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Continuing Engineering Education (CEE) in Changeable and Reconfigurable Manufacturing using Problem-Based Learning (PBL)

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Abstract

Changeability and reconfigurability are some of the most important sources of competitiveness in today's manufacturing industry. However, the development and implementation of reconfigurable manufacturing systems still appear to be challenged and limited in industry. Therefore, it is increasingly relevant for engineers and professionals in the manufacturing industry to build knowledge and competences in reconfigurability. This paper presents preliminary insights and learnings from developing and running a problem-based learning (PBL) course in reconfigurable manufacturing for continuing engineering education (CEE). Presented insights cover both observed benefits and learnings for professionals participating in the course, as well as important learnings on how to best transfer knowledge from research to practice.

Keywords: Changeable manufacturing; Reconfigurable manufacturing; Engineering education, Problem-based learning; Continuing engineering education

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1. Introduction

Knowledge and competences are among the most important competitive criteria in modern manufacturing and companies are continuously faced with rapid technological improvements that constantly put new requirements on engineers [1]. While a global relocation of production has occurred in the past decades, a challenge for especially high-wage countries is to achieve both scale and scope in manufacturing in order to satisfy increasingly individualized customer needs and pressure for cost reduction [2]. As a result, companies must optimize both the design and operation of products and manufacturing systems and transfer newest research, knowledge, and technology into business at a rapid pace [3]. Thus, sustaining competitiveness in such increasingly volatile, changeable, and complex manufacturing environments makes Continuing Engineering Education (CEE) or Continuing Professional Development (CPD) of engineers increasingly relevant and a major factor for industrial development [4]. Consequently, models for fast and effective information transfer between universities and companies are needed, where focus consequently needs to be on application to real-world settings and learning within the job [5]. Traditionally, professional development and continuing education has been a task for private course providers or technological institutes and is still a relatively new field for most universities [3,6]. However, the importance of CEE and CPD is growing in research fields that are both increasingly needed in industry and fast evolving, such as smart manufacturing, industry 4.0, variety management, changeable and reconfigurable manufacturing, sustainability, remanufacturing, etc. This implies that CEE and CPD is a new task and challenge for universities and researchers [3].

As such the field of changeable and reconfigurable manufacturing is not new, as the concept of the Reconfigurable Manufacturing System (RMS) was introduced by Koren in the

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90s as an intermediate paradigm between flexible manufacturing systems and dedicated manufacturing systems [7]. However, while the relevance of changeability and reconfigurability is strong in many industries, previous research indicates a general mismatch between the needs on one hand and the required knowledge and level of implementation on the other hand [8-10]. An additional challenge for CEE and CPD in such frontier research fields is that knowledge is constantly changing and may not yet be fully established, which questions classical learning methods [11]. Therefore, the objective of this paper is to describe how to develop continuing engineering education in reconfigurable manufacturing, which ensures fast research transfer to industry, as well as meaningful application of learning to create value and competitiveness in manufacturing companies. Thus, the paper presents both the theoretical background for the establishment of a CEE course in reconfigurable manufacturing, as well as the empirically founded insights following implementation of the CEE course.

The remainder of the paper is structured as follows: Section 2 briefly outlines requirements and context of CEE, while Section 3 describes the appropriateness of problem-based learning (PBL) for CEE. Section 4 describes the field of changeable and reconfigurable manufacturing in relation to CEE and PBL, while Section 5 presents the proposed CEE course. Preliminary insights from applying the proposed CEE course are presented in Section 6, while conclusions are provided in Section 7.

2. Continuing Engineering Education (CEE) and Professional Development (CPD)

Engineers need to be life-long learners, which involves enhancing and upgrading engineering skills on a continuous basis. Such continuing engineering education (CEE) or continuing professional development (CPD) involves advancing professional theoretical skills in addition to practical work [12]. However, the context of CEE is different than the context of traditional under-graduate and graduate engineering programs in universities. In Table 1, some of the distinct requirements of CEE are outlined.

Various forms of CEE and CPD exist, which meet these requirements in different ways. Fink [13] distinguished between learning/teaching methods that are company-oriented i.e. on-demand and focused on company defined topic/goals, and methods that are university-oriented, i.e. largely ready-made and targeting a group of companies or individuals. Evidently, the university-oriented forms of CEE are usually formal, whereas work-based learning is within the category of company-oriented forms [5,6,14].

The term work-based learning refers to learning situated in the workplace and most often includes both teaching (e.g. courses) and research (e.g. involvement of facilitators in learning projects or within the company setting) [6]. Various applications of work-based learning to CEE and CPD are described in previous research [6]. For instance, Fink and Nørgaard [14] proposed a facilitated work-based learning model that has been successfully applied for CEE. Moreover, Fink [15] described work-based problem-based learning and argued for combining the regular engineering task of solving problems with the task of learning by problem solving. In particular, the problem-based learning approach has recently gained interest and attention for industry learning and CEE [4, 14-18], which is further elaborated in the following section.

Table 1. CEE requirements based on review of related research

Requirement	Explanation
Limited time [12]	CEE has to be fitted into regular working schedule and ongoing tasks at company, thus, engineers may find limited time for professional development.
Focus on application [3, 12]	Expectations are that the new academic knowledge and personal development of the engineer can be applied in the company to create value.
Different theoretical foundation and experience level [6, 12]	CEE targets company employees entering on different academic and experience levels, as well as with different educational backgrounds.
Integration of new research and knowledge [13]	CEE needs to be based on company and industry demand, often involving newest innovation, knowledge, and technology.
Flexibility in learning and educational model [13]	Dynamic class size, learning content, and schedule is needed in CEE.
Integration of practice and theory [5, 6]	Both high level learning and relevance in different practice contexts is required in CEE.
Supporting self-managed and self-directed learning [6]	CEE should support engineers in being self-directed life-long learners in own workplaces.
Certification [12]	Standardized approvals, credits, or diplomas are often needed in CEE to document personal development.

3. Problem-based and Project-based Learning (PBL)

Problem-based learning (PBL) is an educational approach founded in Canada at McMaster University in the 1960s, which is now widely used in education all over the world and for various educational fields [19, 20]. Thus, PBL exists in an array of forms and its extent of implementation varies with different institutions e.g. as a wide-spanning central learning principle, a specific educational model, or a single practice within traditional educational models [20]. However, central to the idea of PBL is that the learning process is student-centered, organized around problems, and takes place in smaller groups with the teacher taking the role of a learning facilitator [20]. Universities renowned for successful PBL approaches include McMaster University in Canada, Aalborg University in Denmark, Monash University in Australia, as well as Delft University in the Netherlands [20, 21]. As an example of comprehensive PBL implementation, Aalborg University has since its establishment been completely based on PBL in all study programs and is among the first universities to include progressive PBL knowledge, skills, and competences within the study curriculum for all semesters. In this way, learning takes place through a combination of courses and semester projects conducted in groups. In engineering programs, these projects cover more than half of the entire study and are conducted in close cooperation with industrial companies, facilitated by an academic supervisor. This “Aalborg PBL model” is internationally recognized as an advanced and efficient learning model and relies on the following key principles [20]:

- An authentic or real-world problem is the starting and focal point for the learning process.
- Based on exemplary problems, students are supported in transferring knowledge, theory, and methods to new areas and contexts.
- The learning process is self-directed, and learners have resposibility both for problem formulation and selecting approaches for problem analysis/solution.
- The learning process is activity-based and builds on the experience and existing understandings/knowledge of learners.
- The learning process is inter-disciplinary and focuses on real situations rather than subject-oriented syllabuses.
- Learning is project-based and takes place is groups with cooperation on knowledge creation.

Countless examples of successful application of PBL to engineering education exist, e.g. in fields of manufacturing/industrial engineering [22], project management [18], electrical engineering [23], civil engineering [24], etc. Moreover, the transfer of PBL from university settings and undergraduate/graduate education to CEE and industry has received attention as well. For instance, Nørgaard [16] emphasizes the fact that most companies develop products and systems in a problem-based and project-based way, thus, incorporating PBL principles for CEE learning facilitation appears as an obvious choice. Moreover, Fink [15] emphasizes the appropriateness of PBL to CEE; i) PBL applies problem formulation and problem solving as tools for learning, which is the main goal, ii) engineering problem solving (i.e. everyday practice in manufacturing companies) applies skills as tools and have problem solving as the main goal. Thus, combining the two is an obvious choice, denoted as work-based PBL.

The requirements of CEE stated in Table 1 are clearly related to the principles of PBL as a learning approach, e.g. taking outset in relevant context as focus in learning process, self-direction of learners, focus on application and real-world relevance, supporting team-based work, and integration of practice and theory. Moreover, PBL has been set forward as a successful approach to learn new or frontier technology, knowledge, and theory stemming from ongoing research advancements [11]. The following section continues along these lines and argues for the application of PBL for CEE in changeable and reconfigurable manufacturing, which are increasingly relevant and required themes in the manufacturing industry.

4. Application of PBL for CEE in Changeable and Reconfigurable Manufacturing

Changeable manufacturing is defined as the ability to accomplish early and foresighted adjustments on all factory levels in an economically feasible way e.g. through reconfigurability, flexibility, and changeoverability [25]. Topics within this field include manufacturing system design for changeability, reconfigurability planning and scheduling, product family formation and modelling, integrated product and manufacturing platform development, etc. [26]. Whether in regard to design or operational issues, changeability and reconfigurability are increasingly important themes for engineering education and also CEE in order to aid the transition into industry [1,27,28]. However, since the concept of the reconfigurable manufacturing system was coined more than 20 years ago, the field of changeable manufacturing is still advancing and several challenges exist in terms of practically implementing changeability [29]. Besides the pure technological considerations of how to realize changeability and reconfigurability, the following considerations needs to be addressed by a company as well; i) the need and requirements of changeability in terms of time, risk, and opportunities when reacting to change or uncertainty, ii) economic justification and evaluation of important trade-offs such as flexibility versus efficiency, and iii) motivation and qualifications to ensure production adjustments [30]. Francalanza et al. further described the design of changeability as a wicked problem, characterized as follows [31]:

- There is no definitive formulation or solution to it.
  There is no ultimate solution, as the system will evolve continuously.
- There is not a true or false solution, but only good and bad solutions to future product evolutions.
- Evaluation of solutions towards future product evolutions are difficult and decisions have high impact on cost.
- There are enumerable solutions to it and no well-described set of potential options e.g. in terms of realization of changeability enablers which is unique in every company/context.
- The problem of designing the system can be explained in various ways, e.g. not having adequate methods, not having sufficient enablers, not having the correct means to provide support, not identifying future product evolution, etc. Thus, a single true approach does not exist.

In addition, research on changeability and reconfigurability continues to receive great attention in both research and funding schemes [26]. Thus, knowledge in the field is developing quickly and involved solutions, competences, and technology is quickly emerging. In general, knowledge dissemination and learning of such types of research fields is challenging due to e.g. lack of established learning material, fast evolving material, lack of demonstrated state-of-the-art, lack of well-defined and validated tools, etc. [11]. It is important to take these characteristics of changeable and reconfigurable manufacturing theory into consideration when designing CEE and CPD within this field.

Generally, successful teaching and learning experiences are based on both a teacher’s strong knowledge about the taught subject and about how the subject is best learned [32]. Thus, designing a meaningful and successful CEE learning experience in changeable and reconfigurable manufacturing requires that the right pedagogical approach is selected. Therefore, an outline of the abovementioned main challenges in regard to learning and teaching changeability and reconfigurability is linked to corresponding PBL principles as potential solutions in Table 2.

Table 2. Main challenges in learning changeability/reconfigurability and PBL principles as solutions in CEE and CPD

Challenges	PBL principles
Knowledge is not yet complete about the topic or is evolving continuously, so should the teaching material [11]. Knowledge and information typically come from distributed sources [11].	In PBL, learning is often comprised by lectures/courses and project(s)/workshops. The lectures support the project/workshops. The leaners become familiar with a wide range of theories and methods that they can investigate further or apply in the project based on relevance [20]. Thus, standard information is no prerequisite, nor is learning solely based on a reading-list [33].
Lack of material or established references to use [11].	PBL is learning and not teaching, thus, being an open process of investigation or knowledge creation [20]. In PBL, the teacher i.e., expert in field and an industrial resource are often main sources of information [11].
Learners demand information relevant to their own context or operational environment [11].	In PBL, a real-world problem is the starting-point of the learning process and learning is active and participant-led [20].
Every CMS/RMS design problem is unique and depends on the company/context [31].	The learning content is related to the context, and the specific problem to address comes from specifically selected contexts [20].
There is no definitive solution or approach to the CMS/RMS design problem [31].	PBL is flexible, meaning that problems can be new and defined differently every time, as learners are working on authentic problems [20]. It is essential that learners have participatory and self-directing influence in the learning process and in addressing the problem [20].

Evidently, the intentions of PBL i.e. that learners become self-directed life-long learners able to navigate in complex scenarios by seeking relevant information and knowledge to address the problem, is largely consistent with the requirements of CEE and requirements of learning in changeable and reconfigurable manufacturing. Thus, in the following section, the "PREMIUM" CEE learning model for this purpose is outlined on the basis of PBL.

5. Outline of a "PREMIUM" course in Changeable and Reconfigurable Manufacturing Development

The educational project "PREMIUM" (Professional Education for Manufacturing Education) had the objective to enhance life-long learning of engineers and practitioners in the Swedish manufacturing industry. As part of this project, a course equivalent to the workload of a 5 ECTS university course was created in the field of development of changeable and reconfigurable manufacturing. The intended learning outcomes for the course were formulated in cooperation with industrial stakeholders:

- Display knowledge of changeable, reconfigurable, and flexible manufacturing concepts.
- Demonstrate knowledge of co-development of products and production systems.
- Demonstrate knowledge of methods and tools to support design.
- Demonstrate the ability to conduct development for changeable production solutions.
- Demonstrate the ability to assess current state of implementation and readiness of changeable production systems.
- Demonstrate the ability to identify need for changeability and reconfigurability.

Thus, course content included both some of the fundamentals of changeability and reconfigurability, e.g. characterization of manufacturing paradigms and systematics of reconfigurability. However, the main part of the content took outset in state-of-the-art research within the field e.g. assessment models for reconfigurability, investment justification, integrated product and production modelling, etc. Therefore, limited readily available information beyond some relevant academic publications was a significant challenge to consider in the course design. Therefore, in designing this course, the CEE requirements outlined in Table 1 and the reflections in Table 2 were considered.

5.1. Overview of Learning Process

The course was titled "Development of Changeable and Reconfigurable Manufacturing" and was in terms of content divided in three parts with progressive learnings. In Table 3, each block is outlined.

Table 3. Overview of course content, activities, and progressive learning

Course part	**Content**	**Activities**
Part 1: Introduction to changeability and reconfigurability	Introduction to changeable, reconfigurable, and flexible manufacturing systems. Fundamentals of changeability and reconfigurability. Industrial potentials and examples.	Lectures introducing theories, methods, etc. to apply in project as relevant. Individual study of reading material and video lectures. Seminars in groups discussing theory. Project work in groups. Presentations and plenum evaluation og preliminary project progress.
Part 2: Development for changeability and reconfigurability	Manufacturing system development and co-development of products and production. Modularity and platforms in manufacturing. Virtual support for designing changeable manufacturing systems. Assessment of reconfigurability in manufacturing.	
Part 3: Evaluation of changeability and reconfigurability	Concept generation. Evaluation and justification of changeability/reconfigurability. Configuration of products and manufacturing systems.	

Each of the parts contained a combination of the outlined learning activities, which all relied heavily on learners being active and self-directed in e.g. selecting theories to investigate in depth, apply in own context, use in reflections, etc. Moreover, several of these activities were conducted in groups, both within-company and across-company groups, thus fostering multi-disciplinary work.

The targeted participants were primarily manufacturing specialists, manufacturing engineers, and managers with manufacturing-related responsibilities. Evidently, participants had very different experience level and different academic background. Researchers/course coordinators took the role of domain experts and facilitators in the learning process and in activities. Each part covered two weeks and one week between parts allowed participants to seek out relevant information needed in their own companies. Moreover, the course was conducted as a mix of physical and online activities and took place in both companies and in universities.

5.2. Projects in Companies

In the course, a project taking outset in a company relevant problem was conducted throughout all parts and in groups of participants from the same company. In this project, participants were required to actively select problem within the frame of the course, select approaches and theories to apply, and cooperate on learning the content of the course through this project work, while at the same time addressing company-relevant issue. This project was the primary basis for student assessment, where participants' learnings were continuously assessed in project presentations. In Table 4, a description of the overall themes of this project is provided.

Table 4. Project scope and content

Project Part	Content
Part 1: Define requirements and potentials of changeable and reconfigurable manufacturing in the company.	*Initial analysis and problem formulation:* Evaluating current solutions in company, finding examples of dedicated, flexible and reconfigurable solutions, evaluating change drivers, identify appropriate candidate (i.e. system, cell, workstation, equipment) for reconfigurability design and identify requirements for next parts of the project.
Part 2: Investigate production manufacturing and assess existing reconfigurability in company.	*Problem analysis:* Describing and evaluating company's approach to manufacturing and product development, identify barriers on different levels, assess current enablers in manufacturing, relate existing level of reconfigurability to previously identified requirements, drafting concepts to proceed with in last part.
Part 3: Develop concept(s) for changeable and reconfigurable manufacturing and evaluate feasibility and readiness in company.	*Problem solution and evaluation:* Generation of concept(s) for reconfigurability to fulfill the previously identified requirements, consider changeability enablers and relation to existing and future product design, evaluate costs related to concepts, justify investments, prepare detailed design to proceed with after course.

6. Preliminary Insights and Learnings

The CEE course described in this paper has so far been running three times, with more than 35 participants from different companies in total. After each run of the course, extensive evaluations were conducted both as informal discussions and more formal surveys. Some changes were done based on this, e.g. increasing the extent of online resources such as videos, quizzes, forums, etc. However, all participants generally evaluated the course as being either very satisfactory or satisfactory in terms of quality, relevance to own context, and possibility to achieve intended learning outcomes. Moreover, the following points were evident in the evaluations:

- Participants indicated that the course often succeeded in challenging them to analyze ideas and concepts in depth.
- Participants generally indicated high relevance of the topic of the course and also high level of academic content.
- Participants were satisfied with the connection to research and newest knowledge. However, some raised issues regarding understanding and using academic papers as course material and wished for having handbooks instead.
- Communication between students and teachers being experts/facilitators were appreciated by participants.
- Difficulty in relation to prior knowledge and experience of participants was considered too high, high, and medium. In connection to this, the hours spend on the course varied greatly among participants.
- Participants appreciated the opportunity to engage with other companies.
- The participants appreciated the course project and the ability to put learning into their own reality.
- Some participants indicated that being able learn the topic of reconfigurability, while also learning how to implement this in own work was a significant benefit. Some also indicated that they would bring back presentations to further audiences in their companies.

It is clear that there are both advantages and drawbacks of a highly research and state-of-the-art oriented CEE course, where educational background, previous experience, age, etc. varied greatly among participants. Particularly, one challenge that was mentioned in all three course evaluations was the need for more basic introductory material or fundamental textbooks. Moreover, the need for sharing industrial examples and examples from previous courses were also clear from evaluations, which was however difficult due to confidentially reasons. In terms of learning reconfigurability theory and how to apply these principles in practice, some main challenges were clear during the courses. For instance, participants often struggled in distinguishing between reconfigurable and flexible solutions in their own company contexts. In this regard, there is clearly a need for research to explain and describe enablers and characteristics of reconfigurability and flexibility in relation to both physical and logical system/cell/station/equipment components, while also emphasizing flexibility and reconfigurability as part of changeability corridors i.e. as described by Zäh et al. [34]. Moreover, the participants often stressed the need for supportive approaches for evaluating costs and benefits of their proposed reconfigurable concepts to further create business cases in the companies. Thus, insights from the CEE course also resulted in valuable insight for how to extent research in order to aid a transition towards changeability in industry.

7. Conclusion

The objective of this paper was to describe how to develop CEE in changeable and reconfigurable manufacturing ensuring both fast research transfer to industry and meaningful application of learning to create value and competitiveness. Findings presented in this paper indicate that PBL is a valuable learning approach for CEE and more importantly that CEE is able to aid the transition of research into industry by creating bottom-up initiatives in companies led by engineers, specialist, and manufacturing managers that participated in the CEE course. Moreover, the CEE approach presented in this paper exemplifies how CEE benefits not only professionals, but also researchers in creating valuable insights on future research directions to follow.

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