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A Systematic Approach to Development of Changeable and Reconfigurable Manufacturing Systems

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Abstract. The implementation of changeable and reconfigurable manufacturing systems and realization of benefits connected to rapid, efficient, and dynamic change of functionality and capacity is key to achieve manufacturing competitiveness. Therefore, this paper proposes a systematic methodology for the design and development of changeable and reconfigurable manufacturing systems, derived from design theory, reconfigurability theory, as well as practical experience. The methodology consists of a concrete course of actions that connects design phases and working steps based on the content of the design task. Furthermore, the paper addresses project-related and contextual aspects of reconfigurability development, which indicates how the proposed methodology should be adapted to the specific company and task at hand. Thus, the proposed methodology is intended for further validation in different types of manufacturing companies that are transitioning towards reconfigurability.

Keywords: Reconfigurable manufacturing, Reconfigurability, Changeable manufacturing, Engineering design, Manufacturing system

1 Introduction

Changeability and reconfigurability are widely recognized as principles that can be implemented and utilized in manufacturing systems for responding efficiently to product variety, rapid new product introductions, and demand fluctuations [1, 2]. Related benefits include reduced capital expenditures, shorter lead-time, higher capacity utilization, and prolonged life-time of systems, machines, and equipment [3]. Compared to traditional manufacturing systems with static, pre-planned, and built-in functionality and capacity, changeable and reconfigurable systems have dynamic abilities to change [4]. However, as these systems are not solely designed for their immediate and initial purpose, but rather in combination with properties having more long-term exposure, they represent complex engineering development tasks [5, 6].

In this regard, traditional approaches to manufacturing system design and development are largely insufficient for supporting a transition towards reconfigurability [7]. First of all, as changeability and reconfigurability can be categorized as non-functional

system requirements that express the behavior of the system in the long-term, system design and evaluation need to be aligned with product evolutions that represent significant uncertainty [8, 9]. Secondly, translating uncertain and dynamic requirements into system designs that embed the reconfigurability enablers is a task that requires evaluation of multiple realization options, e.g. in terms of combination of flexibility and reconfigurability, level of implementation, and system constituents to implement these enablers [9, 10]. Furthermore, in practice, design of manufacturing systems is usually conducted largely iteratively, trial-and-error based, and with limited explicit consideration of reconfigurability characteristics [11]. Therefore, there is both an academic and industrial need for a systematic approach to engineering design and development of changeable and reconfigurable manufacturing systems. In this regard, a systematic engineering design methodology prescribes a concrete course of actions for the design of a technical system, usually in form of design phases, design activities, and their related sequence [12]. Thus, while design in general is a largely creative task, a design methodology can support this task by prescribing a general working procedure, while still being adaptable to the specific task at hand [12]. Moreover, while design and evaluation constitute the important parts of the system development process, the project-related and contextual aspects supporting the implementation of this process should also be addressed [11].

Based on these requirements, this paper proposes a systematic methodology for the design and development of changeable and reconfigurable manufacturing systems. The remainder of the paper is structured as follows: Section 2 outlines related research as background for the proposed methodology. Section 3 describes the phases, activities and supportive tools of the proposed design methodology, while Section 4 summarizes the contribution and outlines future developments of the methodology.

2 Related Research

Changeable manufacturing systems have been defined as systems that are able to accomplish early and foresighted adjustments on all process levels in an economically feasible way [15]. Thus, changeability can be regarded as an umbrella term for manufacturing that depending on the context is realized by the most economically feasible combination of a-priori flexibility and dynamic reconfigurability [15]. The concept of the Reconfigurable Manufacturing System (RMS) was originally introduced by Koren [13] as a manufacturing system paradigm combining the high efficiency of the Dedicated Manufacturing System (DMS) and the high flexibility of the Flexible Manufacturing System (FMS). The key feature of the RMS is the ability to be continuously changed in order to provide the exact functionality and capacity needed at the exact time needed [3]. In this regard, a successful reconfiguration is enabled by the three necessary RMS characteristics i.e. convertibility, scalability and customization, as well as the three supportive characteristics i.e. modularity, integrability, and diagnosability [3]. Thus, compared to the flexibility, which is pre-planned and built-in, reconfigurability is a dynamic capability to expand and change the flexibility boundaries of the

system [14]. Depending on the company and manufacturing setting, the level and combination of flexibility and reconfigurability need to be matched with the specific changeability requirements. An overview of the fundamental aspects involved in this has been proposed in various forms [2, 4, 15], covering the following:

- Change drivers are external and internal factors that request or necessitate some response by the company and are represented by demand volatility and variety [4].
- Change focus/object is the impact of change drivers, which externally towards the market and customers covers mix, product, and volume, and internally is focused on the production processes, equipment, and organization [4, 15].
- Change strategy is the degree and importance of changeability to pursue [4, 15].
- Change extent/extension is the level, time, and effort involved in the selected change strategy, which have to be comparable with the expected benefits [15].
- Change enablers are the system properties that ensure changeability, e.g. reconfigurability characteristics such as modularity, integrability, etc. [15].
- Change utilization is the planning, training, and implementation of the changeability of the system [15].

When relating these fundamental aspects of changeability to the design of changeable manufacturing systems, key questions concern for instance the need and requirements for change, the optimal and feasible combination of flexibility and reconfigurability to select, as well as concrete and technical design of related enablers [4]. Thus, the aforementioned changeability aspects are both interrelated and related to different stages during manufacturing system design. In Fig. 1., a sequence of the changeability aspects is proposed, which outlines a relevant order of how these are involved during manufacturing system design [10, 15].

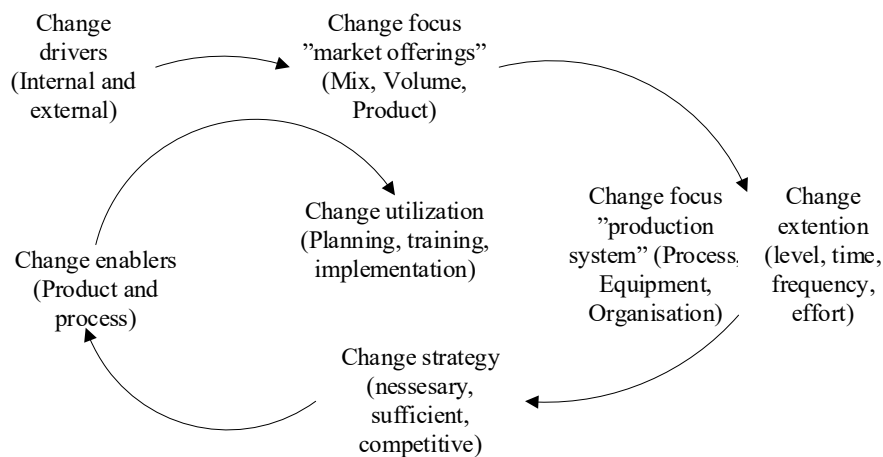


Fig. 1. Fundamentals of changeability and their sequence during system design.

Several methodologies and frameworks for the design of changeable and reconfigurable manufacturing systems have been proposed in previous research [16]. To mention a few, Schuh [17] focused on object-oriented design for changeable systems, while Benkamoun [6] proposed systemic design for changeability in manufacturing system architectures. Azab et al. [14] proposed a framework for the mechanics of change in a manufacturing system that is dynamically changeable and reconfigurable. Likewise, Francalanza et al. [18] proposed a methodology for designing changeable manufacturing systems based on a traditional design cycle approach. Tracht and Hogreve [19] proposed a framework for the design of reconfigurable systems, as well as the reconfigurations phase, while Deif and ElMaraghy [20] proposed a method for design of reconfigurable hardware, software, and human aspects of the manufacturing system. Abdi and Labib [21] focused particularly on designing for reconfigurability using AHP for justification analysis. Finally, Andersen et al. [10] focused on synthesizing all previous methods for design of reconfigurability into a number of design phases and activities. However, while the issue of designing changeable and reconfigurable manufacturing systems appears to attract increasing research attention [16, 22], there appears to be limited consideration of industry-applicability as a main principle in the existing methodologies [23]. In general, designing changeable and reconfigurable manufacturing systems involves decisions in various categories similar to any manufacturing system design activity irrespective of the level of changeability, i.e. decisions on process type, layout, capacity, machines, automation, organization and human resources, etc. [11]. However, in addition, design of changeability requires knowledge of the key enabling principles and competences in how to design and realize these [16]. In order to support this task, a structured system design methodology for changeable manufacturing should enable the following aspects, which is largely overlooked in previous research:

- Application in manufacturing companies to allow for a transition towards changeable and reconfigurable manufacturing, i.e. by allowing for a problem-directed approach and by being adaptable to different types of design processes in different types of companies [12].
- Application in already existing company approaches to manufacturing system design, e.g. by being applicable to traditional and widely used phases in engineering design, while also providing the necessary tools to apply in the phases [12, 16, 23].
- Guidance in the design and evaluation steps specifically involved in establishing requirements and solutions for changeable and reconfigurable manufacturing systems that are dynamically changeable [7, 16].
- Continuous evolution and utilization of changeability in the long-term, i.e. capture the continuous loop of designing, evaluating, and utilization changeability and reconfigurability in manufacturing [14].

3 Proposed Four-Step Development Approach

Based on the requirements elaborated in the previous section, this section describes the proposed systematic methodology for the design and development of reconfigurable

manufacturing systems. In the methodology, design phases where the level of abstraction is gradually decreased is combined with knowledge of the fundamental aspects of changeability and their design sequence as outlined in Fig. 1. Furthermore, the methodology was tested and modified in an iterative way during five research projects on different aspects of reconfigurability development in five different case companies. Specifically, a first version of each phase was created based on theory, which was elaborated and changed during the interactions with the case companies. For instance, one research project in a specific case company focused largely on tools in phase 1 to clarify the company's potentials, while another research project in a second case company focused largely on developing and evaluating reconfigurable concepts. Thus, the different projects and case companies assisted in further developing and modifying each phase in order to meet the requirements stated in the previous section.

3.1 Development Process and Activities

The proposed systematic methodology consists of four phases, which are depicted in Fig. 2. The process starts with an initial clarification of the design tasks and changeability requirements, continues with conceptual design, detailed design, and finally implementation and utilization of changeability. Thus, these phases largely follow the traditional phases of engineering design in order to support easy application in manufacturing companies. However, one main difference is the addition of the last phase, where implementation and utilization of changeability takes place. This phase either results in a system in operation or a repetition of some design phases before once again resulting in a system in operation. Thus, the proposed methodology enables companies in supporting dynamic reconfigurations to various extents throughout the system's lifetime.

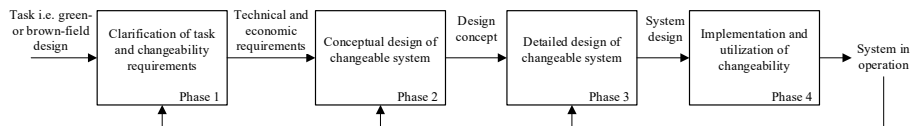


Fig. 2. Four-phased design steps related to changeability and reconfigurability.

Each of the four phases contain both design and evaluation activities that support the realization of changeability and reconfigurability. Fig. 3, Fig. 4, Fig. 5 and Fig. 6 depict the specific activities of each phase, while at the same time outlining the covered fundamental aspects of changeability as described in Fig. 1. Thus, phase 1 covers the clarification of the design task and changeability requirements through analysis of change drivers, external and internal change focuses, change extension, and finally the change strategy. Phase 2 and 3 focus on the necessary and supportive change enablers, while phase 4 covers the implementation and utilization of changeability. One of the main decisions in the design phase is to determine the optimal combination of flexibility and reconfigurability to reach the change requirements. This decision is primarily dealt with in phase 2, which evaluates different concepts build on the explicit change requirements from phase 1.

Furthermore, for each phase and activity, different design and evaluation tools should be applied. Generally, previous research suggests numerous different methods and tools that could potentially be applied during reconfigurability design [16, 23]. However, only tools ready for application after testing and further development in the case companies are included here. For brevity, tools and the availability of these are not elaborated further in this paper, however, some evident gaps exist that are elaborated further in Section 4.

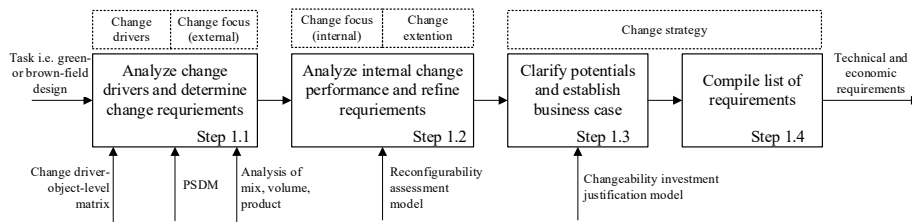


Fig. 3. Phase 1 containing clarification of task and changeability requirements.

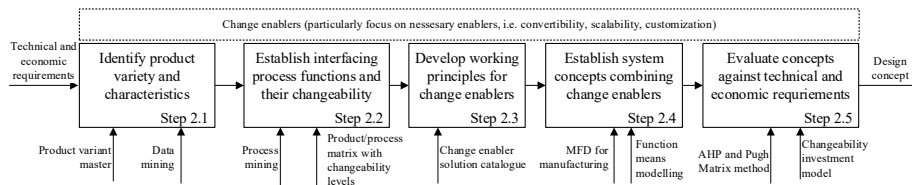


Fig. 4. Phase 2 containing conceptual design of changeable system.

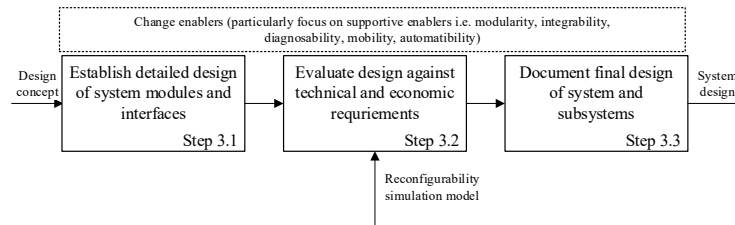


Fig. 5. Phase 3 containing detailed design of changeable system.

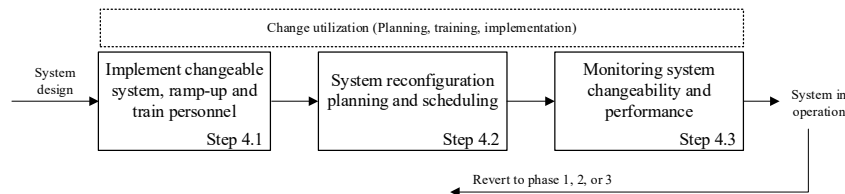


Fig. 6. Phase 4 containing implementation and utilization of changeability.

3.2 Project-Related and Contextual Aspects of Development

The proposed methodology incorporates the fundamental aspects of changeability and connects related design activities in a sequence going from initial clarification of change drivers to a changeable and reconfigurable system in operation. Thus, the methodology is intended as an addition to manufacturing development methods in companies that most often follow the same overall design phases, rather than as a stand-alone method that substitutes conventional design methodologies for manufacturing. Likewise, the methodology should be adapted to the specific company context and design task at hand. Specifically, the methodology can be adapted in the following ways related to how development projects are conducted and how the development process is implemented in a company:

- Design task: Both a green-field and a brown-field design task can be accommodated by the methodology, i.e. designing a new manufacturing system for a new product or redesigning an existing manufacturing system for improving changeability performance. The alteration of the methodology here lies primarily in regards to whether existing equipment is considered in phase 2 or whether such constraints are not considered in the phases.
- Starting point: Depending on the pre-existing knowledge within the company, emphasis can be on different development phases. Clearly, some companies need extensive focus on phase 1 e.g. in terms of clarifying needs and identifying the business case, while other companies can progress quicker to conceptual and detailed design.
- Development focus: Development can take outset in a specific product and manufacturing system or alternatively be a pre-project that establishes solutions for changeability enablers that can be used in later specific development projects.
- Tools applied: Depending on data availability and preferences within companies, some phases have different alternatives of which tools to apply. For instance, more advanced data mining techniques are possible to use in some phases, however, may not be feasible in all types of companies.

4 Conclusions and Future Research

In this paper, a systematic methodology for the development of changeable and reconfigurable manufacturing systems is proposed. Industrial application was a main objective in the creation of the methodology in order to support a wider industrial transition towards changeability and reconfigurability. The methodology consists of four phases roughly following traditional phases in engineering design; clarification of task and requirements, conceptual design, detailed design, as well as implementation and utilization of changeability. To summarize, the proposed methodology contributes with the following benefits:

- Allows for a problem-directed and company-specific approach, i.e. the starting point of the methodology can be both green-field and brown-field development, emphasis

can be on different phases depending on company need, and the tools applied can also be adapted in various phases depending on data availability, etc.

- Enables direct application in a manufacturing company as a sequence of development activities and tools specifically targeting changeability and reconfigurability that can be “added” to the already existing engineering development methods.
- Provides a systematic guidance for the engineering designer, which ensures the appropriate match between changeability requirements and enablers.
- Ensures that manufacturing system development takes long-term and dynamic requirements into account, as well as captures the continuous loop of designing, evaluating, and utilizing changeability and reconfigurability.

Nevertheless, several further research directions are prevailing. First of all, the proposed methodology needs further testing and validation in manufacturing companies. This would also produce further insights on how to support companies in successful implementation of reconfigurability principles, as well as provide further insights on the contextual aspects of development. Secondly, well-proven and readily applicable supportive tools are still missing for some development activities. In particular future research should focus on maturing methods for establishing reconfigurable concepts, as well as focusing on supportive tools for phase 3 and 4.

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