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Reconfigurable Manufacturing Development: Insights on Strategic, Tactical, and Operational Challenges

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Abstract

The paper provides empirical insight on how changeable and reconfigurable manufacturing system concepts can be developed to meet requirements in manufacturing companies, as well as the related organizational and technical challenges. The findings reveal that there are still strong barriers towards the wider implementation of reconfigurability and that a paradigm shift in industry is required, e.g., in terms of managing stepwise investments, organizational culture and mindset, approaches to production development, organizational structures, and knowledge on changeability and reconfigurability.

Keywords: Reconfigurable manufacturing, Changeable manufacturing, changeability, case-study, manufacturing system

1. Introduction

The Reconfigurable Manufacturing System (RMS) introduced by Koren in the mid 1990's was proposed as an intermediate paradigm between the Dedicated Manufacturing System (DMS) with rigid structures and high efficiency and the Flexible Manufacturing System (FMS) with high in-built a-priori flexibility [1,2]. Since then, reconfigurability has received significant attention in research, focusing on a broad spectrum of areas from design to operation [3,4]. In spite of the growing interest and promising potentials of reconfigurable manufacturing systems, their development and implementation still appear to be challenged and limited in industry [5-7], including limited practical guidelines and case studies to promote the practical implementation [8]. Likewise, previous research provides only limited insight into the multi-dimensional and complex nature of reconfigurability which, however, should be addressed in order to promote its implementation rather than target reconfigurability as an overall capability for the system as a whole [4,9]. Various design and development methodologies have been proposed that consider reconfigurability characteristics, e.g. how modularity, integrability, scalability, and convertibility enables reconfigurability in the designed system solution [10-12]. However, empirical insight into how reconfigurable solutions can be designed and developed to meet company-specific change requirements are limited and knowledge of how the anticipated benefits of reconfiguration can be achieved in different company settings is largely neglected in previous research.

Therefore, the research presented in this paper addresses the following two research questions through a multiple case study approach: How can changeable and reconfigurable manufacturing system concepts be developed to meet requirements in manufacturing companies and what are related strategic, tactical, and operational challenges? Thus, this research addresses not only the applicability of reconfigurability, but also differences in its development and application, as well as related barriers. The remainder of the paper is structured as follows: Section 2 discusses related research and describes the design problem of reconfigurability. Section 3 present the research method, and Section 4 present

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the case study findings. Section 5 presents a discussion of results, while Section 6 conclusively present implications of the paper and future work.

2. Literature Review

The design of reconfigurable manufacturing systems has been addressed in numerous previous works [13]. Tracht and Hoegreve [11] proposed a framework for decision making within the design and reconfiguration phase of a modular and reconfigurable manufacturing system. Similarly, Deif and ElMaraghy [12] proposed a three-layered framework for systematic design of reconfigurable manufacturing systems spanning from capturing market demand for defining design parameters to the physical implementation of hard, soft, and human elements. Methodologies focusing specifically on the reconfigurability characteristic modularity have been proposed, e.g., by Rossi et al. [14] presenting a systematic methodology for system modularization. Wiendahl et al. [15] argue that reconfigurability is widely accepted as a primary class of changeability on shop-floor level , which needs to be considered in combination with additional classes such as flexibility and changeoverability. Thus, rather than focusing solely on embedding reconfigurability characteristics in soft and hard system elements during design of manufacturing systems, design methodologies for changeability address additional issues of e.g. the appropriate combination of reconfigurability and flexibility enablers [16], synthesizing enablers of changeability and changeability level with system design elements, e.g. layout, services, machines and material handling [17], defining interdependencies, interfaces, and system elements based on changeability requirements and change profiles [18], or defining system architecture and configurations based on the decided changeability strategy [19]. Thus, a transition from research targeting RMS design to design and development methodologies targeting reconfigurability as a manufacturing capability that can be realized in various ways and extents can be identified. However, from previous research it is commonly recognized that phases and steps from traditional engineering design methodologies have to be supported with new tools and procedures in order to accommodate reconfigurability and changeability in the following way:

- Identification and assessment of drivers of change and reconfigurability
- Deriving the objectives and needs of reconfigurability from the drivers
- Determination of the appropriate extent, level, and enablers of reconfigurability for the system design
- Evaluation of the reconfigurable system concept regarding relevant cost and performance criteria

From the steps involved in designing reconfigurable manufacturing systems described in previous subsection, it is clear that a systems perspective is needed, as requirements, system goals, structuring levels, and enabling system constituents of reconfigurability must be addressed interrelatedly. As systems perspective covers both the functional aspects of the manufacturing system, the structural aspects, as well as the hierarchical aspects [20, 21]. In Figure 1, relevant system aspects are depicted in relation to reconfigurability objective, drivers, enablers, and level of implementation as derived from the essential steps for designing reconfigurability.

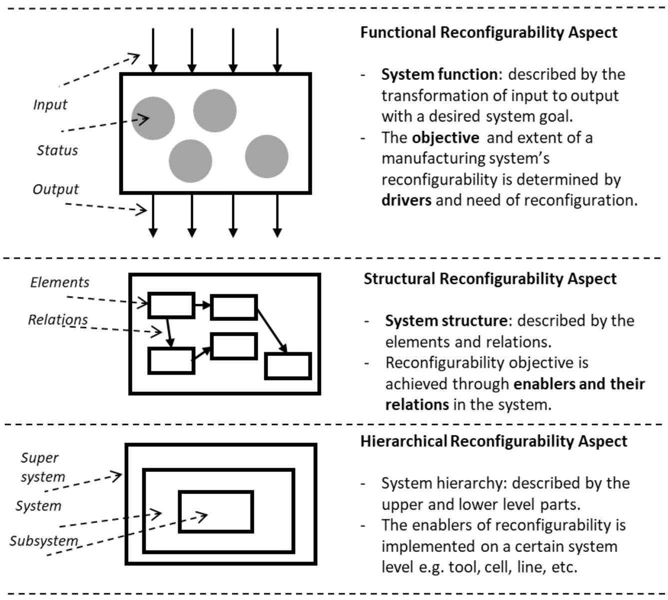

Fig. 1. Relevant systems aspects in relation to reconfigurable manufacturing system design and development, extended from [21].

Designing reconfigurability requires consideration of multiple aspects and dimensions [4,9]. In previous research, this multi-dimensionality of reconfigurability has been labelled as context-dependency of reconfigurability [22], as well as in terms of differences in required reconfigurability enablers in different business production strategies from engineer-to-order to make-to-stock [5]. Additional related research has proposed the notion of wicked problems to describe design of changeable manufacturing systems, thereby emphasizing the uncertainty and unknown factors involved in designing manufacturing systems that are dynamically and efficiently changeable to changing market conditions [17]. In a similar way, Benkamoun [19] considered the design of changeable manufacturing systems as the design of nun-functional or life-cycle system requirements, which implied that the desired properties, e.g. changeability or reconfigurability manifest themselves after the system has been put to use [23]. To summarize, this section has outlined different challenges in designing reconfigurable manufacturing systems, which can be condensed as the "reconfigurability design problem":

- Complicatedness: Designing a reconfigurable manufacturing system involves interrelated functional, structural, and hierarchical system aspects to adequately cover unique and case-specific design decisions on reconfigurability objective, drivers, enablers, extent, and level of implementation.
- Complexity: Designing a reconfigurable manufacturing system involves decisions and evaluation on non-

functional or life-cycle properties implying a high level of uncertainty.

In this regard, complicatedness refers to the difficulty in designing reconfigurability, as the task requires several knowledge disciplines, and the system has many parts and aspects making it difficult to comprehend and understand [24]. In addition to this, complexity refers to the uncertainty in the design, development, and evaluation process [24]. Collectively, this complicatedness and complexity makes development of reconfigurability a challenge in practice and implies a need for practical guidelines and case studies.

3. Research Method

Case research consists of investigations with no attempt to isolate the investigated phenomenon from its context, rather the interest in the phenomenon is important specifically due to its relation to its context [25]. The case study presented in this paper seeks to generate new knowledge and theory from the empirical settings in which the case studies were conducted, in terms of describing how reconfigurability can be designed differently to meet company needs, but also to explore and uncover challenges in the broader implementation of reconfigurability.

3.1. Case Selection

Four case studies in three companies were conducted. Case study A and B were carried out in company 1, case study B in company 2 and case study D in company 3. The companies were selected based on theoretical replication logic, as they represent relatively different industrial settings in terms of e.g. product size, production volume, product variety, degree of customization, etc., and, therefore, appears suitable for investigating differences in reconfigurability design and application. All three companies had prior to the case studies already established some knowledge and experience with developing reconfigurable manufacturing systems and had decided to further explore how reconfigurable manufacturing systems could be designed to increase manufacturing competitiveness.

3.2. Case Study Protocol, Data Collection and Data Analysis

The researchers conducted data collection over a period of more than 3 months and followed the companies' development projects as they unfolded from requirements specification to system concept design and evaluation. This research was done primarily through workshops and seminars production manager/director or equivalent positions and production engineer/specialist or equivalent positions. The participants in the workshops and seminars included personnel who had production development as their main task in their positions. All sources of information were collected in accordance with the case protocol, which is depicted in Table 1.

During the data collection, extensive field notes were taken by authors. After within-case analyses, findings were compared across cases in order to identify differences, similarities, and establish patterns in relations between the developed solutions and the requirements and specific company contexts.

Table 1. Case study protocol based on theoretical framework.

Aspects/questions to guide data collection	**Source(s) of information**
Case company background	
Company and manufacturing context	Workshops, company presentations, websites, archival documents, etc.
Analysis and specification of changeability and reconfigurability requirements (Functional system aspect)	
Identification of change drivers	Workshop and seminar
Analysis of existing manufacturing setup/level related to dedicated, flexible and reconfigurable manufacturing	Documentation from companies e.g., product information, production layouts, process mappings.
Identification of reconfigurability objectives	
Requirements for the changeable and reconfigurable manufacturing system concept	Archival sources and data
Identification of relevant requirements for the reconfigurable solution	
Concept design of and evaluation based on reconfigurability enablers, extent, and structuring level (Structural and hierarchical system aspects)	
Identify enablers, level, and extent of reconfigurability	Workshop and seminar
Cost evaluation and justification related to the reconfigurable concept	Documentation from companies, archival sources, and data
Technical and product-related evaluation	
Organizational and technical challenges in developing and operating reconfigurable system concept	
Existing approach for manufacturing system design and development	Workshop and seminar
Project and process challenges towards reconfigurability development	Documentation from companies, archival sources, and data.

4. Case Study Findings

The findings of the cases are summarized in Table 2. In all cases, product related change drivers were primarily motivating reconfigurability. Also, volume related change drivers were mentioned in case study C and D. Based on this, the objective for increasing the reconfigurability level was to deal with product variations within one machine cell/ production line and not by using parallel cells/lines. To be able to produce several variants in the same production line and by efficient reconfiguration reach, low set up times were pinpointed as a goal. Also, to be smarter in developing new production systems by reusing existing equipment and doing stepwise investments were considered as a motivation for reconfigurability. In the existing production systems, few examples of reconfigurable solutions could be identified and, in the cases where reconfigurability existed, it was not consciously designed based on reconfigurability enablers.

The candidates for reconfigurability varied in terms of structuring level, from cell level (case B and C) to line level (case A and D). Moreover, the specification of the requirements differed in amount of requirement between the cases. All cases, however, had a holistic view and included requirement linked to the technical system, the material handling, ergonomics, and the competence required. The development projects differed between greenfield development (case A and B) and brownfield development (case C and D).

In all cases, existing competence, software systems and material handling (to and from the cell/system) concepts had to be considered. Common for all cases where the goal to reach a solution with low perceived complexity, i.e., a clear structure and low degree of coupling between system elements, i.e., a modular structure, to limit the amount of changes in the system during reconfiguration. Uncertainty regarding the future was considered as a main element during the design and development of reconfigurable solutions, e.g., in terms of demand uncertainty or uncertainty about future technological changes in the product or processing technology. However, considering such uncertainty explicitly during design also increased the complexity of evaluation the solution and justifying investments in the solution. The evaluation of the conceptual design solutions was done based on the requirement specifications. However, in case C a rough evaluation was also made based on different future scenarios.

Table 2. Summary of case study findings.

Case A – Company 1
Change drivers: New product and production technology. More variants
Existing MS: No purely reconfigurable machining or assembly lines, several reconfigurable principles/enablers, e.g., free floor space in machining, modularity in final assembly.
Objectives: Enable implementation of upcoming product generations in a production line. Limit the maximum number of simultaneous variants.
Specified requirements (in selection): Floor space limitation, Reconfiguration for a new product generation should be possible in X days including ramp-up, Reconfigurability enablers, Test proposed KPI's.
Reconfigurability enablers: New production line for a new product
Case B – Company 1
Change driver: See case A
Existing MS: See case A
Objectives: To reach a low investment cost and low lead times in development.
Specified requirements (in selection): Maximum weight for part, Product size, parts/variant, Material-specification, X h/year on X shifts, Scalability in specified volume steps, HMI is prepared for future reconfiguration, Working environment and ergonomics, Traceability, Modular transport system, Flexible routing, Low startup cost and step-by-step investment. Specified time for reconfiguration, Reuse of tools in machining center, Diagnosability
Reconfigurability enablers: New machining line for a new part
Case C – Company 2
Change driver: Volume variations. Changes in product variants
Existing MS: Few reconfigurable production solutions, AGV system considered reconfigurable
Objectives: To be more adaptive for new products
Specified requirements (in selection): Maximum weight for part, Product size, Product material, Machining time, Cooperation product and production development, Fixture points and characteristics on product, Automated fixture handling, Flexible machines and fixtures, Machines possible to rearrange, Virtual models available, Standardized HMI / machine communication
Reconfigurability enablers: Adaption of machining cell for new product variant
Case D – Company 3
Change drivers: More variants, Conceptual changes, New technology, Higher volumes, Faster volume changes
Existing MS: Not reconfigurable today
Objectives: All variants in the current family should be included and to be able to handle both existing variants and new ones
Requirements: A flexible MES- system, Agreed fixture points and characteristics on product, Capacity/speed in equipment, Specification of interfaces, Mobility in assembly and logistics, Reconfigurability time
Reconfigurability enablers: Improvement of assembly line

5. Discussion

In the cases, challenges on both strategic, tactical, and operational level could be identified.

5.1. Strategic Challenges

In none of the cases, the manufacturing strategy advocated a reconfigurable mindset. All companies primarily followed lean strategies to keep the production as efficient as possible. This affected the production development and operations heavily. The problem, according to the participants in the case studies, were the efficiency and effectiveness in the longer term and not only for existing production. In e.g., case C, the lean strategy was highly advocated by top management, but the participants from the companies could see a lack of long-term thinking. The lean focus seemed to be a reason for the lack of reconfigurability in existing manufacturing systems and solutions, as focus on lowering standard unit cost and eliminating waste in some ways are contradicting reconfigurability. On the other hand, reconfigurability and lean may not be seen as exclusive to each other, as reconfigurability indeed is focused on efficiency to higher extent than purely flexible solutions and lean theory also advocates a long-term perspective in manufacturing [26].

All case studies showed that designing a reconfigurable manufacturing system required a different mindset for all company representatives compared to previous production development projects. The case studies highlighted that designing for reconfigurability is indeed both a complicated and complex task. For instance, developing a system not only for today's product and parts, but also for future unknown products, parts, and even families constituted a major change for the companies. Thus, in the cases, reconfigurability transitions were primarily a bottom-up approach initiated by production specialists and production system designers, whereas all case studies showed the need for reconfigurability focus on higher management levels to accommodate e.g. reconfigurability investments proposals, pay-as-you-grow manufacturing capacity plans, etc.

The main reason for today's high amount of dedication and low level of reconfigurability was in all cases explained by the manufacturing and investment strategies within the companies. None of the case companies supported a long term and stepwise investment, which is required in order to consider not only the existing product but the current life cycle of the product and even the upcoming generation. In case A, attention was put on the initial investment and the fact that a stepwise investment would decrease the cost for each changeover was not considered. In case C, a main challenge was, thus, to convince the management of the high initial investment cost and to be able to show that it would be cost efficient in the long run. Also, in case D it was hard to justify investment for management due to the estimations used in calculating the payback time. In case D the investments were financed by one project and was difficult to motivate a project to cover a cost for a future project that would be the case in stepwise investments. Therefore, they argued that reconfigurability appeared to represent a difficult transition. Therefore, from the case studies conducted in this research, it can be concluded that research focus on investment evaluation and justification models that are practically applicable is highly needed.

5.2. Tactical Challenges

In all cases, production development guidelines of how to design production system, either on global level and/or site level existed. In none of the guidelines, instructions or guidelines for reconfigurable production where explicitly described. The reconfigurable production system development activities studied in the four cases all aimed for enabling smoother changes. In case A, the aim was to design a productions system different from the existing ones that were highly rigid, expensive, bulky and complicated in terms of flow. In case B, the aim was to reduce investment and lead time when introducing new products and to decrease lead time when changing between known products from the start. Also, in case C and D, the overall aim was to be more adaptive to new product introductions and variant changes. However, the importance of measuring these benefits was expressed, since the existing performance indicators did not support a mindset of reconfigurability. Examples of reconfigurability performance indicators proposed included long-term investment, volume steps versus demands, ramp-up time, reconfigurability time, project lead time, number of variants handled, total manufacturing cost, share of standard interfaces in process/production, and share of movable equipment.

A well-known problem, that became even more evident in order to succeed with a reconfigurable production in the long term, was the requirement to bridge R&D and production development [27, 28]. In all cases this was expressed as a challenge. In case B, every product had a number of standard surface points in order to enable standard fixtures. When new production equipment was designed, this standard surface points guided the fixture design. If a change was done in the standard surface, it could imply much complication and increased cost in production development. Even if this was a frequent problem it could easily be solved through better communication between the departments. Another barrier for reconfigurable production development was the unbalance between long term view in product development compared to the long-term view in production development. New product variants were presented just before the development project would begin. The chance to have a long-term view in production was, thus, prohibited. Moreover, the lack of long-term view also put manufacturing projects under time pressure caused by both product development and project organizations.

The innovation capability is another factor that might be hindered by not using reconfigurable production, both for product and production solutions. The existing dedicated production solutions can be a barrier for product innovations since the products must be designed for the systems. The dedicated system does neither open for implementing new manufacturing technology. In two of the cases, an existing production system was to be redesigned for increased level of reconfigurability. This can possibly be regarded as the most common cases since the length of life of a production system normally is longer than the product [15]. In these cases, existing machines and equipment had to be used which was a challenge in the development for reconfigurability.

5.3. Operational Challenges

On an operational level, several barriers were identified related to adopting existing dedicated/flexible systems into reconfigurable systems or developing new reconfigurable production systems within a current site. In all cases, logistic barriers had to be removed and floor space had to be made available. All cases also described the importance creating reconfigurability in both hardware and software solutions. Machines of different type and different software interfaces were today not connected, and an interface adapter needed to be developed to enable integrability.

The fixturing was also described as a central aspect to be solved and new solutions would be required for fixtures, loading, unloading, and docking. In case C, solutions for flexible fixtures that could handle different parts with different clamping points were developed and in case B, to design fixtures for future unknown variants. In case C, well proven technologies and solutions were prioritized and sometimes the participants could meet a fear for new technology within production by e.g. the management. This can be related to the competence and work force in development and operation which were identified as another challenge. In terms of competences, new skills might be required which was expressed as a challenge.

To summarize, a clear relation between the challenges by e.g., a lack of reconfigurability mindset in the manufacturing strategy is related to few reconfigurability guidelines, which is related to few reconfigurable solutions in hardware and software. In the cases, a bottom-up approach was primarily represented in the transition towards reconfigurability. In case A and B, the limitations in dealing with product related change drivers had led to that production engineer reviewed different changeability approaches and motivation for reconfigurable manufacturing systems were proposed for the management and, thereby, included in the strategies. In case C and D, a reconfigurable manufacturing approach was not included in the strategy, but the reconfigurable design was proposed from production engineers. Thus, the cases studied in this research shows that implementing reconfigurability is not just an issue in terms of developing modular, convertible, and scalable hardware and software solutions, but rather a capability that needs be implemented on all levels within the companies' structures.

6. Conclusion and Future Research

The purpose of this paper was to provide empirical insight on how changeable and reconfigurable manufacturing system concepts can be developed to meet requirements in manufacturing companies, as well as the related organizational and technical challenges in this regard, given the complicated and complex nature of reconfigurability development. The theoretical implications of the research presented covers not only knowledge about functional, structural, and hierarchical system aspects of reconfigurability which emphasizes its multi-dimensional and context-dependent nature, but also knowledge on reconfigurability as a brown-field development process and project, which is largely neglected in previous research on reconfigurability. The imperative findings of the paper are that there are still strong barriers towards the wider implementation of reconfigurability e.g. in terms of managing stepwise investments, organizational culture and mindset, approaches to production development, and organizational structures, and knowledge on changeability and reconfigurability.

Future research should focus on overcoming these barriers and suggest solutions towards this industrial paradigm shift. To avoid suboptimizations a holistic view on the system development is required including both humans, technology, and organization [29]. Regardless of technology development in production systems, human work activities will be a crucial part of the system and the need to understand the conditions of people involved in work activities will increase as requirements change and production becomes more complex and changeable. In future studies, a HFE perspective need to be applied in reconfigurable production system development. Even if the requirements of changes in competence of blue-collar workers were not studied in detail in this research the system perspective is becoming increasingly important to deal with increased complexity.

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