Changeable Manufacturing: A Comparative Study of Requirements and Potentials in Two Industrial Cases

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Abstract. Today's global manufacturing environment is characterized by intense competition in dynamic and uncertain markets. Consequently, manufacturers are required to accommodate a higher variety of products with frequent new introductions and shorter life-cycles in a rapid and cost-efficient way, to sustain competitiveness. In light of these requirements, changeable manufacturing systems appear promising. However, empirically founded research is limited in regard to how different requirements lead to different applications and resulting potentials in various industrial settings. Therefore, this paper presents a comparative study of requirements, enablers, and potentials of changeability in two industrial cases (i) a Danish manufacturer of capital goods for the energy sector, (ii) a Danish manufacturer of sporting goods for the maritime sector. The objective of the paper, is to generate insights which can support various industrial settings in the transition towards changeable manufacturing. Findings include: (i) in high-volume contexts, reconfigurability is suitable to accommodate a production mix with increasing dimensions of parts, with potential to improve equipment utilization to reduce capital expenses (ii) in global manufacturing contexts, reconfigurability is suitable to accommodate frequent changes of production location, with potential to improve demand proximity to gain a competitive advantage.

Keywords: Changeable manufacturing systems, Reconfigurable manufacturing, Changeability requirements, Changeability potentials, Changeability enablers.

1 Introduction

More than 20 years ago, Reconfigurable Manufacturing Systems (RMSs) were introduced with the aim to combine the throughput of Dedicated Manufacturing Systems (DMSs) with the functionality range of Flexible Manufacturing Systems (FMSs) [1, 2]. DMSs are cost-effective when market requirements are stable, as they are designed to produce a single product or part at a high rate, usually through fixed automation [3, 4]. In contrast, FMSs are designed to produce a wide variety, usually at a lower rate [4]. To do this, FMSs embodies capital-intensive general-purpose flexibility which might not be needed as market requirements evolve [3]. While DMS and FMS are static systems, RMS can be adapted over time as its capacity and functionality can be changed to what is needed, when needed [3, 5]. Therefore, unlike DMS and FMS, RMS can dynamically meet evolving market requirements. Thus, enabling manufacturing companies to face the current context characterized by increasingly frequent and unpredictable market changes [6]. This capability of RMS is enabled by several characteristics which are presented with definitions in Table 1. The table also provides information on the relative importance of characteristic in accordance with Koren et al. [1], Koren [5] and Rösiö [7]. These authors either classify the characteristics as: Necessary (Ne), Core (Co), Basic (Ba), Critical (Cr), Supportive (Su) or Non-Categorized (NC).

Table 1. Enabling characteristics of reconfigurability.

Characteristic	Definition	[1]	[5]	[7]
Convertibility	The ability to convert functionality to new products or parts	Ne	Co	Cr
Scalability	The ability to increase or decrease the rate of production	Ne	Co	Cr
Customization	The limitation of functionality to a product or part family	Ne	Co	Ba
Modularity	The grouping of functional elements to physical modules		Co	Su
Integrability	The ability to integrate modules through standard interfaces		Co	Su
Diagnosibility	The ability to detect and diagnose errors in reconfigurations		Co	Su
Automatibility	The ability to increase or decrease the degree of automation			Nc
Mobility	The ability to move or relocate modules			Nc

To ensure competitiveness in increasingly dynamic contexts, RMS deserves the interest of manufacturing companies. However, despite the general trend, it is not likely to think that all companies need RMS against DMS or FMS. Many researchers instead refer to changeability as a combination of capabilities associated to either RMS, DMS and/or FMS [8, 9]. To embed changeability into the design of a manufacturing system, it is essential that manufactures analyze their specific requirements. Then, hereafter, select and implement the appropriate type and extent of changeability by embodiment of the suitable classes and enablers in the appropriate manufacturing constituents [8].

However, previous research on this subject generally has a limited empirical focus on the industrial transition toward changeable manufacturing [4, 10]. One of the few industry-applicable tools allowing the identification of changeability requirements, suitable enablers, and resulting potentials is the "Participatory System Design Methodology for Changeable Manufacturing Systems" (PSDM) proposed by Andersen and ElMaraghy et al. [8]. The steps of the PSDM are: (i) identify relevant company data based on a questionnaire requiring the participation of stakeholders in the company, (ii) define patterns of change requirements, (iii) determine appropriate manufacturing paradigm, (iv) determine required change enablers, (v) determine existing change enablers, constraints, and manufacturing paradigm and (vi) recommended transition towards new manufacturing paradigm. Applying the PSDM allows manufacturers to identify their requirements and potentials in terms of combination of RMS, DMS and/or FMS capabilities. Although Andersen and ElMaraghy et al. [8] applied the PSDM in two industrial cases, to the best of the authors' knowledge, there is no further literature applying the PSDM in industry. Given the necessity to extend the empirical focus of research on changeability, this paper further applies the PSDM in two manufacturing cases in order to address the following research question: *"What are differences in requirements and potentials of changeable manufacturing in different manufacturing settings?"*

The remainder of the paper is structured as follows: Section 2 outlines the case research method, Section 3 presents the case study findings, Section 4 presents the cross-case findings, and section 5 presents conclusions and further research directions.

2 Methodology

The case study approach - following the directions of Eisenhardt [11] - has been adopted given the explorative nature of the research question and the aim of providing both empirical and theoretical insights on differences in requirements and potentials of changeability. The near-polar characteristics and contexts of the two cases included in the study are provided in Table 2. Eisenhardt [11] provides a framework to guide the process of building theory from case study research through a set of steps and activities. Details on how these activities are executed in the focal research, are presented in Table 3. Moreover, the table includes (i) a reference to where the results of executed activities are presented and (ii) an account of how and why an activity has been modified.

Table 2. Overview of company and context characteristics within each case.

Characteristic	Case A	Case B
Company type	Public-limited and large company	Privately held medium-sized company
Industry	Capital goods for the energy sector	Sporting goods for the maritime sector
Product	Large size, modular architecture	Medium-sized, integral architecture
Demand	Global and project-based demand	International and order-based demand
Competition	High degree of competition	Medium degree of competition
Position	Largest actor and market-leader	Second largest actor in niche market
Area of focus	Manufacturing of product module	Manufacturing of product family
Prod. location	Global manufacturing footprint	Local manufacturing facility
Prod. strategy	Make-to-stock and make-to-order	Make-to-order

In terms of data collection, semi-structured interviews were conducted with various representatives from the companies in order to capture emergent themes and unique case features. In case A, this resulted in (i) three meetings of five, one and two hours with a product and manufacturing engineer at the headquarters (ii) one meeting of one hour with a supply chain planner during an online session (iii) one meeting of one hour with the lead of new product introductions at the mother-factory. In case B, two meetings of four and two hours were held with the production manager at the factory. In both cases, archival data were extracted from (i) ERP system, (ii) spread-sheets and (iii) presentations, to validate and enrich the qualitative statements related to the change requirements. Furthermore, direct observations from tours at the mother-factories and discussions with workers, aided the identification of existing enablers and constraints.

Table 3. Details on the execution of activities.

Step	Description
Get started	The research question is defined with supportive motivation in Section 1.
Select cases	Two companies have been selected for the case-study. Due to theoretical reasons, the cases differ on their company and context characteristics in order to generate as many insights as possible from the cross-case comparison. Thereby, increasing the possibility to extend emergent theory and provide examples of polar types. This is needed in order to satisfy the research question sufficiently, despite the inclusion of a small sample size. Due to practical reasons, the companies should (i) be located in proximity to Denmark and (ii) have interest in the research topic of changeability.
Craft protocol	The protocol provided by the PSDM have been applied with minor modifications for the joint collection and analysis of data in the focal research.
Collect data	A combination of qualitative and quantitative data has been collected using multiple sources of evidence in order to strengthen the grounding of theory by triangulation of synergistic evidence. Details are provided in the text.
Analyze data	Within-case analyses are provided in Section 3 where the PSDM has been applied. The cross case-comparison is provided in Section 4.
Shape hypothesis	The within-case analyses and cross-case comparison are used to shape the hypotheses of the focal research. These hypotheses constitute the emergent theory which is presented in Section 4 and summarized in Section 5.
Enfold literature	The emergent theory of the focal research is compared with the extant literature on the topic of changeability and reconfigurability e.g. the seminal works of Koren et. al. [1, 5]. Aforementioned, is provided in Section 4 where complementary and conflicting findings, in-between, are presented.
Reach closure	Closure have been reached prematurely, where the inclusion of additional cases is expected to enhance the theoretical saturation in further research.

3 Findings

The results of applying the PSDM are presented in Fig. 1 for case A and in Fig. 2 for case B. The figures present the mapping of (i) the specified changeability requirements in the stakeholder domain, (ii) to appropriate manufacturing system paradigms in the functional domain, (iii) to existing constituents, enablers and constraints in the physical domain. These mapped connections between system design domains indicate gaps between (i) the appropriate and the existing paradigms, (ii) the changeability requirements and the changeability extent of existing constituents. In order to continuously and efficiently match the requirements, the identified gaps should be mitigated through embodiment of suitable enablers in the constituents where they are present. For both industrial cases, the identified suitable enablers of the appropriate paradigms to be embodied in existing constituents are presented in Table 4 along with the derived operational, tactical, and strategic potentials of the context-specific embodiment.

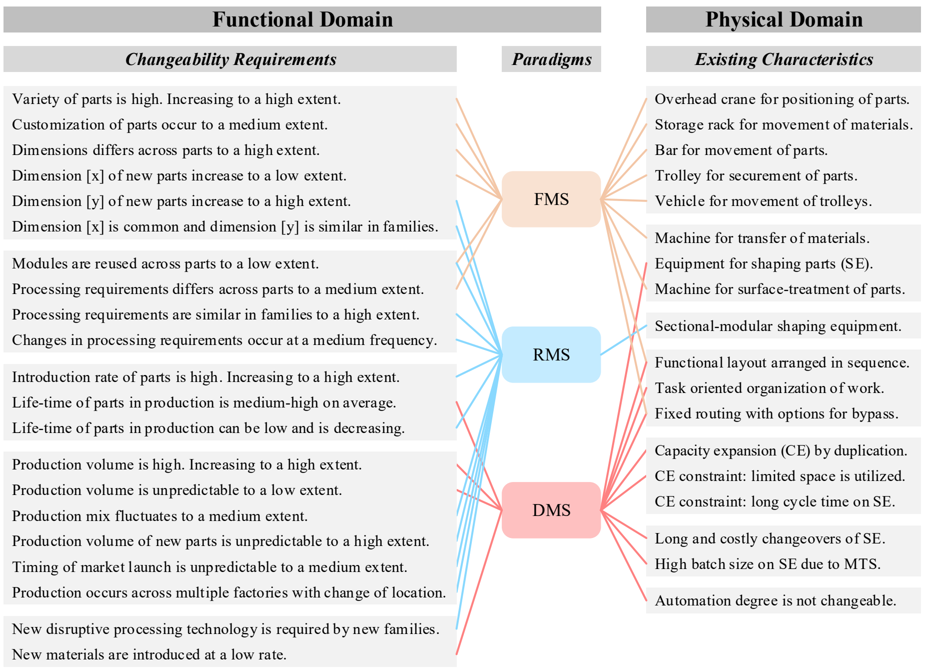

Fig. 1. Mapping between system design domains in case A.

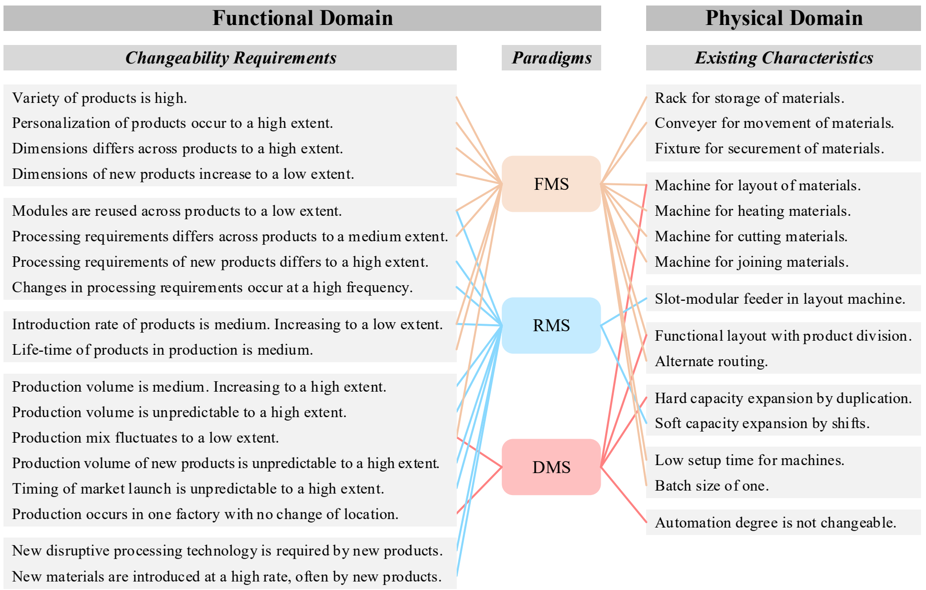

Fig. 2. Mapping between system design domains in case B.

Table 4. Potentials of recommended transition and embodiment in case A and case B.

	Case A	Case B
Suitable Paradigm	The suitable paradigm is a mix of FMS and RMS. Flexibility is suitable to be retained for the handling equipment and production machines to cope with different materials and dimensions of parts. Reconfigurability is suitable to be embodied in the shaping equipment to cope with the increasing dimensions of parts that are similar within new families.	The suitable paradigm is a mix of FMS and RMS. Flexibility is suitable to be retained for the handling equipment and majority of production machines to cope with different dimensions of products. Reconfigurability is suitable to be embodied in the layout machines to cope with the change of materials and processing technology.
Suitable Enablers	The shaping equipment is suitable for embodiment of sectional modularity, mobility, integrability and customization to enable convertibility between parts within families where dimension [x], materials and processing technology are common and dimension [y] is similar.	The layout machine is suitable for embodiment of slot-modularity and integrability with respect to the material feeder, to enable convertibility between current and new generations of products where the materials and processing technology are different.
Derived Potential	Operational potential in terms of rapid and cost-efficient response to changes in production mix across multiple factories. Tactical/strategic potential in terms of: (i) increasing the proximity of production to demand to reduce transport cost and to achieve a competitive advantage (ii) increase the lifetime- and capacity utilization of shaping equipment to reduce capital costs (iii) negate the need for MTS to reduce inventory levels.	Operational potential in terms of rapid and cost-efficient response to changes in production mix within the factory. Tactical/strategic potential in terms of: (i) reducing the time-to-market of new product generations requiring new materials and new processing technology (ii) increasing the lifetime- and capacity utilization of the layout machines to reduce capital expenses.

4 Discussion

A noteworthy cross-case finding is the relation between the industrial context and the change requirements related to the product, which results in a difference of suitable changeability classes to embody in the manufacturing system constituents. Despite geometrical dimensions and materials being primary determinants of product performance in both cases, the material mix is stable in case A as opposed to a high rate of change in case B. Moreover, the dimensions increase at a higher rate in case A whereas the range of dimensions is higher in case B. This result in flexibility being suitable to cope with the stable material mix in case A and differing dimensions in case B, whereas reconfigurability is suitable to cope with the increase of dimensions in case A and change of materials in case B. These differences in change requirements related to the product can be attributed to the following contextual differences:

- The highly competitive and industrialized B2B context of case A, which generates a higher clock-speed of dimensional increase (order winner) and need for the material mix minimizing the weight (order qualifier). The solution space of the latter is exhausted due to industrialization, where the solution is applied across competitors.
- The niche B2C context of case B where the (i) dimensions are dependent on the customers system, (ii) materials are selected in accordance with customers objective i.e. for casual or competitive purpose, generating a higher need for personalization.

Another noteworthy cross-case finding is the relation between the industrial context and the change requirements related to the geographical location of production, resulting in differing potentials of changeability. Despite global markets with fluctuating demand being supplied in both cases, there is a difference in terms of changes to the: number, location, functionality and capacity of factories. Production in case B is rooted in a single factory with no change of location. In contrast, production in case A is spread across multiple external and internal factories where each factory has a unique range of functionality and capacity that is changed several times per year. These changes are among others made in order to:

- Decrease the time and thus the cost of transporting the large-scale capital goods, by means of increasing the proximity of production to the location of the demand.
- Gain a competitive advantage to win project-based orders in competitive tendering schemes, by means of complying with requirements for localized manufacturing.

Although both case-companies remain competitive through the capability to *deliver the desired product, in the correct quantity, at the correct time, at the right place*, the findings emphasize the need for global manufacturers of large-scale capital goods to produce at the correct place as well. These findings extend the propositions of Koren [5] regarding the aforementioned capability required to remain competitive in the 21st century. Moreover, as reconfigurability is an enabler of the capability in case A, RMS is thus, not only aiding to provide *exactly the capacity and functionality needed, exactly when needed*, but also where needed. This enforces the propositions of Andersen and ElMaraghy et al. [8] regarding that reconfigurability is a multi-dimensional and context-dependent capability where the enablers can be embodied in constituents in various ways depending on the context-specific drivers and potentials of reconfigurability.

Moreover, with regards to case-A, the capability to produce everything, everywhere, can be enabled to a higher extent through flexibility in the shaping equipment by means of additive manufacturing. However, as flexibility requires the functionality range to be pre-determined, an extensive range would need to be pre-specified to cope with the high rate of increase in dimensions without risking low capacity and lifetime utilization of the equipment. This is assessed by the company to be economically infeasible since a high production volume is required which necessitates a larger quantity of equipment if flexible as opposed to the reconfigurable counterpart. These findings thereby indicate that reconfigurability is suitable in high volume cases if the variety, extent of dimensional increase and rate of production location change, is high as well. This application of RMS in case A thereby goes beyond the intention of RMS being suitable in medium volume cases as originally proposed by Koren et al. [1].

With regards to the PSDM, it proved applicable in generating relevant input for further concept design in both cases, although the industrial context, unit of analysis, data foundation and degree of participation, differed. An insight gained throughout the process of applying the PSDM is that the degree to which the output was deemed relevant by the company stakeholders were higher when (i) the requirements and existing characteristics were respectively based on quantitate data and observation of the shop-floor, (ii) a high degree of participation, follow-up questions and free flow of thoughts were present during the collection and analysis of data. The latter stimulated the identification of the drivers for changes to the production location in case A, and the tactical/strategic potential of enabling these changes through reconfigurability.

Another insight gained, is that some patterns of requirements could not be identified as being suitable to be met by only one of the changeability classes. For example, the low reuse of part modules present in both cases constrains the possibility to achieve economies of scale with regards to part modules through DMS, thereby leading to FMS or RMS being suitable instead. Moreover, the existing manufacturing systems and their constituents could neither be classified as strictly being one of the changeability classes. For example, the layout machine in case B is dedicated to a material type while being flexible in its range of dimensions it can handle. This multi-dimensional aspect is not supported to be identified and mapped by solely applying the factual questions, provided by the PSDM. Therefore, the PSDM is proposed a modification where the questions lead to a degree and rate of change with respect to context-specific production parameters from which a gap with the related functionality and capacity range of existing manufacturing constituents could be mapped. The latter is expected to stimulate conceptual design to a higher extent by increasing the boundary of the solution space in terms of potential classes and enablers to embody in constituents to achieve the required type and extent of changeability and the resulting potentials.

5 Conclusion and Further Research

This paper contributes with insights from a comparative case-study on differences in requirements and potentials of changeability in two companies with different industrial settings of manufacturing. The primary insights gained are listed in the following:

- Reconfigurability is suitable to cope with increasing product parameters resulting from a high clock speed of industrialization in competitive B2B contexts, whereas flexibility is suitable to cope with a high extent of personalization in B2C contexts.
- Reconfigurability is suitable in high volume cases if: variety of parts, dimensional increase of new parts and rate of production location change, is high as well.
- Reconfigurability is suitable for global manufacturers of large-scale capital goods to gain a competitive advantage by enabling the capability to provide exactly the capacity and functionality needed, exactly when needed, exactly where needed.
- Changeability requirements can be enabled through the embodiment of various types of classes and enablers in existing constituents of manufacturing systems.
- Existing manufacturing systems and their constituents can embody multiple classes of changeability e.g. dedicated on one parameter and flexible on another parameter.

Future research should aim at applying the PSDM in additional cases to advance the theoretical saturation on differences in requirements and potentials of changeability. Moreover, future research should aim at providing a tool to map the degree and rate of change of context-specific production parameters from which gaps with the related functionality and capacity range of existing manufacturing constituents can be drawn. This tool is suggested, as the limited methods provided by research i.e. the PSDM constraints the boundary of the solution space of conceptual manufacturing system design in terms of limiting the possibility of multiple classes and enablers of changeability being able to meet the context-specific requirements for changeability. By accounting for the former, the suggested tool is expected to support the industrial transition towards changeable and reconfigurable manufacturing systems in brownfield contexts.

Acknowledgements. The research presented in this paper is supported by the REKON research project and the MADE research program. REKON is funded by the Danish Industry Foundation and MADE is funded by the Innovation Fund Denmark.

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