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Engineering Education in Changeable and Reconfigurable Manufacturing: Using Problem-Based Learning in a Learning Factory Environment

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Abstract

In today's manufacturing environment, the development and implementation of changeable and reconfigurable manufacturing systems is essential in order to manage and capitalize on increasing market volatility, product variety, customization, and smaller batch sizes. Teaching future engineers the skills and competences needed for this requires application of new and innovative learning approaches. Therefore, this paper presents an example of how blended and problem-based learning in a learning factory can be applied for an engineering course in changeable and reconfigurable manufacturing, in order to educate engineers that comply with requirements in the modern manufacturing environment.

Keywords: changeable manufacturing; reconfigurable manufacturing; engineering education; problem-based learning; learning factory

1. Introduction

Continuous change and increasing complexity are main challenges facing today's manufacturing companies [1, 2]. Accordingly, competitive advantage is now rarely achieved by solely exploiting economies of scale, standard production methods, or lean principles. Rather manufacturing companies need to realize robust and cost-efficient production, while at the same time capitalizing on decreasing batch sizes, growing demand for customization, as well as frequent changes in the market [3, 4]. Particularly, these demands are present in high-wage countries with pressure from low-cost competitors and increasing outsourcing. Consequently, aligning business models that exploit mass customization, product development that exploit modularity and platforms, and changeable manufacturing systems exploiting reconfigurability, flexibility, and emerging smart technologies such internet-of-things, sensor networks, big-data, and cloud computing has become a key to competitive success [4]. Thus, the paradigm of changeable manufacturing, defined as the ability to accomplish early and foresighted adjustments on all factory levels in an economically feasible way, e.g. through reconfigurable manufacturing systems, flexible machines, or workstations with high changeover ability [5, 6], appears as an increasingly important topic to include in engineering curricula, in order to educate engineers that comply with requirements in the present manufacturing environment. Nevertheless, including changeable manufacturing in education of industrial and manufacturing engineers implies certain requirements for the way courses are designed. In particular, this implies:

- Change of courses from being single-topic focused on engineering science or technical topics towards integrated courses that address several disciplines and topics [7, 8], in order to adequately comprehend the complexity involved in designing and operating changeable manufacturing systems, such as product development, production planning, etc. [2, 9, 10].
- Change of courses from being largely content-oriented where students learn from readings-lists to being oriented

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towards real-world problems [1, 7, 8, 11], in order to enable students to become future engineers that can address constantly changing manufacturing conditions.
- Focus on strengthening students' skills in analysis, synthesis, and evaluation of complex problems and on providing design experience for students [1, 7, 8, 11].
- Involvement of new technologies and digitalization to promote learning and prepare students to meet demands in a changeable manufacturing environment with smart technologies and increasing digitalization [11, 12].
- Increased focus and strengthening of team-based learning that fosters better communication and teamwork skills towards solving cross-disciplinary problems [2, 7, 13].
- Focus on more frontier engineering and state-of-the-art theories and knowledge [13] to adequately equip future engineering for more advanced manufacturing systems that are rapidly changeable and factories of the future [12-15].

Collectively, all of these requirements placed on engineering education when covering the topic of changeable manufacturing focus on creating engineers that are self-directed, life-long learners, and have a holistic and systems-view on design, operation, and improvement of manufacturing systems that are rapidly changeable in accordance with markets, products, and technologies. The objective of this paper is to address the issue of how to design and run an engineering course that fulfills all of these demands, by presenting a course on changeable and reconfigurable manufacturing based on problem-based learning using a learning factory and a highly blended learning environment.

The remainder of the paper is structured as follows: Section 2 briefly presents the area of changeable and reconfigurable manufacturing as background for the paper. Section 3 presents important principles of problem-based learning, blended learning, and the use of learning factories for the purpose of designing a course on changeable and reconfigurable manufacturing. Section 4 outlines the course design, while Section 5 describes the course evaluation and main learnings and Section 6 briefly summarizes the paper.

2. Changeable and Reconfigurable Manufacturing

Changeable manufacturing is defined as the ability of a manufacturing system to accomplish early and foresighted adjustments of structures and processes on all levels in an economically feasible way [5]. Thus, changeability is an umbrella term that covers various structuring levels, as well as various ways to realize changeability in terms of scope and degree of change [6, 16]. Reconfigurability, introduced by Koren in the late 1990s as a way of achieving functionality and capacity on demand through enablers of convertibility, scalability, modularity, integrability, customization, and diagnosability [17, 18], is a closely related term which together with flexibility represent changeability classes on shop floor level [16]. However, while flexibility refers to the ability to change with limited effort within a pre-defined range of functionality and capacity e.g. in terms of products, processes, or quantities, reconfigurability refers to a dynamic ability to change the functionality and capacity boundaries of the system to new requirements [5, 19, 20]. This distinction makes reconfigurability a particularly relevant approach to achieving changeability, as it offers potential to reduce the traditional trade-off between productivity and flexibility, and enables reuse of manufacturing resources across a product family and for several product generations [21]. In order to achieve reconfigurability, the six core characteristics denoted in Table 1 must be considered during design [21].

Table. 1. Design principles for reconfigurable manufacturing [21].

Reconfigurability characteristic	Design principle
Scalability	The system is designed for cost-efficient adaption of capacity to future market demand by adding/removing/changing resources.
Convertibility	The system is designed for transforming its functionality to new production requirements.
Diagnosability	The system is designed for real-time monitoring and rapid diagnostics.
Customization	The system and machines are designed around a part/product family thereby obtaining customized flexibility.
Modularity	The system is designed with compartmentalization of operation functions into units.
Integrability	The system modules can be easily integrated through standard hardware and software interfaces.

These design principles require a cross-disciplinary approach to system design, implementation, and improvement. For instance, in order to design a system customized for a product family which and allows for easy system conversion, product development needs to be closely integrated with manufacturing development [21]. Likewise, designing modular systems requires knowledge of architectures and platforms, which is commonly known from product development [10], whereas ensuring productivity during operations following a reconfiguration requires rapid system balancing, configuration design, as well as performance measurements [21]. Accordingly, Koren [4] defines manufacturing competitiveness as three interrelated components: i) reconfigurable manufacturing systems, ii) customizable products, and iii) responsive business models.

Changeability and reconfigurability have attracted significant attention in research for the past decades and appear to be increasingly relevant in industry as well [22]. However, their wide implementation remains limited, e.g. in terms of reconfigurable machines, platform-based production, or scalable capacity [8-11], and knowledge on reconfigurability and its principles appears to remain relatively low in industry [23]. These conditions result in growing demand for industrial and manufacturing engineers with knowledge and skills in reconfigurable manufacturing and its principles. In this regard, Pasek, Koren and Segall [24] present a graduate course design on agile and reconfigurable manufacturing, which takes outset in the aforementioned integration of product development, business practice, and manufacturing system. Salah and Darmoul [14] present an industrial engineering course on computer integrated manufacturing, which focuses on reconfigurable manufacturing principles through product design, process design, system operation, and performance assessment. Following these contributions, this paper presents a recently developed course on changeable and reconfigurable manufacturing designed specifically with the cross-disciplinary focus as explained above and with the goal of creating engineers that are self-directed, life-long learners, and have a holistic and systems-view on design, operation, and improvement of manufacturing systems. In the following, the background for the design of this course is described.

3. Course Design with Technological Pedagogical Content Knowledge

It is widely acknowledged that successful teaching and effective course design is not only based on a teacher's strong content knowledge, but also on knowledge of how students best learn the content through suitable pedagogical approaches and learning strategies, denoted as pedagogical content knowledge (PCK) [25]. Additionally, technology plays an increasingly relevant role in teaching and course design, meaning that effective teaching requires not only pedagogical content knowledge, but also knowledge of how technology can change the taught content, denoted as technological content knowledge (TCK) and knowledge of how technology can be appropriate in the teaching setting and aid learning, denoted as technological pedagogical knowledge (TPK) [26]. Following this notion, this paper approaches course design as an interplay of integrated knowledge as depicted in Fig. 1. In the following, each of the three areas in Fig. 1 will be addressed, as a foundation for presenting the resulting course design in Section 4.

3.1. Problem-based Learning

Problem-based learning (PBL) is an educational approach widely used in engineering education, founded in Canada in the 1960s [36, 37]. The main principles of PBL are [27]:

- The problem is the starting point for the learning process, which is usually a real-world problem from a specific context or organization.
- Learning is self-directed and students have resposibility for formulating problem statements and for taking decisions on how to address the problem.
- Learning is activity-based and builds on experience of students and understandings previously formed.
- Learning is inter-disciplinary and the focus is not on subject-oriented syllabuses but rather on real situations.
- Learning is based on exemplary problems, which supports students in transferring knowledge, theory, and methods to new areas and contexts.
- The learning process is group-based and students learn how to co-operate in all stages of learning.

Evidently, the principles of PBL are vastly consistent with the requirements for engineering education in modern manufacturing environments, as well as for learning the changeable and reconfigurable manufacturing paradigm as outlined in Section 1. As an example of PBL, Aalborg

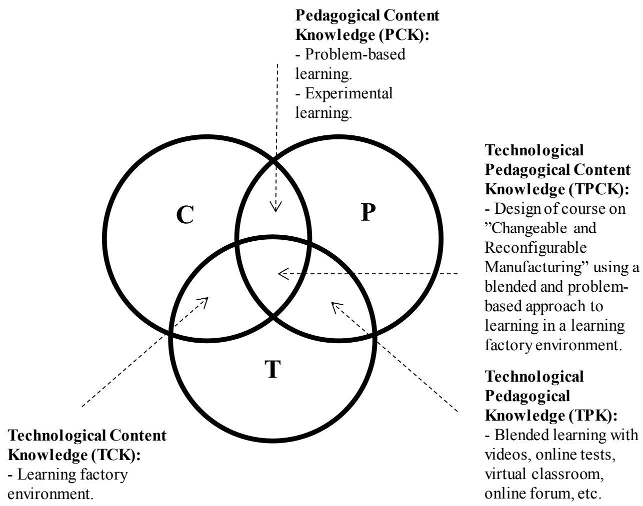

Fig. 1. The interplay between technology knowledge (T), pedagogical knowledge (P) and content knowledge (C) as a basis for course design.

University has since its establishment employed a problem-based and project-centered approach. In all engineering Bachelor's and Master's programs, 50% of the curriculum consists of problem-based project work in groups of 5-7 students taking outset in problems from real industrial or research settings The remaining 50% consists of course work e.g. lectures, seminars, laboratory work, etc. that to some extent is also problem-based. Other universities such as McMaster University in Canada, Monash University in Australia, as well as Delft University in the Netherlands are renowned for their successful PBL approaches to university teaching [8, 27].

3.2. Learning Factories

Learning factories in various forms present attractive environments for engineering education. In a general sense, a learning factory supports a learning environment with authentic processes, a changeable setting resembling a real value chain, a physical product being manufactured, as well as learning enabled by actions on-site [28]. Thus, a learning factory environment provides the foundation for various PBL principles: working with "real-world" problems, exemplarity in problem-orientation, action or activity-based learning, and inter-disciplinarily in learning [28]. Accordingly, learning factories receive increasing attention in engineering education. Various overviews and classifications of the increasing number of existing learning factories have been proposed, e.g. by Wagner et al. [29] and by Abele et al. [28]. Generally, the purpose of learning factories can take various forms e.g. process improvement, logistics optimization, management and organization, automation technology, changeability and reconfigurability, etc. [28]. Concerning the latter, which is the focus of this paper, one of the first reconfigurable learning factories was the iFactory in the Intelligent Manufacturing Systems (IMS) center at University of Windsor in Canada, being a changeable and modular assembly system. The iFactory has provided the foundation for research on e.g. co-evolution of products and manufacturing [30, 31]. A recent addition to changeable learning factories was established at Aalborg University, which demonstrates smart technologies and Industry 4.0 principles, including changeability and reconfigurability [32].

3.3. Use of Digital Tools and Blended Learning

One of the primary challenges of engineering education as outlined in Section 1, is to keep up with digitalization and advances in technology that are also transforming manufacturing. New possibilities for supporting teaching and learning have emerged with advancements of information and communication technologies [26], resulting in e-learning concepts such as flipped classroom, online courses (MOOCs), and blended approaches. Whereas flipped teaching completely changes the traditional lecture-based educational approach, blended learning offers a variety of face-to-face and virtual teaching elements that can be mixed to suit the exact context, e.g. sessions with teacher, video lectures, video conferences, chat sessions, students collaborations, active learning, online quizzes, etc. [33]. Among the primary objectives of the implementation of such approaches is to increase student learning and engagement both in the classroom and beyond the classroom [33]. For instance, a blended learning environment, where face-to-face sessions with the teacher is mixed with online virtual classroom activities, has potential to create and sustain a sense of community and increase learning beyond the temporal limits of the meeting with the teacher [34]. Other benefits from using blended learning include possibilities to engage in more active learning or experimental learning during meetings with the teacher, as instructions and fundamental theory can be moved online for student self-study [33, 34]. This aspect of using blended learning in course design appears particularly relevant in combination with problem-based learning in a learning factory environment, which requires a high level of active learning and student activity.

4. Engineering Course on Changeable and Reconfigurable Manufacturing

Based on the foundation described in the previous section, an engineering course on changeable and reconfigurable manufacturing was designed at Aalborg University. The course is placed on the 1st year of industrial/manufacturing engineering education on Master's level and covers 5 ECTS equivalent to approximately 140 hours of student workload. Approximately 60 students follow the course each year.

4.1. Course Outline

The course is organized in 13 modules covering the three interrelated topics of changeable and reconfigurable manufacturing described in Section 2: the business model, product development, and manufacturing system design and operation. The objective of the course is that students learn both the content in each domain, but also the important synergies between the domains. In Table 2, the course modules are outlined. As the course takes a blended approach to learning, each module contains a combination of individual preparation before class using online resources such as video lectures, group preparation before class, a face-to-face session, and problem-based project work in groups. A virtual classroom was set up in Moodle, which is an online learning and course management system. The course workload was divided as 52 hours of face-to-face sessions with teachers (13 modules of 4 hours), used for some lecturing but mostly active learning through project work, 52 hours of student self-study and project work in groups, 12 hours of hands-on activities in the learning factory, and 24 hours for exam preparations. The examination of the course was done as a combination of a 3 hour written online exam and an oral group-based evaluation of the project.

Table 2. Syllabus of course on changeable and reconfigurable manufacturing.

Course content area	Course modules
Business model	Mass customization, industry 4.0, and smart manufacturing. Mass customization capabilities: robust process design, solution space development and choice navigation. Mass customization and performance measurement.
Product development	Product architectures and modularity. Product variety management and complexity management. Product configuration, methods, and tools.
Manufacturing system (design and operation)	Manufacturing system paradigms: DMS, FMS, and RMS. Changeable and reconfigurable manufacturing fundamentals and principles. Development of changeability, reconfigurability and manufacturing system platforms. Plant design and material handling systems. Assembly line balancing. Robotic assembly lines and automated production lines. Machine and AGV scheduling.

4.2. Problem-based Project and the Learning Factory

In the course, all modules are linked to a project running through the entire course. This project takes point of departure in the learning factory at Aalborg University. This learning factory (Fig. 2) is an interdisciplinary platform for teaching and research as described by Madsen and Møller [32], which is available for students in the department laboratory.

Fig. 2. Aalborg University learning factory (AAU Smart Lab).

The system is based on the FESTO Cyber-Physical didactic learning factory expanded with additional technologies. The system produces a customized dummy cell phone (Fig. 3) with housing, top cover in different colors, and the options of adding circuit board and fuses, making up 816 possible variants. The system has conveyer modules that can be combined through standard interfaces and different process modules that can be attached e.g. feeders, drilling, assembly, quality check, and rework. The system can currently be combined in 9 million different configurations.

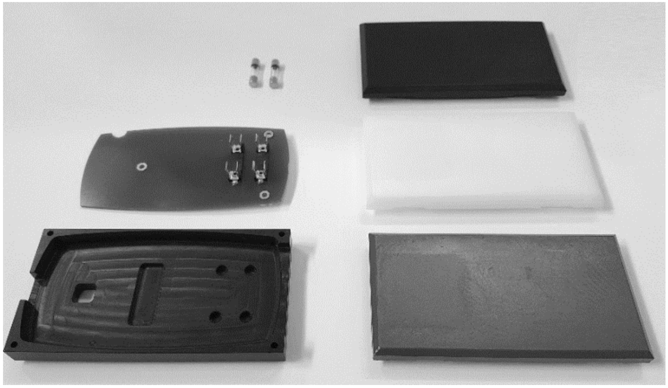

Fig. 3. Product produced in learning factory.

The learning factory at Aalborg University exemplifies a modular and reconfigurable manufacturing system that can be changed in accordance with a customized product. In the course, this was used as the basis for a problem-based project conducted in groups of 5-7 students. The project addressed the factory's extent of changeability and reconfigurability to successfully support mass customization as a business strategy through producing products customized in a product configuration system. Students were required to complete some mandatory training in the laboratory before the project, where after students were mostly self-directed in decisions on project approach, methods, as well as in the learning factory experiments. The project was evaluated based on a written report and an oral group-based examination. In Table 3, the project scope and content is outlined.

Table 3. Project scope and content.

Project scope	Project content
4x1 hour lab sessions, mandatory training, self-study and group-based work.	The factory's extent of changeability and reconfigurability to successfully support mass customization through producing products customized in a product configuration system: 1) Build a product configuration system based on product family modelling. Analysis of configuration limitations and possibilities. 2) Analysis of system changeability level, extent, scope, and enablers (e.g. flexibility and reconfigurability) and ability to efficiently change in accordance with product family expansions and demand increases. 3) Establishment of process schedules and different system configurations to support product configurations. 4) Factory diagnostics and evaluation of mass customization metrics.

In the project work, students were able to transfer the knowledge covered in the different course modules to an authentic industrial setting. Moreover, students were self-directed in deciding approach, methods, and tools used for addressing the problems stated in Table 3. For instance, in addressing the system's ability to support mass customization, students had to not only select and apply various mass customization related metrics (module commonality, solution space profitability, capacity utilization, used variety, configuration time, etc.), but also to run the system and extract data from the MES database e.g. number of produced variants, processing time, produced quantities, idle time, etc. In enabling customization of the products being produced, students engaged in making product family models based on existing product variety using e.g. product variant master and UML class diagrams, and in setting up configuration systems based on the configuration software "Configit Model". Moreover, students would be able to initiate the configured orders in the learning factory, as the configuration system would create bill-of-material received by the factory's MES, which also made the students realize configuration constraints based on the product architecture and the MES support, as well as interface specifications. In relation to this, students analyzed and addressed the learning factory's changeability using different changeability classes in terms of system levels and different scope and extent of changeability. For instance, students analyzed changeability enablers on both system-level and on the different workstation, and identified constraints on its responsiveness towards introduction of fuses in new colors and enlarged product dimensions. As a result, students were able to gain a deeper insight into the topic, rather than solely covering manufacturing system paradigm (DMS, FMS, and RMS) on an "arch-type" level. Moreover, students were able to see real-life system-level enablers of modularity and integrability, however, completing a physical reconfiguration was not a requirement for student due to practical concerns and time constraints.

5. Course Evaluation and Main Learnings

The course described in this paper has been running for a few years, where recently the course was transferred into the learning factory environment combined with increased focus on blended learning. As a result, the course received significant student evaluations and was praised as being "the best course" and "an ideal course that other courses should strive for". Some of the main learnings from the course were:

- Students engaged with the content and curriculum to higher extent, as they could see the application in the project, which was transferable to real industrial settings.
- Students were heavily involved in "working" in the learning factory environment to complete the project, and meaningful interactions between students and teachers increased significantly in relation to the course content.
- Students stressed that the project taking outset in the reconfigurable learning factory supported the transferring of theoretical knowledge into practical experience.
- The blended approach increased students' engagement and supported students in taking responsibility for own

learning, in preparation, and in collaboration during active learning sessions in the learning factory.

An important aspect in designing and running a blended and problem-based course rather than traditional lecturing is the significant amount of resources and time required for its establishment, e.g. in making video lectures and other online resources. Moreover, in a highly cross-disciplinary course like this, various researchers and teachers are involved in both its establishment and in running the course, which places high demands on coordination, particularly in regard to the learning factory project. Also, extensive coordination is required in order to enable more than 60 students to work in the learning factory, among other courses and projects that also utilize the factory. Finally, even though traditional lecturing was reduced and replaced by more online activities and active learning, confrontation time between students and teachers was generally increased, as support in the learning factory is needed, even if the students are largely self-directed.

6. Conclusion

In industry, the relevance of manufacturing systems that are rapidly changeable and able to efficiently realize product customization is increasing and the demand for engineers with related knowledge and skills will grow accordingly. Moreover, advancements in manufacturing and technologies places new demands on engineering education: creating self-directed learners with a holistic, cross-disciplinary and systems-view on design, operation, and improvement of manufacturing systems that are rapidly changeable in accordance with markets, products, and technologies. This paper presented an engineering course on changeable and reconfigurable manufacturing that meets these demands through an application of blended and problem-based learning in a learning factory environment.

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