven generalizability of the proposed methods across manufacturing industries and company contexts.

2.3. Partial methods for reconfigurable manufacturing system development

Besides methods for system design and development, literature addressing partial problems of manufacturing system development is abundant. These partial problems include, among others:

- Design of reconfigurable machines (RMs) [36,37] or reconfigurable machine tools (RMTs) [12,38,39].
- Configuration design of RMSs at system level [40–44] and network level [45,46].
- RMS evaluation methods in the pre-design, [47], design, and re-design phase [48]
- RMS layout design in brownfield scenarios [49,50] or as a greenfield scenario [49].
- RMS ramp-up productivity improvement [51]
- RMS control architecture design [52]

Although essential, these studies only address a subset of the activities involved in developing an RMS. For example, focusing only on the development of individual machines or tools omits the development task's system-level perspective. Furthermore, only a few studies [12,36,47] include industrial cases to demonstrate the applicability of their proposed methods, whereas the remaining studies only include illustrative examples to different extents.

2.4. Research objectives

Based on the above findings from reviewing related literature on changeable and reconfigurable manufacturing development, the objective of this paper is to bridge the gaps in current literature by presenting a systematic development methodology for changeable and reconfigurable manufacturing systems that exhibits the following features:

1. **Adopts a comprehensive system life cycle perspective**: Manufacturers must account for the entire life cycle of their manufacturing systems, and any development methodology that offers only a partial perspective on development challenges along the system life cycle will be of limited value to practitioners. Thus, the proposed development methodology must consider the entire system life cycle to be viable in the industry.
2. **Encapsulates the complexity of comprehensive system development methods**: High-level development methodologies, which do not specify individual activities necessary to reach a viable system design, may be too abstract for practitioners to apply in practice. Therefore, the proposed development method must provide an

Table 1
Characteristics of reviewed methodologies for designing and developing reconfigurable manufacturing systems.

Author	System life cycle focus	Levels of abstraction	Tools suggested	Validation method	Validation context
Abdi and Labib [29–31]	Design	Steps and activities	AHP, clustering	Case study	Automotive industry
Deif and ElMaraghy[33]	Development	Steps, activities, and sub-activities	Capacity and functionality scalability planning tool, system configurator	Illustrative example	Electronics manufacturing
Heisel and Meitzner[14]	Design	Steps and activities	Standard module library	Illustrative example	General manufacturing
Bi et al.[34]	Development	Steps, activities, and sub-activities	N/A	N/A	N/A
Schuh et al.[25]	Design	Steps	Object-oriented design	Multiple case studies	Automotive industry
Tracht and Hogreve[28]	Development	Steps, activities, and sub-activities	Requirements list, brainstorming, clustering	Case study	Transportation accessories
Al-Zaher[11]	Development	Steps and activities	DSM, clustering, virtual manufacturing development environment	Multiple case studies	Automotive industry
Bryan et al.[32]	Design	Steps	Precedence diagrams, genetic algorithm	Illustrative example	Furniture manufacturing
Francalanza et al. [27]	Development	Steps and activities	N/A	Illustrative example	General manufacturing
Andersen et al. [23]	Development	Steps and activities	Multiple (see source for full list)	N/A	N/A
Andersen et al. [26]	Design	Steps and activities	Questionnaire	Multiple case studies	Pump manufacturing and construction equipment industry
Napoleone et al. [35]	Development	Steps and activities	Multiple (see source for full list)	N/A	N/A
Andersen et al.[1]	Development	Steps and activities	Multiple (see source for full list)	N/A	N/A

increased instruction level by including individual activities comprising the development methodology.
3. **Is adaptable to different manufacturing contexts**: RMS development methodologies designed for specific manufacturing industries or contexts may prove infeasible to apply outside their intended scope. Therefore, for a RMS development methodology to be broadly applicable in industry, the proposed development methodology must be sufficiently generalizable and adaptable at the same time to accommodate various manufacturing contexts.
4. **Is industrially applicable**: RMS methods and development tools that rely on their users having intricate knowledge of changeable and reconfigurable manufacturing systems theory may negatively impact widespread adoption in the industry. The proposed development methodology must consequently provide development tools tailored toward practitioners.

3. Proposed development methodology

The systematic methodology for changeable and reconfigurable manufacturing system development is presented here and shown in Fig. 3. The methodology comprises the following four sequentially structured and iterative steps:

- Step 1 identifies the need for reconfigurability based on internal and external change drivers.
- Step 2 then focuses on developing and evaluating reconfigurable system or equipment concepts.
- Detailed design, evaluation, and documentation of the reconfigurable manufacturing system is then carried out in Step 3.
- Finally, Step 4 focuses on implementing, exploiting, and continuously monitoring the reconfigurable manufacturing system.

Evident from the descriptions of the four steps of the method is its similarity to traditional development methods from the manufacturing and engineering design domains, such as Pahl et al. [19] and Bellgran and Säfsten [17], respectively. Nevertheless, as noted in Section 2.1, traditional development methods often overlook the impact of changes on the manufacturing system life cycle, which, on the other hand, should significantly affect design choices during the development of a changeable manufacturing system.

The proposed development method extends beyond existing RMS development methods since it was matured in collaboration with the industry to ensure the practical applicability of the method in the manufacturing industry. The method employs a hierarchical structure spanning different levels of abstraction, as shown in Fig. 4.

Each of the four steps comprises several logically structured activities with corresponding tools to support the application of the method, as further detailed in Sections 3.1 - 3.4. It is important to note that while these activities are likewise structured sequentially, iterations may also occur between these, as shown in Fig. 3. The wide range of manufacturing environments to which this methodology is applicable suggests that it is beyond the scope of this paper to offer detailed descriptions of the various conditions that might trigger an iterative loop at some point during the development process.

The tools included in the proposed development method support practitioners and are, therefore, fundamental to the method's applicability in industry. In principle, most existing RMS development tools could be mapped to the specific activities of the proposed development methodology. However, only tools validated in an industrial context have been included in this study. As demonstrated in Section 2.3, several existing methods and tools to support RMS development are available. Where possible, these tools have been integrated into the proposed development method. Where this was not feasible, tools were developed specifically for the proposed development method. To support this process, seven manufacturing companies were involved, acting as "pilot companies" for development iterations and maturation of the tools and overall development methodology.

Sections 3.1 to 3.4 introduce, in greater detail, the purpose of each step of the development method, its activities, and the supporting tools. Section 3.5 thereafter describes potential case-specific considerations of the methodology.

3.1. Step 1: Clarification of the need for reconfigurability

The proposed method's first step is identifying the extent to which an increase in changeability or reconfigurability is valuable to the manufacturing company. This step is of specific importance as the potential value of increased reconfigurability depends on company-specific change drivers, such as product variety, demand fluctuations, product road maps, and strategic goals set by the company. These aspects are clarified throughout the four activities of this step, as illustrated in Fig. 5.

First, activity 1.1 analyzes external and internal change drivers, whether product, technology, market, or strategy-related. These drivers are analyzed for one or more selected product families concerning their current and potential future impact on the reconfigurability requirements. A screening tool to support this activity was presented by Napoleone et al. [53].

Based on the identified need for reconfigurability, activity 1.2 analyses the existing level of reconfigurability in the manufacturing company and identifies any gaps. The relevance of this activity naturally depends on whether the company is pursuing greenfield or brownfield development, as the activity will only be relevant in the latter scenario. Boldt et al. [54] and Boldt and Rösiö [55] introduce a screening tool applicable to this activity.

Based on identified needs, capabilities, and gaps between these, activity 1.3 focuses on establishing a business case for increasing reconfigurability. At this stage of the development process, details are typically sparse. Therefore, a general business case focusing on overall benefits and costs may be established. Andersen et al. [56] developed a model to support this activity.

Lastly, a list of technical and economic requirements related to the reconfigurability of the manufacturing system is generated in activity 1.4. Examples of relevant requirements are available in Andersen et al. [8].

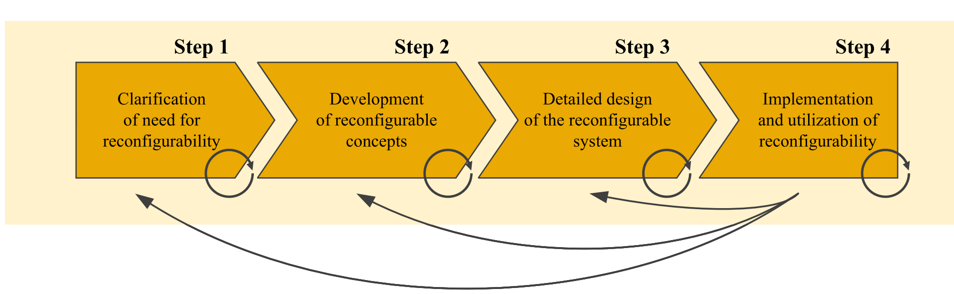

Fig. 3. Illustrates the four steps of the proposed development method with possible within-steps and between-steps iterative loops.

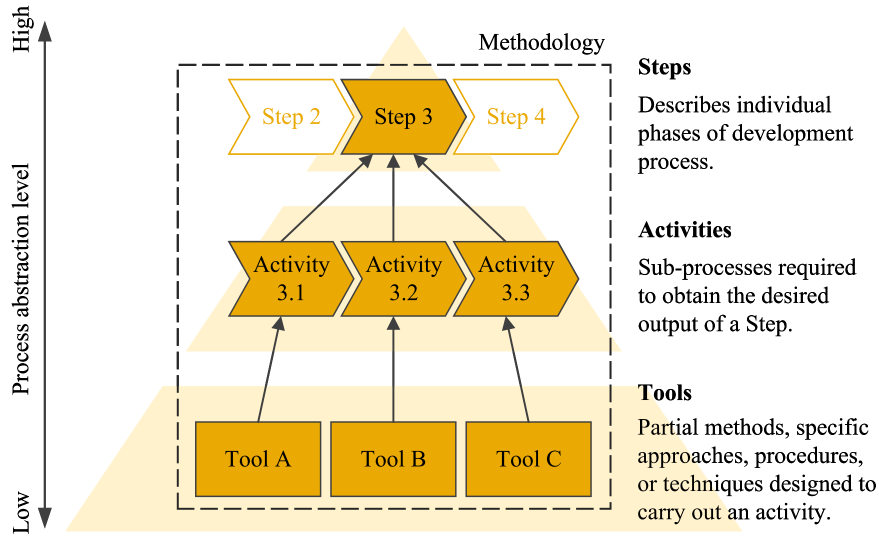

Fig. 4. The development methodology uses a generic hierarchy of steps, activities, and supporting tools.

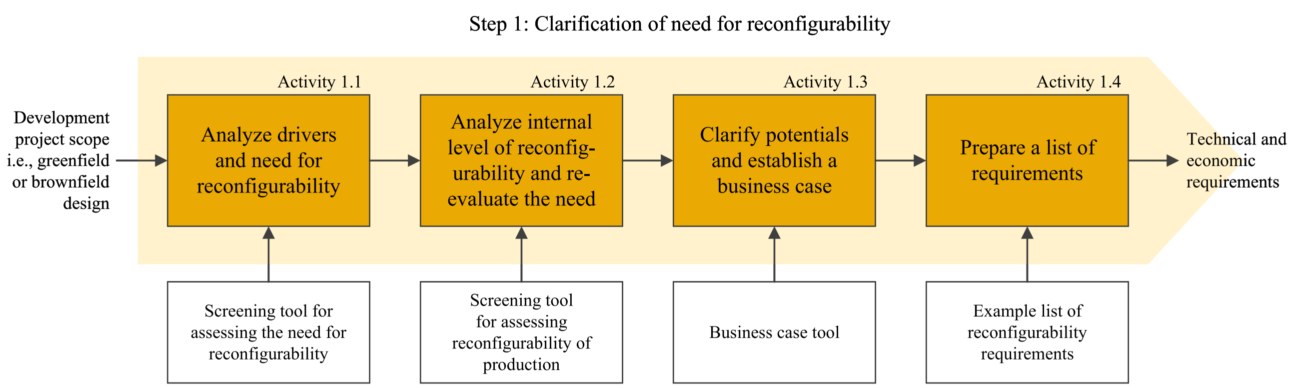

Fig. 5. The first step of the proposed development method – "clarification of need for reconfigurability" – including its four activities and supporting tools and examples.

3.2. Step 2: Development of reconfigurable concepts

Based on the potentials identified and requirements specified in Step 1, this second step focuses on developing and evaluating concepts for reconfigurable manufacturing. This is achieved through the five activities of Step 2, illustrated in Fig. 6.

Based on the initial potential for improving reconfigurability, activity 2.1 is concerned with further specifying where and to what extent reconfigurability is needed. This is done by analyzing product differentiation using, for example, the product variant master introduced by Mortensen et al. [57].

Having investigated the product side, activity 2.2 focuses on how the related manufacturing processes can meet current and forecasted product variety or volume needs. Such an analysis promotes further delimitation of focus areas for improving reconfigurability in manufacturing. Schou et al. [58] and Kjeldgaard et al. [59] developed product-process mapping tools to aid this.

Before design concepts can be generated, activity 2.3 focuses on selecting a suitable technical solution. To facilitate this, technical and economic evaluation criteria should be established, and consideration should be given regarding including RMS design characteristics as additional criteria. Due to the plethora of available technical solutions,

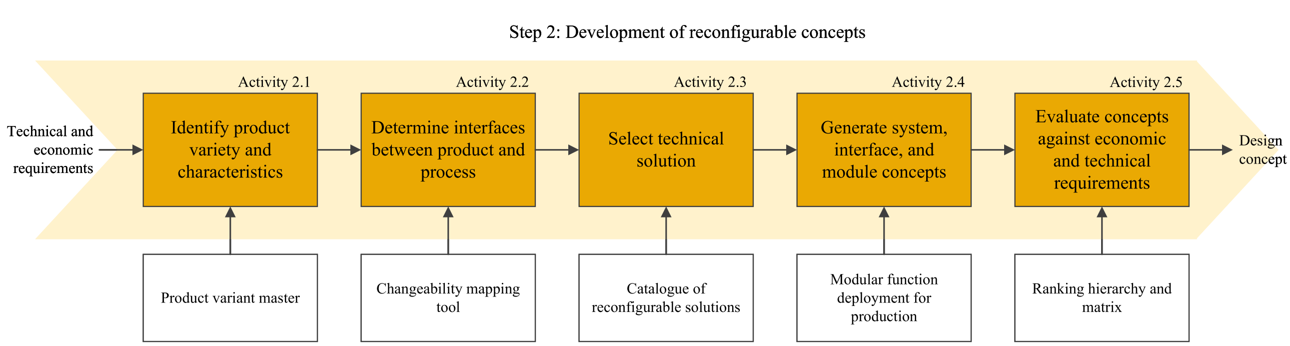

Fig. 6. The second step of the proposed development method – "development of reconfigurable concepts" – including its five activities and supporting tools.

an inspiration catalog was compiled by Andersen et al. [8].

Activity 2.4 emphasizes the creative process of generating design concepts through combinations of chosen technical solutions and module drivers. The concept of module drivers is known from product development (e.g., Ericsson and Erixon [60]) and acts to generate modules, based on the company's strategic goals. Brunoe et al. [61] listed manufacturing-specific module drivers to support the concept generation process.

Having generated one or more concepts for reconfigurable manufacturing, activity 2.5 concerns the evaluation of these concepts against general technical and economic criteria as well as reconfigurability-specific criteria. Depending on whether a quantitative or qualitative approach to evaluation is sought, this activity can be supported by using the business case tool by Andersen et al. [56] with more detail or by applying the ranking tool by Napoleone et al. [62].

3.3. Step 3: Detailed design of reconfigurable system

In this third step of the proposed method, the most feasible system design concept has been selected, and a detailed design of its components can be initiated. The three activities of this step are illustrated in Fig. 7.

The detailed design activity of a reconfigurable manufacturing system is structurally similar to traditional manufacturing systems. However, in activity 1.3, additional emphasis is placed on how design decisions may affect the reconfigurability of the system. This can be achieved by actively considering RMS characteristics during the design process. As inspiration, Andersen et al. [8] present different design principles of reconfigurability through a case.

Once the detailed design has been concluded, its performance regarding technical and economic criteria is evaluated in activity 3.2. This activity can, like activity 1.3 and activity 2.5, be supported using the business case tool by Andersen et al. [56], although in even greater detail than in previous steps. A more detailed evaluation model by Kjeldgaard et al. [63] is also available to support the activity.

A core principle of reconfigurable manufacturing is the reuse of equipment. Activity 3.3 supports this by focusing on proper documentation of module designs. In addition to traditional documentation such as CAD drawings, design documentation should include information concerning, for example, module drivers used in the design, interfaces, and their types [60]. Physical or digital repositories, or module libraries, are an effective way of facilitating the reuse of design knowledge. Ericsson and Erixon [60] present a module specification template as input for design repositories.

3.4. Step 4: Implementation and utilization of reconfigurability

The fourth and last step of the proposed method concerns realizing the reconfigurable manufacturing system designed in Step 3. This involves its physical installation, ramp-up, subsequent operational phase, system reconfigurations, and performance monitoring. This is done through the three activities illustrated in Fig. 8.

Activity 4.1 concerns the commissioning of the reconfigurable manufacturing system. This activity also considers future planned and potential system reconfigurations and the supporting processes. Emphasizing the development and integration of reconfiguration procedures into the organization facilitates organizational learning and improved benefits from reconfigurable systems. Mortensen and Madsen [64] developed a framework to support this process.

In activity 4.2, the reconfigurable manufacturing system is operational in a specific configuration. During its operational life, minor changes to the system may be necessary to accommodate dynamic market demands. Such changes may be accomplished using the current flexibility of the system rather than having to revert to activity 4.1 to perform significant reconfigurations. Andersen et al. [8] developed a tool to utilize existing system flexibility.

The third and last activity in Step 4, Activity 4.3, is concerned with continuously monitoring the performance of the reconfigurable manufacturing system. This involves both general system performance and monitoring the manufacturing system's reconfigurability. The information gained from this activity provides insights into the need for improved reconfigurability within the manufacturing system, thereby facilitating timely interventions. The extent of these needs for improved reconfigurability may vary from minor changes requiring the revision of Step 3 for the design of new modules to significant changes requiring the development of new system concepts, necessitating a revision of Step 2. The use of discrete event simulation is a powerful tool to evaluate future needs as well as compare design options. Raza et al. [65] demonstrate the application of a simulation study for an RMS, and Andersen et al. [8] present general insights into using simulation for RMS.

3.5. Case-specific adaptations of the proposed methodology

Uncertainty is integral to changeable and reconfigurable manufacturing systems, as described in Sections 1 and 2. In systems development projects, uncertainty leads to adopting iterative loops in development methodologies. This is also demonstrated in the multiple iterative loops spanning activities within each step and the loops spanning across steps in Fig. 3. Several other iterative loops, e.g., between adjacent steps, could also be conceived, yet demonstrating all possible iterative loops of the development methodology is left out for readability. The iterative loops included in Fig. 3 aim to illustrate how the systems life cycle perspective in either greenfield or brownfield development projects is considered and how the proposed development methodology facilitates multiple reconfigurations of the manufacturing system. The degree to which the individual iterative loops become relevant depends on the manufacturing context the methodology is applied within.

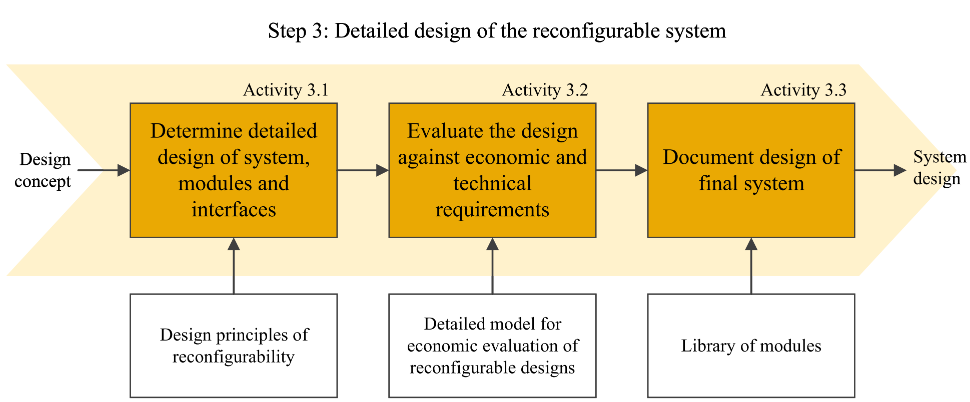

Fig. 7. The third step of the proposed development method – "detailed design of reconfigurable system" – includes its three activities, supporting tools, and examples.

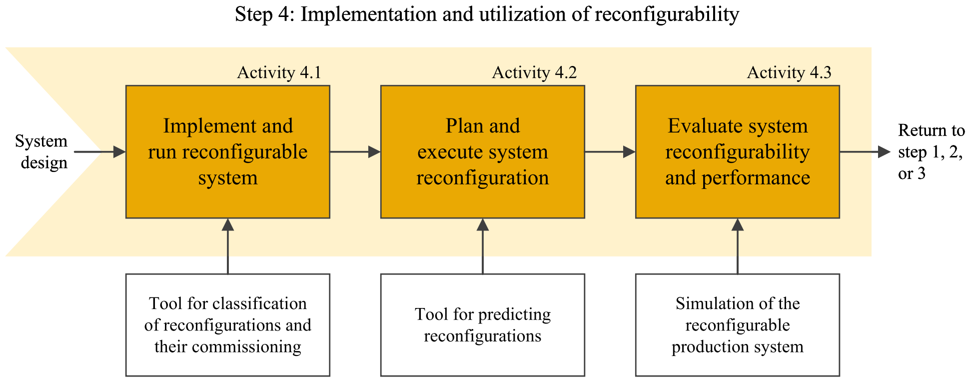

Fig. 8. The fourth step of the proposed development method – "implementation and utilization of reconfigurability" – including its three activities and supporting tools.

It is important to note that while general market trends, as described in Section 1, make changeable and reconfigurable manufacturing relevant to many manufacturing companies, some companies will, e.g., find that they do not need increased manufacturing changeability as a result of Activity 1.1 or that there is no business case for a more reconfigurable production system following Activity 1.3. In such cases, regardless of which step or activity in the development method the uncertainty relates to, revisiting analyses or their underlying assumptions may be relevant – either they corroborate the original findings or identify crucial missing parameters to include in the analyses. Regardless, multiple outcomes from the individual analyses are possible. Therefore, to avoid prescribing a specific course of action to follow, which may not apply to all manufacturing contexts, it is suggested that the aforementioned frame of thought be adopted.

An objective of the proposed development methodology is that it is applicable in the manufacturing industry in general. The proposed development method can be applied in various manufacturing contexts, suggesting that it may need to interface with multiple software and hardware systems to support the necessary analyses. Different activities throughout the proposed development methodology may benefit from integrating these systems. For example, in Activity 1.1, an enterprise resource planning (ERP) system would facilitate analyzing production volumes and product variety for different product families within the company. A product life cycle management (PLM) system could further augment this analysis by also enabling analysis of planned product variety [66]. An ERP or PLM system would facilitate the product variety analysis in Activity 2.1. Although not specific to companies pursuing increased manufacturing changeability, computer-aided design (CAD) systems have clear application potential during detailed design in Activity 3.1 and support evaluation in Activity 3.2 and Activity 4.3 in connection with simulation software. Continuous performance monitoring of the implemented RMS in Activity 4.3 is facilitated by the presence of an MES or a business intelligence (BI) system capable of reporting system performance in real-time or periodically. In conclusion, while the development methodology states no requirements concerning specific hardware or software systems, the presence of these systems may augment the individual activities of the development methodology.

4. Application of methodology in industrial cases

Including industrial cases in developing the method serves multiple purposes, as briefly described in Section 1. Besides collaborating with the selected companies to develop and mature the tools developed for the proposed development methodology, an essential aspect of including multiple case companies in this study was demonstrating how the proposed methodology works in practice, thereby validating its utility.

Seven manufacturing companies from Denmark and Sweden were selected as case companies. The selection of these companies was based on several criteria seeking to ensure broad representation from the manufacturing industry and thus promote the generalizability of findings. The selection criteria covered company size, manufacturing industry sector, unit of analysis, and RMS experience. Table 2 presents an anonymized overview of the seven companies and their characteristics.

The following sections describe each case in detail, including motivation, steps, tools applied, findings, and significant challenges experienced.

4.1. Case A

Case company A is an innovative company specializing in vertical farming. The company aims to enlarge the variety of farmed crops to meet the market needs of increased demand for fresh and sustainable food. To achieve this, the company needs to increase its farming capacity rapidly. Additionally, the manufacturing system must be designed to optimize the growth of crops in a controlled manner to ensure high-quality produce.

Based on expected market trends, the company focused on Step 4 of the proposed development method and used discrete event simulation to analyze scalability. The simulation study modeled the existing and two alternative system configurations and evaluated their performance against a future demand scenario.

This analysis identified the manufacturing bottleneck and showed that only two additional packaging machines were required to improve

Table 2
Overview of case companies involved in the development and maturation phases of the proposed development method and its supporting tools.

	Employees (approx.)	Product portfolio	Level and unit of analysis	RMS Maturity
CASE A	50	Agricultural products	Packaging machine and factory	Low
CASE B	100	Sporting goods	Manual assembly system	Low
CASE C	130	Relaxation and sleeping goods	Automated manufacturing lines	Low
CASE D	1.500	Metering solutions	Semi-automated assembly lines and factory	Low
CASE E	20.000	Pump systems	Semi-automated manufacturing lines and factory	Moderate-high
CASE F	30.000	Sustainable energy solutions	Manufacturing equipment	Moderate-high
CASE G	95.000	Vehicles and transportation solutions	Mixed assembly line	Moderate-high

capacity by 40% while simultaneously increasing the utilization of existing manufacturing resources. Results from the research collaboration have led the company to develop the two packaging machines. The equipment is designed according to design principles of reconfigurability. It includes standard modules, which will be used to move, weigh, and palletize all product variants, while differentiated modules will be used to sort, clean, and bag different variants of crops.

4.2. Case B

Case company B is a leading manufacturer of tailor-made products involving designing, cutting, and assembling processes. The product portfolio is, therefore, wide due to different customization options, including materials, shapes, and sizes. The company must ensure adequate customer delivery time to maintain its market position. This is challenging, primarily due to demand fluctuations.

The company focused on Step 2 of the proposed development method and applied the changeability mapping tool to assess the existing level of changeability at both automated and manual bottleneck processes. The analysis concluded that the current level of changeability was sufficient to meet the required variety. Focus was therefore directed towards Step 4 to improve the utilization of the existing changeability. Large fluctuations in processing times in the manual assembly processes were observed, which prompted the development and introduction of a tool for predicting reconfigurations in this part of the manufacturing system. Here, multi-skilled operators perform specialized tasks that have highly variable durations, depending on the product and customer requirements.

Currently, the tool is introduced to predict assembly times for each product variant and calculates the number of person-hours required each day at each assembly station. This information is used for daily planning of the assembly stages, allowing for better matching of employees to the day's workload. The result is a significant decrease in manufacturing lead time, proving valuable for the company's competitiveness.

4.3. Case C

Case company C, known for producing premium products that offer comfort and durability, uses high-quality materials and advanced manufacturing technologies in the manufacturing processes. Competing on product performance, the company must frequently invest in manufacturing equipment to accommodate new product variants.

Realizing the poor financial sustainability of this practice, the company focused initially on Step 1 of the development method to investigate the feasibility of developing a reconfigurable manufacturing line that can enable incremental investments and more condensed development processes, leading to reduced capital investment over time.

Collaborating with researchers and a technology provider, the company embedded the proposed methodology into the existing systems development process. Among others, the screening tool assessed the need for reconfigurability. It revealed that short- and mid-term requirements related to variant and volume changes presented a need for increased reconfigurability in the analyzed manufacturing line. This made it possible to identify where reconfigurability would benefit manufacturing, considering changeovers, capacity adjustment, and technology evolution. This knowledge enabled the progression to Step 2, where the modular function deployment tool was utilized to make a concept for a new reconfigurable manufacturing line. Simulations showed that standard modules would reduce changeover times while adapting manufacturing volume to different demand levels. The positive outcome of the evaluations has led the company to develop the detailed design of the reconfigurable line.

4.4. Case D

Case company D has three factories, each dedicated to one specific family within the offered product portfolio. The company is facing challenges due to (i) significant growth in overall sales, (ii) increasingly unpredictable demand volumes for specific product variants and families, and (iii) the need to perform a wide variety of assembly tasks for the offered range of variants within each product family.

Adopting the presented development method, focusing on Step 2, the company generated an overview of existing process capabilities. The product variant master was used to map existing varieties and gain insights into similarities between product variants within a specific product family. The changeability mapping tool connected existing process capabilities to particular product characteristics. This resulted in a comprehensive overview of assembly modules that could be shared across variants, depending on demanded volumes over time.

In summary, using tools from Step 2 allowed the company to establish the foundation for reusing existing equipment to address the challenges mentioned earlier rather than investing in new manufacturing equipment. Currently, the company is utilizing the tool in one of its factories for a specific product family and its associated assembly line. The company plans to expand the overview to understand the similarities across the three product families.

4.5. Case E

Case company E is a global leader in the development and manufacturing of pumps, with a globally dispersed manufacturing network. The main challenge for the company is fluctuating demand. This is mainly due to the wide variety of variants and families within the product portfolio in combination with the continuous introduction and phasing out of product generations and variants. This challenge ultimately results in highly variable utilization of lines and equipment. With hundreds of existing manufacturing lines, the company had difficulties identifying lines that could be reconfigured to introduce new products or adjust capacity.

The company focused initially on Step 2 and the use of the changeability mapping tool to identify potentials for sharing capacity across manufacturing lines and factories, connected to similarities within characteristics and dimensions of variants, families, and generations of products. To gain an overview of the capabilities of existing systems that could be reconfigured, a data mining approach was introduced that used ERP data to determine the capabilities of existing equipment based on product specifications, thus automating parts of step 2. The company took the outset in this analysis to justify progression to Step 3 and the development of a digital catalog of the existing variety of process capabilities matching product characteristics and dimensions.

This digital catalog is currently under development and is expected to simplify the search and identification of equipment that may take over specific manufacturing tasks within an individual factory and across geographically dispersed manufacturing facilities.

4.6. Case F

Case company F is one of the most prominent players in the renewable energy industry. As with any company operating in a rapidly evolving and highly competitive industry, the company faces several challenges, such as (i) emphasis on cost reduction to ensure competitiveness in a highly regulated industry, (ii) need to manufacture and supply increasingly larger product variants, and (iii) need to manage a global and often disrupted supply chain.

The company has geographically dispersed factories dedicated to manufacturing one or more components of the final product. Focusing on a specific manufacturing stage for one of the main components, the company analyzed historical trends and expected changes to the component's dimensions. It determined the existing ability of the manufacturing stage to handle these changes. This analysis was made for all factories in the existing manufacturing network dedicated to manufacturing the analyzed component. Focusing initially on Step 1, the company used the business case tool to clarify the potential of replacing the existing manufacturing stage with a changeable machine tool, enabling equipment reuse across factories and reducing investment costs in manufacturing equipment. The business case analysis results justified the effort to focus on the subsequent conceptual design in Step 2. Here, the company used the modular function deployment tool to develop modular concepts for the manufacturing stage, considering both functional requirements and limitations in the value chain. Afterward, the ranking hierarchy and matrix tool were used to compare these concepts and justify the selection of the best option to be further developed in the detailed design.

The company is now developing the detailed design of the reconfigurable machine tool. It expects to maintain its competitive positioning, reducing reinvestment costs and potentially reducing the effect of global supply chain disruptions.

4.7. Case G

At one of its assembly lines, case company G faces three challenges: (i) uncertain demand patterns, (ii) the need for rapid introduction of new product variants, and (iii) sharp reduction of products' life cycles. The assembled product family requires specialized and complex automated and manual operations. This assembly has traditionally been a high-volume process focusing on efficiency and cost-effectiveness. However, changes in regulations and uncertain customer preferences require the company to increase the assembly capacity while ensuring the capability to assemble the necessary variety. Moreover, due to uncertainty around future demand patterns, the company is interested in making gradual adjustments and investments instead of investing in entirely new assembly systems.

The company embedded all four steps of the proposed development method into its existing system development process. In Step 2, the application of the changeability mapping tool allowed the identification of current changeability levels at various assembly stages. In Step 3, using the detailed model for the economic evaluation of reconfigurable designs allowed for quantifying potentials from investing in reconfigurable manufacturing equipment. In Step 4, the focus was on a tool for balancing assembly lines following reconfigurations.

Therefore, the current changeability level was compared with the required level in predicted scenarios. In this way, the company could identify focus areas within assembly stages (i.e., those expected to need increased levels of changeability in the future) and plan reconfigurations cost-effectively and responsively.

4.8. Validation of proposed development method

This section seeks to describe how the proposed methodology was validated. First, a summary overview of the application extent of the proposed methodology across the seven industrial cases described in Sections 4.1 to 4.7 is presented. Next, the efficacy of the proposed RMS development methodology is demonstrated by quantitative measures relating to the manufacturing changeability of participating manufacturing companies. Finally, findings from the seven industrial cases related to the generalizability or limitations of the proposed RMS development methodology are included.

4.8.1. Summary of RMS methodology application across industrial case studies

Besides covering different manufacturing industries, company sizes, and units of analysis, Table 3 shows that the industrial cases likewise demonstrate the broad applicability of the steps and methods and tools applied from the presented development method.

The case companies also differ in which change drivers motivate

Table 3
Overview of case findings from the seven case companies, including the manufacturing change drivers, steps, and tools applied, as well as their outcomes.

	Change drivers			Development methodology steps				Methods and tools applied
	VAR	VOL	PRO	1	2	3	4	
Case A		X					X	• Simulation
Case B	X				X		X	• Changeability mapping • Reconfiguration prediction
Case C	X	X		X	X			• Screening tool for assessing the need for reconfigurability • Modular function deployment for manufacturing
Case D	X	X			X			• Changeability mapping
Case E		X			X	X		• Changeability mapping • Module library
Case F	X		X	X	X			• Business case tool • Modular function deployment for manufacturing
Case G	X	X	X	X	X	X	X	• Changeability mapping • detailed model for economic evaluation of reconfigurable designs • Reconfiguration prediction

(VAR = Product variety, VOL = Product volume, PRO = Product change)

pursuing a more reconfigurable manufacturing system. While short-term changes driven by product variety and mid-term changes caused by volume changes are present in five cases, the longer-term changes often driven by new product introductions are only identified as a challenge in two Cases (F and G). The extent to which the cases have applied the development method differs. While Case A and Case D have only focused on a single step in the development method, most cases have involved at least two steps, including Step 2. Interestingly, while the overall concern of Step 2 is the development of reconfigurable concepts, several of the cases have focused on the application of the changeability mapping tool as a means of generating an overview of their existing process capabilities as a precursor to increasing reuse of manufacturing assets across product variants, families, and generations. Only Case G focused on completely integrating all development steps into their current development process during the study. Generally, the earlier steps of the development method are represented more frequently, indicating a generally lower maturity in reconfigurable manufacturing in the case companies. Even so, based on the learnings from their participation in this study, all case companies have subsequently pursued further development projects to increase the reconfigurability of their manufacturing.

4.8.2. Evaluating RMS development methodology efficacy

A survey was constructed and sent to the seven case companies to evaluate the impact of the proposed RMS development methodology. The respondents were asked questions concerning the outcome of the research project relating to several parameters. The three project outcome measures and their results summarized in Fig. 9 are interesting to the study reported in this paper. The three outcome measures in the survey were related to i) reuse and utilization of production equipment, ii) investments in production equipment, and iii) time-to-market for new products. The project outcome measures were chosen as they reflect typical improvements expected from an increase in the changeability of a company's production system.

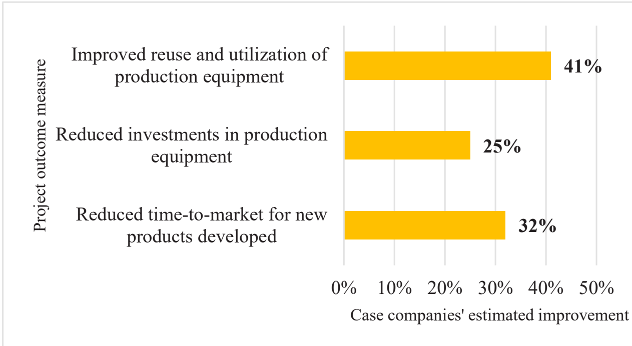

Fig. 9. The three outcome performance measures of the research project concerning the seven case companies. The reported impacts are based on evaluations by the participating companies.

As shown in Fig. 9, the highest impact in the case companies was related to an improvement in production equipment reuse and utilization, with lower, although significant, impact reported for the two remaining outcome measures. The results reported align well with both theory (see, e.g., [24]) and case findings reported elsewhere in the literature (see, e.g., [10]). In general, the case companies reported that the proposed RMS development methodology provides value by i) making the development methodology to implement RMS accessible to practitioners and ii) making it possible for the case companies to continue working with implementing RMS regardless of their earlier experience with the topic following the end of the research project. In particular, the case companies emphasize the value of the provided methods and tools being actionable. One of the case companies reported their experiences and difficulties with implementing existing methods for system reconfiguration. They found these methods overly complex and academic, making them impractical for real-world application. In summary, the results reported indicate the efficacy of the proposed RMS development methodology.

4.8.3. *Assessment of generalizability and limitations of the proposed methodology*

It is possible to identify several relevant aspects from Table 3 concerning the generalizability and limitations of the proposed RMS development methodology. First, the successful application of the development methodology across seven vastly different manufacturing contexts, in terms of products manufactured, company size, and experience with RMS, demonstrates the broad generalizability of the methodology in the manufacturing industry. However, some aspects of the demonstrated generalizability could have been further strengthened. For example, only Case G – which is by far also the largest company in the study – has integrated the full RMS development methodology into its manufacturing systems development process. It would have further strengthened the generalizability of the methodology if more than one case company had successfully integrated the development methodology into their existing development processes. Of particular interest would be insights from one of the smaller organizations in the study, as this would demonstrate greater generalizability across company sizes. Additionally, understanding the practical implementation of the detailed design phase (Step 3) in the proposed RMS development methodology could be strengthened. Only two of the seven case companies finished implementing methods and tools from this phase, as outlined in Section 4.8.1, during the project period. Moreover, none of these companies concentrated solely on the detailed design (Activity 3.1), thereby restricting the depth of insights obtained from the application of this activity. On the other hand, the changeability mapping tool was broadly applied across the case companies reporting value gained from its usage, e.g., identifying changeability gaps and needs of processes. Despite these limitations, the extent and scope of the cases included in this study suggest that companies with commonality in their production have the potential, across company size and industry sector, to benefit from changeable and reconfigurable manufacturing.

5. Discussion

This section presents a discussion of the results in the context of previous research, the academic and practical implications of the findings, and potential limitations of the present study.

With more than 20 years of research on various aspects of RMS, the research topic is arguably approaching maturity, which is also supported by the numerous literature reviews on the subject (see, e.g., Bortolini et al. [5] and Pansare et al. [6]). As such, the review of related literature in Section 2 found several studies covering both partial issues of RMS development and overall RMS development methods. Nevertheless, none of the identified studies presented a holistic and practitioner-oriented development method, nor were they validated broadly across different manufacturing industries and contexts. Overcoming these shortfalls was paramount for an RMS development method's relevance to the manufacturing industry [1]. The proposed development method described in Section 3 exhibits these characteristics by (i) considering the complete life cycle of manufacturing development projects, (ii) supporting the process through detailed activities and concrete tools, and (iii) validating the methodology through application in multiple manufacturing companies of varying sizes and originating from different industries. Furthermore, despite the identified shortfalls of previous research in Section 2, it is argued that the research presented in this study is enabled by the existence of the methodology's fundamental "building blocks" in the form of existing tools and methodologies. Even so, the three-phased process illustrated in Fig. 2 and the description of the proposed methodology in Section 3 highlights the extensive research required to link overall development steps with comprising activities and supporting tools.

Integrating AI, digital twins, and similar advanced technologies may prove transformative in RMS development. Renzi et al. [67] highlighted the efficacy of AI for layout and process parameter optimization in RMS development. Mo et al. [68] integrated AI and digital twins to support reconfiguration decisions, which relate directly to activities in Step 4, as described in Section 3.4. However, a modified version of their approach may prove valuable in Activity 2.2 by identifying gaps in process capabilities based on product needs expressed through change drivers. Verna et al. [69,70] propose digital twin-enhanced quality control and zero-defect manufacturing tools, both considered relevant for rapid system ramp-up and real-time quality management, which relate to Step 4 of the proposed RMS development method. A significant limitation of the technologies presented here, and related Industry 4.0 technologies, is their reliance on data, which may not be readily available in all companies seeking to increase the changeability of their manufacturing system [23].

The application of the proposed methodology in multiple industry cases, as described in Section 4, indicated a significant gap between the RMS tools the manufacturing companies were ready to implement and the state-of-the-art tools available in the literature. Most notably, the industry often requested simpler tools. It should, however, be recognized that the case companies differed in their maturity towards RMS. Case G, for example, was a major international manufacturing company that could integrate the proposed development methodology with its existing production development processes. On the other hand, Case D had minimal experience with RMS and found most use of the simpler mapping tool described by Kjeldgaard et al. [59]. The divergence between tools developed by researchers and the apparent state of practice in the industry is arguably interesting concerning future application-oriented research within RMS.

As a result of a multi-year research project, it should be acknowledged that the tools included in the proposed development method are not necessarily state-of-the-art, as newer tools may have been published following the development of the methodology. An updated methodology, including more recent tools, may prove more beneficial for practitioners. However, updating the methodology would require revalidation of the affected steps and activities. Furthermore, the objective of the proposed development method is to be generally applicable across manufacturing industries and contexts, fulfilling the needs of a typical manufacturing company. This generalized perspective can also be considered a limitation of the methodology. Some proposed tools may be too simplistic for some companies, while others may need more advanced ones. Lastly, a fundamental assumption of the research presented in this study is that manufacturing companies already have a structured development process for their manufacturing systems, which can be integrated with the proposed development method. While this assumption may hold for larger manufacturing companies, as Case G demonstrates, this may not necessarily apply to SMEs.

6. Conclusion

This paper has presented a systematic development method for changeable and reconfigurable manufacturing systems. Reviewing related literature highlighted four issues with existing RMS development methods, the primary issue being industrial application. Taking outset in the four issues presented in Section 2, the main contributions and managerial implications of the development method proposed can be summarized as:

1. **Adopts a comprehensive system life cycle perspective**: The development of a manufacturing system, whether as a greenfield or brownfield project, involves more than just the system's design and includes evaluation, implementation, and utilization of the operating system. The four-step method adopts a complete systems life cycle perspective by accounting for development activities ranging from development scoping and initial business impact evaluation, over conceptual and detailed design activities, to implementation, utilization, and monitoring of the operating manufacturing system. Acknowledging the dynamic nature of development projects, the presented development method describes and indicates possible iteration cycles depending on the scope of change needed. For practitioners, the proposed development method provides planning and decision support for all major development activities throughout a system's life cycle. The general similarity between the four steps of the proposed development method and traditional manufacturing systems development methods furthermore facilitates integration into a company's existing development method, as demonstrated by Case G in Section 4.7.
2. **Encapsulates the complexity of comprehensive system development methods**: Manufacturing system development projects can be large and complex, and introducing the dimension of reconfigurability as an added consideration further adds to this complexity. Therefore, a sufficient level of instruction is essential for the industrial application of a development method. This is accommodated by adopting a generic multi-tiered structure for each of the four development steps in the presented method. Specifically, each step comprises several sequentially structured activities paired with a supporting tool. This framework assists practitioners in RMS development by initially outlining the goal of the specific development task (i.e., step). It then details the subtasks required to accomplish this goal (i.e., activities), and ultimately, it describes the techniques for executing these subtasks (i.e., methods and tools).
3. **Is adaptable to different manufacturing contexts**: Manufacturing system development projects may be greenfield or brownfield (i.e., entirely new systems or changes to existing systems), and companies may have different starting points, for example, minor changes involving a system reconfiguration or design of a new module, or more substantial changes necessitating concept development or business case clarification. These circumstances necessitate a systems development method adaptable to the specific context. The presented development method facilitates this by being adaptable to both a greenfield and brownfield development scenario by either omitting or including particular activities in step 2 and by enabling different starting points along the method depending on the scope of the development project. For practitioners, this modular approach to RMS development allows a more resource-efficient approach to increasing manufacturing changeability instead of fully implementing the proposed development method.
4. **Is applicable in industry**: The method must be practically useful to assist practitioners in solving the challenges of manufacturing systems development in uncertain markets. The presented development method has demonstrated its practical relevance and applicability through seven industry cases involving companies of vastly different sizes from different manufacturing industry sectors and with different needs to improve the changeability of their manufacturing systems. In these cases, the actual development work was done by company employees, not researchers, underpinning the maturity and practical applicability. The cases have demonstrated the application of the proposed development method, both through the application of individual steps and through the integration of the method with a company's existing manufacturing systems development method. Industry professionals should view the broad validation of the proposed RMS development method as evidence of its efficacy and, by extension, reconfigurable and changeable manufacturing systems in general.

6.1. Further research

This study's findings underscore the scope for future research in several critical areas related to developing an RMS. These include i) engaging in follow-up studies with participating companies, ii) customizability of the proposed methodology, iii) refinement of RMS evaluation tools, and iv) exploring RMS's role in advancing circular manufacturing practices.

1. **Follow-up on RMS method implementation**: The efficacy of the proposed RMS development methodology was demonstrated through its application in multiple manufacturing companies, as detailed in Section 4. Although this collaboration has encouraged these companies to initiate more RMS projects, this methodology's long-term success and integration remain to be seen. Conducting follow-up studies with these case companies could yield valuable insights into various aspects, such as the extent of method implementation, challenges faced during this process, and any beneficial outcomes.
2. **Addressing varied competencies and maturity levels in companies:** Sections 4 and 5 of this paper describe the varying competencies and maturity levels among the manufacturing companies involved in the study. This diversity emphasizes the necessity of tailoring RMS tools to meet different starting points within the industry. While the tools discussed in Section 3 show adaptability, further exploration into how they can more effectively address these varied requirements is crucial for promoting broader industry adoption of RMS.
3. **RMS evaluation tools**: A distinct aspect of RMS is the need for specialized evaluation and investment models. These models must accurately reflect RMS's unique costs and benefits, differentiating them from traditional manufacturing systems. Despite its importance, research in this domain remains relatively limited, particularly compared to other aspects of RMS development. Therefore, developing comprehensive business cases for RMS holds practical value for industry practitioners and presents a significant area of interest for academic research.

4. **Enabling circular manufacturing through RMS development methods**: Finally, given the growing focus on sustainability within the manufacturing sector and the potential of RMS to facilitate this transition, it is pertinent to explore how the proposed methodology might be adapted to develop circular manufacturing systems. Such research would contribute significantly to the ongoing discussion on sustainable manufacturing practices.

While independent, the proposed areas for further research may also interconnect, offering valuable insights to one another. The above-listed sequence of relevant further research activities represents a suggested roadmap. Starting with a follow-up on the RMS method implementation could provide insights into aspects of the development method that would require change to fit the needs of practitioners. Next, addressing manufacturing companies' varied competencies and maturity levels concerning RMS development would provide valuable knowledge regarding the need to change and customize the method. This knowledge could be partially gained from the previous research activity. Experiences of industry practitioners concerning challenges in adopting the method and individual needs due to differences in maturity and competencies are considered valuable input to subsequent research on further investigation of RMS evaluation methods and tools. The acquired knowledge from industry practitioners is likewise regarded as relevant to enabling circular manufacturing through RMS development methods.

CRediT authorship contribution statement

Rasmus Andersen: Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Ann-Louise Andersen:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Alessia Napoleone:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Kjeld Nielsen:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Thomas Ditlev Brunoe:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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.

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