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Potential Benefits and Challenges of Changeable Manufacturing in the Process Industry

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Abstract

Changeable manufacturing, as an enabler of Mass Customization, has gained increasing interest from industry and academia over the last decade. However, despite increased attention, research has focused primarily on discrete manufacturing, which is likewise expressed through most industry examples. The applicability and requirements of changeable manufacturing in the process industry consequently remains mostly unexplored by academia. Therefore, this research investigates potential benefits and challenges of implementing changeable manufacturing in the process industry through a case study from Danish industry. The findings indicate substantial benefits from implementing changeable manufacturing principles in the process industry.

Keywords: Changeable manufacturing; Changeability; mass customization; process industry; case study

1. Introduction

In today's globalized markets, manufacturing companies are influenced by an increasing diversity in customer requirements, smaller production batches, and shorter product life cycles, all which pressures traditional mass producers [1]. Despite general characteristics of high product volume and low product variety [2-4], the process industries are nonetheless also influenced by these market trends [5]. As a means for accommodating these changed conditions, employing mass customization as a business strategy has become increasingly relevant [6]. This is due to mass customization enabling manufacturers to provide customers with individualized products at near mass production cost. Successfully accomplishing this transition requires that companies focus on aligning their organization by engaging in three interrelated capabilities: (i) Solution space design, which is concerned with identifying both diverging and converging dimensions of customer needs, thereby assisting in determining which product variants to offer to accommodate customer requirements; (ii) robust process design, which focuses on how the processes, including the production system as the main part, can efficiently produce the product variants offered; and (iii) choice navigation, which has the purpose of guiding customers towards the best suited product configurations for their needs [6]. From a production system perspective, an enabler of Mass Customization is the concept of manufacturing changeability, which is concerned with both reactively and proactively changing the production system on multiple levels as a means to complying with changing market needs [7].

Several well-known industry examples of mass customization can be found in the realm of discrete manufacturing: Volkswagen in the automotive industry, Dell in the consumer electronics industry, and MyMüesli in the breakfast products industry. While examples of changeable manufacturing systems are likewise present in literature,

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these examples are scarce and primarily concerned with reconfigurable manufacturing systems (see for instance [8, 9]). Nevertheless, examples of mass customization and changeable manufacturing systems in the process industry are more uncommon in literature, despite the concept of changeable manufacturing being theoretically industry-agnostic, i.e., applicable in both discrete and process industry. The apparent discrepancy between discrete and process industry, concerning the prevalence of manufacturing changeability, is therefore interesting and forms the broader scope of the research presented in this paper. The underlying rationale for the scope of the paper is that with the sparse literature available on the subject, further knowledge is needed in terms of potential benefits and challenges in the implementation of changeable manufacturing systems in the process industry.

The rest of the paper is structured as follows. Section 2 provides a brief overview of manufacturing changeability and provides examples from previous research of manufacturing changeability in both discrete and process industry. Section 3 introduces the case included in the paper and describes the methodology of the study. Then, Section 4 presents the main findings of the case study and reflects on these findings from the broader perspective of the process industry. Finally, Section 5 conclusively discusses and summarizes the findings of the literature review and case study, in addition to emphasizing important future research directions.

2. Changeable manufacturing

In their seminal work on the subject, ElMaraghy and Wiendahl [10] defined changeability as: "[…] the characteristics to accomplish early and foresighted adjustments of the factory's structures and processes on all levels, due to change impulses, economically." The importance of considering changeability on multiple production levels is related to a manufacturer's ability to respond to change impulses [10]. Such impulses may require minor product changes, which can perhaps be accommodated through increased flexibility of individual production cells. However, change impulses can also have more extensive impacts on the production system. An example may involve transforming an entire factory segment to produce a new product group if market demand shifts. Thus, being able to respond successfully to changes in manufacturing companies, whether being minor or extensive changes, requires that the production system can accommodate these changes, which is achieved through changeability. To communicate the relations between production levels and corresponding changeability classes, ElMaraghy and Wiendahl [10] proposed a hierarchical framework relating different production levels with corresponding changeability classes and product levels. This model indicates that within the individual factory, five structuring levels exists ranging from the least aggregate level of the individual station to the most aggregated level of the entire factory. This model is illustrated in Fig. 1.

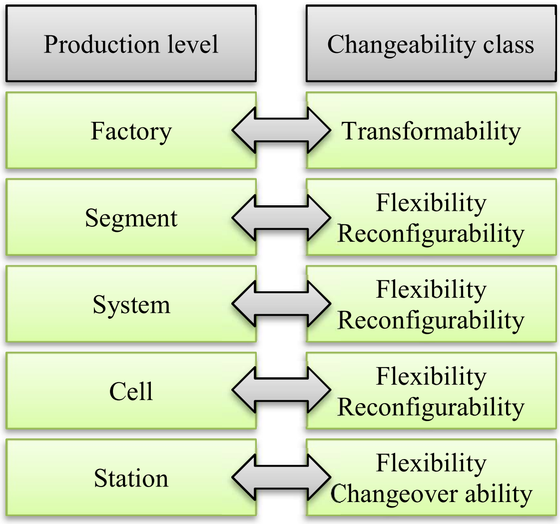

Fig. 1: Production levels and corresponding changeability classes. Adapted from ElMaraghy and Wiendahl [9].

At the factory level, transformability represents the ability to, e.g., quickly expand or retract the factory buildings [11] in order to accommodate, e.g., increased capacity requirements. Following the factory level, the segment, system, and cell levels are successively disaggregated production levels. On these levels, changeability is established through either flexibility, which denotes a pre-defined and built-in feature space, or through reconfigurability, denoted as the ability to add, remove, or rearrange production equipment as a means of achieving a different set of production capabilities or capacity level [1, 12]. At the station level, rapid and efficient change between known tasks is termed changeover ability. In conjunction with flexibility, changeover ability forms the fundamental approaches to obtaining changeability on the lowest production level.

Although changeability in theory is applicable in both discrete and process industry, certain differences exists in the characteristics of each industry [4], which may impact the applicability of changeability in the process industry. Abdulmalek et al. [4] compared typical process industry characteristics with those for discrete industry. One of the main differences is related to their names: discrete and process. In discrete manufacturing, products produced can be counted as individual units. However, in process industry, production is often continuous making it impossible to distinguish individual product units [4]. Nevertheless, products made in the process industry usually becomes discrete at some point during manufacturing, which is referred to as the discretization point [4]. From a production perspective, an additional important characteristic of the process industry is the application of primarily large, dedicated and inflexible equipment. Additionally, dedicated equipment is usually combined with the use of fixed layouts, material transfer, and routings. As a consequence, production changeovers are often long and resource-intensive. These characteristics are in direct contrast to those for the discrete manufacturing industry [4], where, e.g., variable volumes and generally more flexible processes potentially allow for easier adoption of changeability classes.

2.1. Changeability in process industry

The potential differences in applying changeability principles in the process industry compared to discrete industry calls for a review of the existing body of literature on the subject. Thus, a systematic literature search has been conducted, which consisted of two phases. The first phase involved block searches in Clarivate's Web of Science and Elsevier's Scopus. The block searches were comprised by the changeability classes listed in Fig. 1 and conjugations thereof in combination with several terms associates with process industry. The search query was delimited by language including only papers in English. When combined, a total of 191 unique papers was found across the two search engines. Upon screening the title and abstract of these, the total was reduced to 29 potentially relevant papers. Upon full-paper screening of these, 13 papers were deemed relevant for inclusion. The second phase of the literature search applied a snowball approach to the selected papers. This resulted in an additional 3 papers being included in the literature review, which were not uncovered by the block search method

In the following, these relevant research papers are reviewed in relation to the five changeability classes with concern to the potentials and challenges of these in process industry.

2.1.1. Transformability

Plant transformability in process industry has been treated from both a planning and control perspective [13], as well as from an equipment perspective [14], both focusing on the application of modularization as a means of achieving transformability.

The issue of production ramp-up is argued as being a main challenge in process industry [5, 14], because not all processes can be scaled to the desired volume due to physics-related constraints or due to safety restrictions. Furthermore, due to the sometimes-complex physical interactions, such as heat transfer or flow patterns, copying small-scale process modules is the fastest way of increasing production volume. [14] However, this comes at the cost of each module being less efficient, thus proving a potentially expensive solution. Lower efficiency of processes is also argued as being a major challenge in process industry as resources are often scarce [5, 15], thus further emphasizing the importance of process efficiency [5].

2.1.2. Reconfigurability

Several examples of research projects focusing on modularizing process equipment as a means of increasing the changeability of production systems can be found in the literature (see, e.g., [16] and [17]). Although, as mentioned in the introduction, examples of actual industrial-scale versions of such production system designs have not been identified in the current body of literature.

While process modules exist in process industry, often termed "Package units," a major limitation of applying these in the context of changeable manufacturing systems is the fact that the control systems require substantial engineering effort in order to integrate these with the remaining production system [13, 18].

While the physical process units may be modular (defined piping interfaces, etc.) and relatively easy to integrate into the production system, the logical aspect of the process units, i.e., their internal control systems, are much more difficult to integrate due to the lack of standardized information interfaces. Recognizing this, the Module-Type Package has been developed as a standardized document containing all relevant parametric information about a process module for the purpose of easy integration with the overall control system of the production plant [13].

Urbas and Doherr [19] argue that since process control interfaces are generally made manually from process and piping diagrams, typically at the end of a planning process, changing the structure of a production system in the process industry is hampered by the slow process of manually updating these interfaces. To counter this, they present a model-driven approach which relies on both engineering data and algorithms to automatically generate process control interfaces.

2.1.3. Flexibility

Recognizing that product changeovers in process industry are often highly sequence-dependent due to, e.g., the need for cleaning the production line, Wilson [20] proposes a production planning method for optimizing the mix flexibility of a production system. Increased mix flexibility mitigates changeover time penalties and thus increases the number of product variants that can be produced within a given period, without changing the production system [20]. Wilson and Ali [21] argue for the application of product wheels in process industry, where a heuristic approach to production scheduling provides increased flexibility in terms of which products can be produced at a given time. In this regard, a sequence is created grouping products with short changeover times, thereby balancing both changeover times and inventory costs for the product portfolio. The application of lean principles for production planning and control as a method for achieving increased flexibility is reiterated by Spenhoff et al. [22], who investigated the application of such tools in process industry.

Advanced algorithms and distributed sensor technology as a means of achieving real-time process analytical technology has been proposed by O'Mahony et al. [23]. Specifically, the aspect of measuring key process parameters in real time and adapting the process control system based on the data feedback is seen as important contributors to increased flexibility in process industries. This could potentially allow for process optimization during individual production batches, thus maintaining product quality and additionally assist in faster production ramp-up of new product variants. However, optimizing processes based on algorithms is deemed difficult as it requires immense knowledge of the processes in question [23].

2.1.4. Changeover ability

Štefanić and Tošanović [24] argue that one of the main inhibitors of achieving increased responsiveness towards customers is due to time-consuming changeovers. Based on a case study in a water bottling plant, they report that significant improvements to changeover time in the process industry can be achieved by using changeover improvement tools such as Kaizen events. They report a changeover time reduction of 67% in their case study.

2.2. Conclusion on literature review

From the reviewed literature it is evident that there is limited published research on changeability in process industry. A significant part of the reviewed papers focuses on how changes to the production planning and control systems of the production systems can assist in achieving a more changeable production setup. From the papers that focused on how changeability could be achieved from an equipment perspective, a majority of focused on the application of modular process units as a means of transformability and reconfigurability of more aggregated production systems, rather than individual processing cells or stations. At the most disaggregate production level being the individual station, only a single paper was identified, which focused on how to achieve shorter changeover times from an operations perspective.

The literature study furthermore revealed a lack of published industrial scale examples on the subject. This is evident as the reviewed body of literature on changeability in process industry contains nearly no reports on the potential business effects of implementing the identified changeability concepts in industrial scale cases. Indeed, a majority of the identified research papers appears primarily conceptual in nature and demonstrates the presented methods and tools through, e.g., computer simulations (see for instance [18, 19, 25]) or laboratory-scale models (see for instance [13]). Despite a general lack of reports on the economic impacts of changeability in industrial cases, a few, primarily conceptual, research papers investigating the economic effects of transformable plant designs have been identified [25, 26]. Both papers utilize a real options approach to investigate the benefits of gradual capacity scalability and evaluates different options based on the net present value of these.

Therefore, summarizing on the above it can be argued that the current body of literature suggests that manufacturing changeability in process industry is still in a relatively premature stage. Thus, it is relevant to further explore this research area through industrial insights on potentials and challenges concerning this changeability.

3. Methodology

Case-based research is particularly suitable for the explorative stages of research, where the phenomenon of interest is not yet well understood [27] and further insight is needed to generate research questions [28]. Furthermore, an important aspect of case-based research is by Ketokivi and Choi [29] referred to as the duality criterion. It emphasizes that case-based research should acknowledge the empirical context in which the study is made, while simultaneously aim to generalize the findings of the case to a broader context.

As illustrated in Section 2, there is very limited research on manufacturing changeability in process industries, which implies that there is a need for further explorative empirical studies in order to increase the understanding of the topic. This paper addresses this by including a case study from industry.

3.1. Case description

The case company is a mid-sized Danish chemical product manufacturer, which operates primarily within the business-to-business segment. The company has six production lines for the production of liquid products, of which four are fully automated. Although the production lines differ in terms of the exact equipment used, a generic production process consisting of (i) blending the chemicals, (ii) filling and capping the bottles, and (iii) labelling and packaging the bottles. The company is currently experiencing increased pressure and demand for product variety and customization, which requires higher manufacturing changeability to meet these demands in an economically feasible way. Thus, the company is currently initiating a transition towards increased changeability in the production setup, which makes the company an interesting case for studying potential benefits and challenges towards changeable manufacturing in the process industry. For the purpose of this case study, information was collected primarily through interviews and direct observation, however, archival records and internal company presentations were used as well.

4. Case study findings

In the following, the case study findings are presented. These are related to both the general findings from literature, as well as interesting observations made in relation to the potentials and challenges concerning manufacturing changeability in the case company.

4.1. Lacking platform-based product development

Although not addressed in the research papers reviewed, an important prerequisite of changeability is a platform-based approach to product development [12]. In this regard, the underlying argument is that without a well-defined product platform, it is difficult to design a production system that is sufficiently changeable, and furthermore is aligned with the relevant product parameters. The effect of such a lacking approach is evident several places in the case company. One aspect of this is that without knowledge of product parameters and how they cause major changeovers on the production lines, sales managers risk selling a product with a new packaging format that differs from existing format parts. As a consequence, time-consuming production changeover are required whenever switching between this new variant and any existing variants. Furthermore, the introduction of a new packaging format would require investing in matching format parts for the filling line, adding to both the cost and delivery time of the order.

4.2. Rigid material transport infrastructure as an inhibitor of changeability

This potential issue is evident in the case company, where material is transported from the batch mixing area to the production lines through rigid piping systems. Particularly, since not all the company's holding tanks containing semi-manufacture blends are connected to all six of the company's production lines, the production planning flexibility is limited by these routing constraints. This is primarily an issue since some products require an intermediate storage before bottling, due to either the agitation of the product causing air bubbles to form or because of the exothermic reaction of some products. These issues relate specifically to the changed density of the products.

4.3. Challenges related to heuristic production planning

Production planning is currently carried out by employing locally developed heuristics concerning the appropriate schedule of products to be produced. In the case, the scheduling heuristic employed utilizes a combination of a changeover matrix including qualitatively estimated changeover times between all current products in the product portfolio, and the knowledge of the production planner, who has more than 20 years of experience in the company. Using heuristics for scheduling the production is the foundation of the product wheel production planning method [21]. Nevertheless, without a formal, structured approach to scheduling production orders, the company risks formulating production plans that fail to capitalize sufficiently on product commonalities as a means of reducing total time spent on production changeovers. Furthermore, as the company has experienced an increase in product variants, the complexity of the production planning process has increased, further emphasizing the need from the production planner's perspective for a method of coping with this increased complexity.

4.4. Potential for applying SMED on filling line equipment

While the application of lean tools in process industry has been advocated in research [21, 22, 24], Section 2 produced only limited research on the topic related to improving production changeover processes. Despite this, there appears to be a potential in applying lean tools such as single-minute exchange of dies (SMED) on the bottling and capping machines on the filling line, although no such applications have been identified in literature. The potential of applying SMED in the case company relates to the fact that the changeover of these machines takes, on average, 3,5 hours when changing from one format to another. This contrasts with only around 20 minutes, on average, when changing between bottle or cap variants using the same format parts. Thus, applying SMED principles would potentially result in significant reductions of the resources required relating to both changing the actual format parts as well as adjusting the machine settings for the format changed to.

5. Conclusions and discussion

The research presented in this paper explores the application of changeable manufacturing in the process industry, by investigating potential benefits and challenges in the implementation of changeable manufacturing systems in the process industry through a literature review and a case study. In the following, conclusions and discussion points from the literature review and the case study, respectively, will be presented.

5.1. The effect of discretization points in production systems in process industry

Besides Abdulmalek et al. [4], only Spenhoff et al. [22] comment briefly on the existence of discretization points in process industry production systems. However, the potential implications of these on the design of production systems in process industry, with respect to increasing changeability, appears largely overlooked in the reviewed literature. It is suspected that the existence of a discretization point, i.e., an indicator of a hybrid discrete/process production system complicates the design of such production systems, as system designers will have to apply multiple design methods as a means of accommodating the inherent differences between process and discrete manufacturing. This aspect is therefore suggested as a possible future research direction.

5.2. Broader potential for SMED in process industry

Since most products manufactured in process industry becomes discrete at some point during the production, it is expected that there is a broader potential for the application of SMED in process industry since there are potentially several similarities to discrete industry applications of this method. Furthermore, the application of SMED in process industry prior to the discretization point may also aid in obtaining changeability of the production system. Although, as highlighted by Wilson and Ali [21], the characteristics of most equipment in the process industry correspond poorly with rapid changeovers and small batch production. Since no research on the topic was identified, further research into the similarities and differences between discrete and process industry should be conducted in order to uncover the specific potentials and challenges related to implementing SMED in this context.

5.3. Rigid material transport systems as an inhibitor of changeability

Besides brief references to the establishment of utilities backbone in modular production plant designs [5, 13], potential challenges related to changeability and material transport systems in the process industry seem to have received less attention in the reviewed literature.

As noted in both Section 2.1 and 4.2, transformability and reconfigurability of production systems may be hampered by rigid material transport systems in process industry when compared with discrete manufacturing industry. For example, transport of discrete products may be done using automated guided vehicles, which can be re-routed through changes to their programming thus supporting rapid reconfigurations of production systems. Yet, due to the nature of the products in process industry, these are often transported through rigid piping systems. In the event of a production system reconfiguration, the implication of such a rigid material transport infrastructure is that the reconfiguration would require a physical change to the material transport system through, e.g., removal of existing piping sections and the installation of new piping routes. Having to perform such extensive changes to the material transport system would potentially add significant time to the reconfiguration of the production system. Besides the physical changes to the material transport system, there may be additional resources required in adapting the process control system to this new production layout, as well as bringing existing piping diagrams up to date for future reference. Thus, the design of utilities backbones systems and their potential effect on the changeability of production systems in process industry are relevant areas for further research.

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