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Exploring Requirements and Implementation of Changeability and Reconfigurability in Danish Manufacturing

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Abstract

Changeability and reconfigurability can be considered decisive factors of competitiveness in high-wage countries with pressure for cost reduction, extensive relocation of manufacturing, and growing need for product variety and customization. Despite these promising potentials, their current state in industry remains rather unexplored. Therefore, the aim of this paper is to explore requirements and implementation of changeability and reconfigurability in Danish manufacturing through an exploratory descriptive survey. The findings indicate that changeability is both relevant and important in Danish manufacturing. However, the findings also indicate a mismatch between requirements and implementation of changeability, as enablers of reconfigurability are only rudimentarily existing.

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Keywords: Changeable manufacturing; Changeability; Reconfigurability; Survey; Danish manufacturing.

1. Introduction

Danish manufacturing is well-known internationally for premium products such as pumps, thermostats, wind turbines, robotics, and toys. Also, manufacturing remains a cornerstone of the Danish economy, accounting for more than half of all export [1]. However, in recent decades, the share of value added from manufacturing has decreased significantly and major reductions of manufacturing jobs have appeared [1]. As in many other high-wage countries, increased automation, extensive outsourcing and offshoring, and emergence of new global competitors from low-wage countries are among the main reasons for this [2]. From a general perspective, the manufacturing tasks relying heavily on economies-of-scale have been extensively relocated to emerging countries, while the tasks relying largely on economies-of-scope have remained in high-wage countries to cater niche markets with premium products [3]. Thus, manufacturing companies have sought competitiveness by securing a position at only one end of the dichotomies between scale and scope, and between high value-orientation and high planning-orientation in production [2]. Nevertheless, securing a better position in just one of the dichotomies does not appear as a promising strategy towards long-term sustainable competitiveness, as technological advancements naturally will increase competition in small niche markets [2]. Rather it is widely acknowledged that the key to continuous manufacturing strength is to reduce the trade-off between both dichotomies of scale and scope and dichotomies of value-orientation and planning-orientation - the poly-lemma of production [3]. This means that manufacturing companies should move towards achieving a strong position with highly customized and individualized production at mass production efficiency, which can be easily adapted with low planning-effort to market changes and uncertainty [2].

Product modularisation and the use of product platforms have been applied for years for resolving the dichotomy between scale and scope [4]. However, solely utilizing product modularity is not enough to achieve reduction of the poly-lemma of production, as changes in products propagate to the manufacturing processes and systems [4, 5]. Thus, being able to manage and capitalize on smaller batch sizes, fluctuating volumes, frequently changing product mix, and rapid new

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product introductions has become decisive factors of competitiveness as well [4, 6].

Changeable manufacturing and in particular reconfigurable manufacturing are widely recognized as manufacturing paradigms that respond to these requirements through efficient and rapid change of functionality and capacity [7]. Changeable and reconfigurable manufacturing have received considerable attention in research [8], and some successful implementation examples have been set forward. For instance, the "Modulare Produktionsbaukasten Prinzip" from Volkswagen, which involves a common global platform of processes, resources, and equipment with customized flexibility and scalable capacity that resulted in significant savings in investment and increased productivity [9]. Other examples are from Northern American automotive industry [10], French automotive industry [11], and Swedish automotive industry [12]. Only few examples of research with generalizable empirical evidence concerning changeability implementation can be found, e.g. a survey on requirement of design of flexible and reconfigurable manufacturing systems in Italian small and medium sized enterprises [13] and a small-scale expert survey on the state of changeable machine tools [14]. However, the current status of changeability and reconfigurability has not yet been explored in Danish industry, despite its promising potentials in regard to reducing the poly-lemma of production. Therefore, the objective of the research presented in this paper is to explore the current state of changeability and reconfigurability in Danish manufacturing. Particularly, focus will be on drivers of changeability, the competitive advantage of a changeable manufacturing system, the required frequency of change, as well as the current implementation of reconfigurability enablers. The remainder of the paper is structured as follows: Section 2 presents the background on changeability and reconfigurability, while Section 3 presents the applied survey research method. Section 4 presents the results, which are subsequently discussed in Section 5 including future research directions in Section 6.

2. Background

2.1. Changeable and Reconfigurable Manufacturing Systems

In the 90's, the Reconfigurable Manufacturing System (RMS) concept was introduced as a new manufacturing paradigm that through enablers of scalability, convertibility, modularity, integrability, customization, and diagnosability could achieve both cost-efficiency and rapid change of functionality and capacity [7]. Recently, changeability has been accepted as an umbrella term or general property of manufacturing that ensures economical, timely, and proactive adaption on all factory levels [15]. On manufacturing system, cell, and equipment level, changeability is achieved by reconfigurability and flexibility or the combination of both [16]. Thus, a changeable manufacturing system can be illustrated as in Fig. 1, where flexibility corresponds to predefined ranges of capacity and functionality that can be used quickly and with limited effort, whereas reconfigurability corresponds to expansion of the boundaries of the system to suit new processing requirements [16].

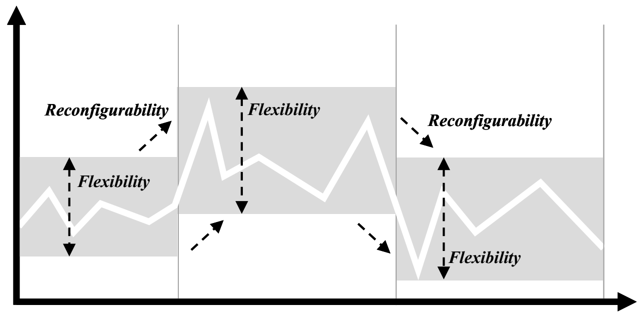

Fig. 1. Illustration of a changeable manufacturing system containing a combination of reconfigurability and flexibility [16].

As depicted in Fig. 1, the timing of realization of flexibility and reconfigurability is different, where reconfigurability is a dynamic property of the system that enables both efficient response to change in e.g. functionality or capacity, adaption of the system over its entire lifetime, as well as customized flexibility corridors to reduce the trade-off between scale and scope [11]. Thus, reconfigurability is a particularly important aspect of changeability in regard to creating competitive manufacturing in high-wage countries.

2.2. Fundamentals of Changeability

In the seminal works by Wiendahl et al. [17] and ElMaraghy and Wiendahl [18], a model for deriving the objects of changeability is proposed. This model defines and explains the fundamental constructs of changeable manufacturing; change drivers, change objects, change enablers, change strategy, and change extent. In Table 1, these fundamentals are briefly summarized.

Table 1. Fundamental constructs of changeable manufacturing.

Construct	Description
Change drivers	Every change is triggered by change drivers, which are usually categorized as being product-related, volume-related, technology-related, or strategy-related [3].
Change objects	The drivers prompt changes in change objects covering products, product mix, and production volume [17, 18].
Change strategy	The change strategy represents decisions and plans on how to respond to the change drivers and the need for change in the change objects, e.g. if responding to changes is solely for survival or for securing competitive advantage [18].
Change extent	The change extent is largely determined by the change strategy and covers the factory level to accomplish changes on, the expected frequency of change, and the effort related to change [17, 18].
Change enablers	The change needed is facilitated by change enablers. On manufacturing system, cell, and equipment level, the most important enablers are the reconfigurability characteristics; modularity, convertibility, integrability, scalability, convertibility, and diagnosability, as well as mobility and automatibility on the system level [17, 18].

When designing and developing changeable manufacturing systems, all the fundamental constructs should be considered [19], which is neither an easy nor a straightforward process [20, 21]. The change drivers indicate the specific requirements of the system, change objects specify the type of change in accordance with the change strategy and required change extent, while change enablers are embedded in the system solution to realize the required change [19]. Thus, in order to explore and evaluate the current state of changeable manufacturing in industry, the changeability constructs in Table 1 should be considered. The change drivers, strategy and extent largely represent changeability requirements, whereas the change enablers represent the ability to meet the requirements.

3. Research Method

In order to address the research objective of exploring the current state of changeability and reconfigurability in the Danish manufacturing industry, data collected from a questionnaire survey were used. This survey was designed as being largely exploratory and descriptive, in order to provide insight into the rather unexplored topic of changeability and reconfigurability in the Danish manufacturing industry.

3.1. Questionnaire Design

The survey questionnaire was designed to reflect the fundamental constructs of changeable manufacturing described in Table 1; change drivers, change strategy in terms of the competitive priority of changeability, change extent in terms of the required frequency of change, and change enablers. Focus is on changeability on manufacturing system level and below, which also means that reconfigurability is particularly emphasized.

Table 2. Description of sections in questionnaire.

Section	Description	Variables
Change drivers	Questions regarding agreement with different statements related to change drivers e.g. volume, technology, or products.	8 measured variables on five-point Likert scale: 1 – strongly disagree, 2 – disagree, 3 – neither disagree og agree, 4 – agree, 5 – strongly agree.
Change strategy in terms of competitive advantage of changeability	Questions regarding agreement with statements on the advantage derived from being able to accomplish changes in three main change objects; capacity, production mix, and introduction of new products.	3 measured variables on five-point Likert scale: 1 – strongly disagree, 2 – disagree, 3 – neither disagree og agree, 4 – agree, 5 – strongly agree.
Change extent in terms of frequency of change	Questions regarding the frequency of changes in three main change objects; capacity, production mix, and introduction of new products.	3 measured variables on four-point Likert scale: 1- daily, 2 – weekly, 3- monthly, 4- annually.
Enablers of change	Questions regarding the current state of implementation of change enablers, specifically hard enablers of reconfigurability on system and equipment level.	13 measured variables on five-point Likert scale: 1 – not implemented, 2 – slightly implemented, 3 – moderately implemented, 4 – mostly implemented, 5 – fully implemented.

In Table 2, the four main sections of the survey questionnaire are described in terms of question design, variables, and measured scale. As such, each section represent a latent variable being a changeability construct and a number of measured variables that are observable in the manufacturing company. For instance, the change enablers are highly latent as they are most often described on very aggregate levels, therefore, their implementation on system and equipment level were used as measured variables. As indicated in Table 2, all variables were measured on ordinal Likert scales, however, respondents were also given the possibilities to indicate uncertain responses. In addition to the four main sections, background characteristics of the responding companies e.g. industry, size, volume, product type, and production type were also included in the questionnaire.

3.2. Data Collection & Analysis

The questionnaire was developed in both an English and a Danish version in SurveyXact, and was prior to the actual data collection tested in a group of experts from academia. This pre-test resulted in minor changes in questions and terminology. In the actual data collection, the questionnaire was distributed to individuals representing Danish manufacturing companies, e.g. production specialists, production engineers, operations managers, plant superiors, as well as other types of managers with production related responsibilities. In addition, the survey was distributed more broadly in various manufacturing forums for Danish manufacturing companies. In total, 50 full responses resulted for subsequent data analysis.

The analysis of collected survey data includes both initial assessments of data quality and the survey instruments, as well as descriptive analyses regarding the distribution of responses in the sample. Cronbach alpha tests were also conducted, which showed sufficient internal consistency of measurements.

4. Results

4.1. Characteristics of Respondents

The sample covers responses from 50 individuals representing Danish manufacturing companies from various types of industries. In Fig. 2, the distribution of industries represented in the sample is depicted.

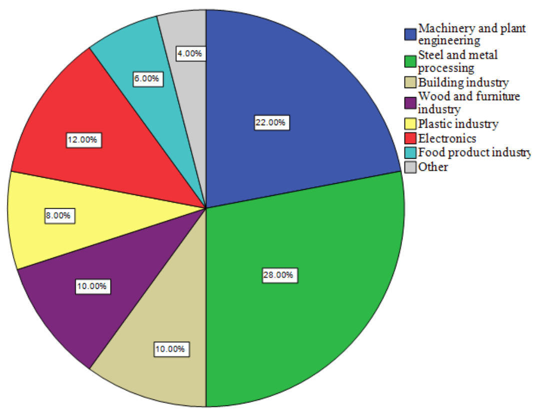

Fig. 2. Industry distribution in sample.

The sample companies are almost equally divided between small and medium sized companies (SMEs) and large enterprises (LEs). In Fig. 3, the distribution of company size in terms of employees is depicted.

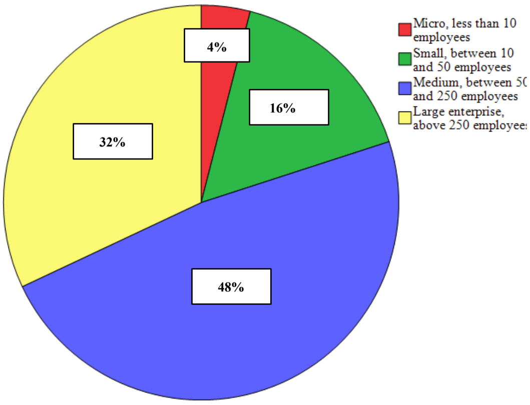

Fig 3. Size of manufacturing companies in sample.

In Fig. 4, the annual production volumes of the sample companies are depicted, which shows that around 25% of companies can be characterized as being low-volume manufacturers.

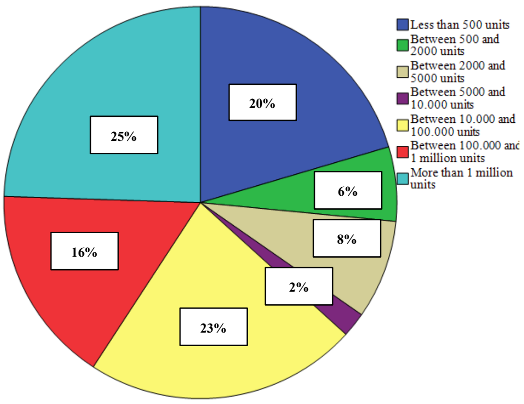

Fig. 4. Annual production volume of sample companies.

In Table 3, characteristics of the sample are presented. Specifically the table shows the distribution of companies regarding percentage of production processes that are automated, percentage of production that is MTS, MTO and ETO, and the percentage of products that are custom-ordered, standard products with variants, or purely standard.

Table 3. Production and product characteristics of sample companies.

Characteristic	0 - 25%	25 - 50%	50 - 75%	75 - 100%
Manual work	25%	25%	25%	27%
Highly automated	75%	19%	2%	4%
Make-to-stock (MTS)	69%	15%	10%	6%
Make-to-order (MTO)	38%	15%	13%	35%
Engineer-to-order (ETO)	83%	6%	6%	4%
Custom-ordered products	49%	12%	8%	31%
Standard products with variants	43%	22%	14%	20%
Standard products without variants	71%	8%	14%	6%

Generally, the degree of full automation of production is low, as around 6% of the responding companies indicate that more than 50% of their processes are highly automated. In contrary, more than half of the respondents indicate that more than 50% of processes are conducted manually. Further, a third of the companies indicate that more than 75% of products are customized, whereas purely standard offerings represent only a minor part of products in most sample companies. Likewise, MTS production is represented only to a limited extent, while MTO production appears to represent more than 50% of activities in approximately 50% of the sample companies.

4.2. Change Drivers, Change Strategy & Change Extent

The results regarding change drivers present in the sample companies are depicted in Table 4. Generally, most of the measured change drivers appears to be present to some extent in the companies. In particular, more than 75% of respondents indicate that customer needs are dissimilar and there is a need for variety in product offerings. Likewise, more than 75% of respondents indicate that it is difficult to predict sales volume of new products, while volume fluctuations and seasonality also are present conditions in most of the companies. Change drivers related to quick technological change appear less dominant, however, more than half of the respondent agree that technological changes provide significant opportunities.

Table 4. Change drivers present in in sample companies.

Change driver	Strongly disagree	Disagree	Neither disagree or	Agree	Strongly agree	Uncertain
Sales volumes fluctuate significantly over time	2%	20%	16%	40%	16%	6%
There is significant variation in demand during different yearly seasons	6%	20%	26%	22%	24%	2%
It is difficult to predict sales volume of new products	0%	16%	8%	38%	36%	2%
Sales volumes change significantly over the product's lifecycle	0%	28%	24%	32%	8%	8%
Customer needs are dissimilar and there is a need for variety in product offerings	0%	8%	14%	44%	32%	2%
Product life cycles are decreasing and we are forced to introduce new products frequently	4%	24%	30%	26%	8%	8%
The technology in our industry is changing quickly	12%	40%	14%	26%	6%	2%
Technological changes provide significant opportunities in our industry	4%	20%	22%	34%	20%	0%

In Table 5, the distribution of answers regarding the competitive advantage of changeability is depicted, where changeability objectives correspond to capacity scaling, production mix changes, and introduction of new products. Evidently, almost all respondents indicate that the different changeability objectives result in competitive advantage.

Table 5. Competitive advantage of changeability in sample companies.

Changeability objective	**Strongly disagree**	**Disagree**	**Neither disagree or**	**Agree**	**Strongly agree**	**Uncertain**
Being able to efficiently up and down scale production capacity provides superior competitive advantage	0%	4%	2%	32%	62%	0%
Being able to change the mix in production provides superior competitive advantage	2%	4%	0%	42%	52%	0%
Being able to quickly introduce new products in production provides superior competitive advantage	2%	8%	10%	36%	44%	0%

In Table 6, the distribution of answers regarding the required frequency of change is depicted. The responding companies indicate that capacity scaling is required mostly on monthly and annual basis, while new products generally happen mostly on an annual basis. However, a fourth of the respondents indicates that new products are introduced even on a monthly basis.

Table 6. Change frequency in sample companies.

Changeability objective	**Daily**	**Weekly**	**Monthly**	**Annually**	**Uncertain**
Frequency of scaling production capacity up and down	0%	16%	52%	24%	8%
Frequency of changing the production mix	20%	20%	18%	36%	6%
Frequency of introducing new products in production	4%	4%	26%	54%	12%

4.3. Implementation of Enablers of Reconfigurability

In Fig. 5, the current level of implementation of change enablers is depicted. All the investigated enablers are enablers of change on manufacturing system/line level and equipment level, thus being the reconfigurability characteristics including automatibility and mobility as described in Section 2. It appears that most of the enablers are only implemented to a limited extent. Particularly, automatibility and mobility of lines are implemented to low extent, as well as convertibility of lines. Moreover, a critical enabler such as modularity of lines and equipment seems to be only implemented in around 20% of the companies. In contrary, customization is implemented to some extent in around half of the responding companies.

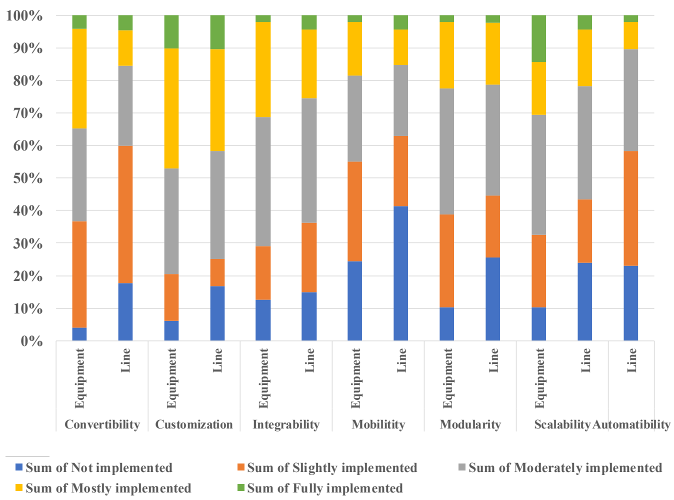

Fig. 5. Implementation of change enablers on manufacturing system/line and equipment level in sample companies.

5. Discussion

The results of the survey indicate requirements for changeability and the existing enablers of changeability in Danish manufacturing, which is summarized in Table 7.

Table 7. Summary of survey findings

Construct	**Summary of survey findings**
Change drivers	Volume, product and technology related change drivers generally appear present in the sample companies. Particularly, the companies indicate volume fluctuation and difficulty in predicting volume of new products as change drivers, as well as need for customization and variety.
Change strategy	The sample companies indicate superior competitive advantage associated with efficient change in product mix, efficient introduction of new product, and capacity scalability.
Change extent	Scaling of capacity is mostly required on monthly and annual basis, product mix change is required on both short-term daily/weekly basis and long-term annual basis, whereas introduction of new product is required mostly on monthly and annual basis.
Change enablers	Changeability enablers in terms of reconfigurability characteristics of system/line and equipment are only basically existing in the sample companies. Full implementation of the characteristics is very limited.

The findings indicate that changeability indeed is required and should be a strategic priority in Danish manufacturing. Both short-term changeability regarding product mix is required, as well as more long-term capacity scaling and product introductions. Particularly, the two latter requirements indicate that reconfigurability in terms of changing existing capacity and functionality boundaries of manufacturing systems is important, as illustrated in Fig. 1. However, the findings also indicate that enablers of reconfigurability are only rudimentarily existing. Thus, the survey findings indicate a mismatch between requirements and implementation of changeability and reconfigurability. In relation to this, various practical challenges and barriers towards reconfigurability have been encountered in previous research, e.g. limited knowledge of reconfigurability [21], lack of design and development methodologies that can be applied in practice [19, 22], complexity of reconfigurability design [20], and separation of product and production design [23]. In order to limit this gap, reconfigurability should be both a managerial and academic priority, e.g. on how to aid the development process in industry through e.g. product and production co-development methodologies. Moreover, this survey explores the overall state of changeability in Danish manufacturing based on its promising potentials to resolve the poly-lemma of production. However, research on specific conditions related to changeability implementation in different types of Danish industrial cases is required as well, in order to uncover the potential in various types of settings, e.g. in SMEs and in low-volume manufacturing versus high-volume manufacturing.

The main limitations of the research presented in this paper relate primarily to the relatively low sample size, n = 50, as well as the non-probabilistic sampling method applied. Generally, these factors limit the generalizability of results beyond the actual sample. For instance, the sample companies cover approximately an equal amount of LEs and SMEs, which does not generally represent the Danish manufacturing industry, where more than 90% of all companies are SMEs. Presumably, low-volume production, engineer-to-order or one-of-a-kind production, and manual processes would be represented to higher extent than in the present sample, if more SMEs had been included. However, despite these limitations, the survey provides valuable initial and preliminary insight into the topic of changeability in Danish manufacturing companies.

6. Conclusion & Future Research

In this paper, an explorative descriptive survey was presented with the objective of exploring the current state of changeability and reconfigurability in Danish manufacturing. The findings indicate that changeability is both relevant and important in Danish manufacturing, particularly in terms of capacity and functionality reconfigurability. However, enablers of reconfigurability are only rudimentarily existing, which indicate a need for further research on how to develop changeable and reconfigurable manufacturing systems in practise. Moreover, a viable future research direction is to increase generalizability of the survey findings by including a larger probabilistic sample design. Additionally, the survey could easily be expanded to other Scandinavian countries, as these have similar conditions as in Denmark, e.g. significantly high wages and reductions in manufacturing jobs, which indicate a need for reducing the production poly-lemma through changeable and reconfigurable manufacturing to gain manufacturing competitiveness.

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