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Development of an Approach for a "Cross Learning Factory Product Production System" for Circular Economy

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Abstract

Circular economy aims to support reuse and extends the product life cycles through repair, remanufacturing, upgrades and retrofits, as well as closing material cycles through recycling. To successfully manage the necessary transformation processes to circular economy, manufacturing enterprises rely on the competency of their employees. The definition of competency requirements for circular economy-oriented production networks will contribute to the operationalization of circular economy. The International Association of Learning Factories (IALF) states in its mission the development of learning systems addressing these challenges for training of students and further education of industry employees. To identify the required competencies for circular economy, the major changes of the product life cycle phases have been investigated based on the state of the science and compared to the socio-technical infrastructure and thematic fields of the learning factories considered in this paper. To operationalize the circular economy approach in the product design and production phase in learning factories, an approach for a cross learning factory network (so called "Cross Learning Factory Product Production System (CLFPPS)") has been developed. The proposed CLFPPS represents a network on the design dimensions of learning factories. This approach contributes to the promotion of circular economy in learning factories as it makes use of and combines the focus areas of different learning factories. This enables the CLFPPS to offer a holistic view on the product life cycle in production networks.

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Keywords: Circular Economy; Production Systems; Learning Factory Networks; Product Life Cycle; Competency Requirements

1. Introduction

The design of circular economy (CE) capable production networks is a highly relevant topic, not least due to the emerging developments of Industry 5.0 aiming on a transition to a sustainable, human-centric and resilient industry [1]. This transition requires profound changes of the design or adaptation of value creation networks for CE capabilities. These changes also highly affect the qualification of employees as a central prerequisite for its realization [1] [2]. The effects of the CE on the competency requirements of employees and the product life cycle phases in value creation networks are still largely unknown. Also suitable methods for teaching these competencies have to be identified [3]. The benefits of learning factories (LF) for teaching competencies also in networks of LF with joint courses have already been proven [4] [5]. The interdisciplinary and cross-value chain requirements in

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connection with the R-strategies of the CE call for novel approaches to imparting the corresponding competencies in networks of LFs and corporate partners to adequately map the circular product life cycles. Therefore a “Cross Learning Factory Product Production System (CLFPPS)” for CE has been defined to support the operationalization of CE methods and systems. This has been done based on the investigation of the state of science of the involved fields of research. The focus of the paper is set on the review of the state of the science and the current situation as well as planned further developments in the area of CE of the considered LFs to define the CLPPS approach in general. In this way, a well-founded starting point is to be created for the necessary definition of the required competencies and detailing of the approach into the direction of a model. This will support the establishment of a CLFPPS for CE in a further step.

2. Analysis of the state of science

In the following, the relevant basics of LF design are outlined. Afterwards the state of science in the field of existing frameworks and models for CE-oriented production systems and required competencies are presented. Joint teaching within networks of LFs and companies will be investigated in the following to highlight the limitations of existing approaches.

2.1. Learning factory design

LFs are environments to develop competencies to improve production systems based on a real industrial setting which incorporates new technologies and processes [6]. In order to structure the design of a LF, Tisch et al. [6] developed the learning-factory-curriculum guide. In their systematic approach for LF design, three design levels are to be distinguished. Starting with the level of the systematic design of the ‘learning factory’ (macro), which refers to the design of the LF itself including infrastructure and production environment, the ‘teaching module’ (meso) and the ‘learning situation’ (micro). This paper focuses on the limitation of LFs in their infrastructural representation of their entire production units [7] and therefore it is primarily based on the macro design level. Beside the infrastructural representation, the intended competencies and targets of the LF environment are defined in this level [6]. To overcome this limitation, networks of LFs can be used to extend the scope of the facilities [7]. For this reason, the paper focusses on the development of a LF network on the macro level integrating the topic CE.

In general, LF are defined based on six dimensions: purpose, process, setting, product, didactics and operating model. These should be addressed in order to meet the definition of a LF [8]. These dimensions are used to further specify the framework. In order to develop the CLFPPS, the dimensions process, setting and product are examined in more detail. However, it is assumed that all participating LFs address all six definitions.

2.2. Circular economy oriented production systems

Traditionally supply chains, production systems and product life (cycles) follow a linear approach. This means that new raw materials are used for production and in the end of their products lifetime products and resources end on landfills or even in nature [9] [10]. The CE is based on three principles of elimination of pollution and waste, circulation of materials and waste and the regeneration of the nature [11]. A major aim of CE is therefore to close product loops. In this way waste becomes a resource for new products following the concept of “cradle to cradle” and customers become suppliers. The roles of members in production networks change in line with the circular value creation processes [10] [12].

Companies are under increasing pressure from legislators, their customers and economic considerations to examine and implement the opportunities offered by CE. A widespread approach to implement and classify activities in the field of CE are the R-strategies defined by Potting et al. [13]. Those strategies can be applied in order to keep materials as long as possible in use (loops) and they are ordered by their level of increasing circularity. While the strategies refuse, rethink and reduce address the product use and manufacture, the strategies reuse, repair, refurbish, remanufacture and repurpose apply to extend the lifespan of a product and its parts. Those two groups of R-strategies are seen as those with a higher level of impact to increase circularity. Recycling and recover are seen as the strategies most related to a linear approach and aim a useful application of product materials. For further details on the R-strategies see Potting et al. [13]. However, these Rs refer to the strategic level and provide direction in the design of production systems but lack details on the actual realization within production systems and product life cycles.

Addressing circularity in production, Schmitt et al. [14] outlined that special attention regarding production layout and infrastructure is needed when designing a circular production system. Further Suzanne et al. [15] examine the challenges of production planning for CE. In their literature review Suzanne et al. [15] highlighted for example lot-size problems as one aspect and identified several papers focusing on disassembly scheduling problems. Thus, there is already some work that links CE with production topics, but Bjørnbet et al. [16] outlined the need for more basic research on CE in the production context. Moreover, Kara et al. [17] showed that further research has to be done regarding the establishment and operation of global production networks as a key enabler for the operationalization of CE.

2.3. Competency requirements

As described in section 2.1 and in addition to the design of the infrastructural framework, competencies and learning targets must be outlined for the LF design on the macro-level. Future topics like CE require new competency profiles of professionals to drive the transition forward and position the own company in this new economic system. Due to the fact, that there is no holistic overview about these required competencies a literature study has been conducted and key competencies for CE have been investigated.

Prieto-Sandoval et al. [18] present an approach to implement CE in small and medium-sized enterprises (SME) and outline the required competency profiles of the employees. The profile of a top manager is strongly aimed at adapting the vision of a CE for the own company and finding starting points for the transition. Charter [19] and Schmitt et al. [14] point out the need for cooperation and communication competencies. In addition, it must be known how to implement the R-strategies in a targeted manner and to bring the CE into actual operational implementation [20]. Furthermore, competencies are required regarding the product design, for instance regarding readiness for disassembly, and the business model behind the products [3] [14].

The required competencies can be summarized regarding openness for change, ability for innovation, holistic value stream thinking, communication skills and in general interpersonal aspects. Also, the above-mentioned product design competencies are crucial for CE. This shows that technical and methodological competencies are currently hardly considered. Social-communicative and personal also play a crucial role. Thus, the approach for CLFPPS should address the highlighted ones and is particularly intended to contribute to the development and teaching of technical and methodological competencies.

2.4. Joint teaching within networks of learning factories and companies

Teaching factories (TF) and learning factories (LF) are two modes of training for education in manufacturing, both aligning education to the needs and challenges of contemporary manufacturing sector [21]. TFs are a two-way knowledge transfer scheme aiming to bring the real industrial problems into the classroom and the research, while LFs focus on educating manufacturing practitioners using facilities and infrastructure in the academic environment. Teaching and Learning Factories frameworks are based on collaboration between academia and industry, sharing the same background of developing and delivering industrial training, addressing the needs for highly trained and highly skilled manufacturing practitioners of the present and the future factories [22]. Cognitive framework acting as a background focuses on three major aspects; (1) attitude, (2) skills and (3) competencies [23]. More specifically for LFs, different concepts and frameworks have been developed based on specific cases, ranging from project based [24] approaches and production based [25] to holistic product creation [26] and holistic design [27] of collaborative work systems.

LFs have been used as a training and education tools for educating regional SMEs, to promote Industrie 4.0 technologies in local companies via holistic model of the company from top floor to shop floor, focusing on different dimensions of the LF [28]. The design of the LF as a close-to-reality learning module improves the learning experience and increases the success of the LF. Joint teaching can be achieved via research, workshops and presentations, not only via teaching knowledge but also through demonstration of novel production concepts and the development, implementation and evaluation of prototypes together with the industrial participants [27]. For example, within the IALF network there is a joint course of the Ruhr-Universität Bochum, Technical University Darmstadt and ESB Business School (Reutlingen University) on digitalization in product development and production using the three LF of the partners [5]. Industry should provide the LF with know-how from their industrial experience and practice, while academia should provide with academic excellence, promoting their research, innovation and education skills and their problem-solving attitude in a modular configuration to allow for flexibility [23]. On the other hand, there are certain challenges to overcome, starting from lack of close communication between industry and academia and the need for content improvement [25].

3. Analysis of existing socio-technical infrastructure and thematic fields of the learning factories

To capture the current state and identify gaps a comparison of the existing socio-technical infrastructure and thematic fields of the participating LFs to the arising requirements has been conducted. The analysis has been done according to Abele et al. [8] following the three dimensions of process, setting and product for each LF in the consortium. The results are elaborated in the following paragraph and aggregated in table 1. Further information about the LFs can also be found in Abele et al. [4].

As one of the contributing partners the Chair of Production Systems (LPS) from the Ruhr-Universität Bochum operates the LPS Lern- und Forschungsfabrik (LFF) for knowledge transfer activities in combination with a research area for experimental usage and state of the art technology. The given infrastructure, hard- and software covers the research fields of industrial robotics, production automation, production management, lean management, sociotechnical digitalization and smart product service systems for hybrid value creation of products and services. Additionally, the LPS contributes to the new Center for the Engineering of Smart Product Service Systems, which provides additional infrastructure and latest technology in the fields of automation, robotics, drones and building information modeling (BIM).

The Institute for Production Management, Technology and Machine Tools (PTW) at TU Darmstadt operates the "Center for industrial Productivity" (CiP) process learning factory for education, teaching and research in lean and digital production with a holistic value stream to produce a pneumatic cylinder. The research focusses on the expansion of existing lean management approaches through digital technologies, such digital twin and data science in value stream management. Learning factory design, virtual reality in LFs, competence development in the fields artificial intelligence (AI) and CE as well as process optimization through artificial intelligence (AI) are also core topics. Next year the third learning and research factory – FlowFactory - will be opened at PTW to expand the infrastructure and to cover topics like CE, resilience and data value ecosystems (Gaia-X).

Table 1: Matrix of Learning Factory infrastructure in the dimensions of setting, process and product

Learning Factory	**Setting**	**Process**	**Product**
Werk150 – Reutlingen University	Physical area: 775 m² Number of machines: 20 Major types of machines and number: additive manufacturing (6), subtractive manufacturing (3), automated transport systems (7) Extension in VR: yes	Direct processes: material processing to packaging Indirect processes: product development, production planning and control, autonomous control of intralogistics	Name: City scooter + new intelligent product (in development) Number of variants: 5 major variants + customer-individual Own development: no (City scooter), yes (new intelligent product) Materiality: Material
LPS Lern- und Forschungsfabrik – Ruhr-Universität Bochum	Physical area: 1000 m² Number of machines: [14] Major types of machines and number: turning machines (4), milling machines (2), band saw (1), automated mobile robot (1), cobots (2) Extension in VR: yes	Direct processes: sawing to packaging Indirect processes: production planning, condition monitoring	Name: UniLokk Number of variants: 75 Own development: yes Materiality: material
Center for the Engineering of Smart Product Service Systems – Ruhr-Universität Bochum	Physical area: 800 m² Number of machines: 11 Major types of machines and number: autonomous mobile robots (3), drones (5), selective laser sintering machine (1), hybrid manufacturing robot (1), 3D-robot-scanner (1) Extension in VR: no	Direct processes: laser cutting, 3D printing, mobile value creation, remanufacturing Indirect processes: autonomous control of intralogistics, digitalization of damaged products, servitization	Name: Customized products Number of variants: no restrictions Own development: both possible Materiality: material and immaterial
Process Learning Factory Center for industrial Productivity – Technische Universität Darmstadt	Physical area: 500 m² Number of machines: 7 Major types of machines and number: machining technology (3) Extension in VR: yes	Direct processes: sawing to packaging Indirect processes: production planning	Name: pneumatic cylinder Number of variants: 8 + customer-individual Own development: no Materiality: material
FlowFactory – Technische Universität Darmstadt	Physical area: 500 m² Number of machines: 20 Major types of machines and number: machining technology (3) Extension in VR: yes	Direct processes: sawing to packaging Indirect processes: production planning, product development	Name: smart office station Number of variants: customer-individual Own development: yes Materiality: material
Laboratory for Manufacturing Systems and Automation (LMS) - University of Patras	Physical area:350 m² Number of machines: 20 Major types of machines and number: machining technology (4), additive manufacturing (4), robots in various configurations (12) Extension in VR: yes	Direct processes: machining, additive manufacturing, hybrid manufacturing Indirect processes: production planning, dynamic scheduling, process monitoring	Name: electric vehicles Number of variants: customer-individual Own development: no Materiality: material

Core topics of Werk150 – The factory of the ESB Business School on campus of Reutlingen University – are digitally integrated product and process engineering & manufacturing, application of 5G, the design of hybrid human-robot-collaboration work systems, autonomously controlled, changeable intralogistics systems and digital shadows and twins. Currently a new CE capable intelligent product aiming on the coverage of the R-strategies is under development which is going to be produced in addition to the existing products of city scooters in Werk150.

Laboratory for Manufacturing Systems and Automation (LMS), based on University of Patras, is focusing on manufacturing processes, automation and manufacturing systems. In terms of circularity driven concept, the focus is on additive manufacturing, hybrid manufacturing, milling, welding and zero-defect manufacturing. Recently developed products from circularity-based approaches as developed by LMS are electric vehicles.

The analysis leads to the result that the classical (linear) product life cycles phases of collaborative product development, rapid prototyping and production (machining, assembly, intralogistics) are widely covered by the considered LFs. In contrast, the CE specific product life cycle phases involving the R-strategies are largely not yet addressed, although all the LFs considered are pursuing activities to take CE into account. For a process-oriented and methodological-didactic coverage of the competency requirements of CE the collaboration of LFs with different focus areas and industrial partners to cover required CE contents outside the scope of the LF (e.g., material recycling) is required. To operationalize this further development an approach for the established of a CLFPPS for CE has been developed.

4. Approach of a "Cross Learning Factory Product Production System" for circular economy

Based on the analyzed state of science (see chapter 2) and the analysis of existing socio-technical infrastructure and thematic fields of the LFs (see chapter 3) an approach to establish a CLFPPS for CE was developed (see figure 1). Considering Braungart's and McDonough's [10] "cradle to cradle" approach of products and materials with its technical and biological metabolisms, this work will focus on the technical cycles.

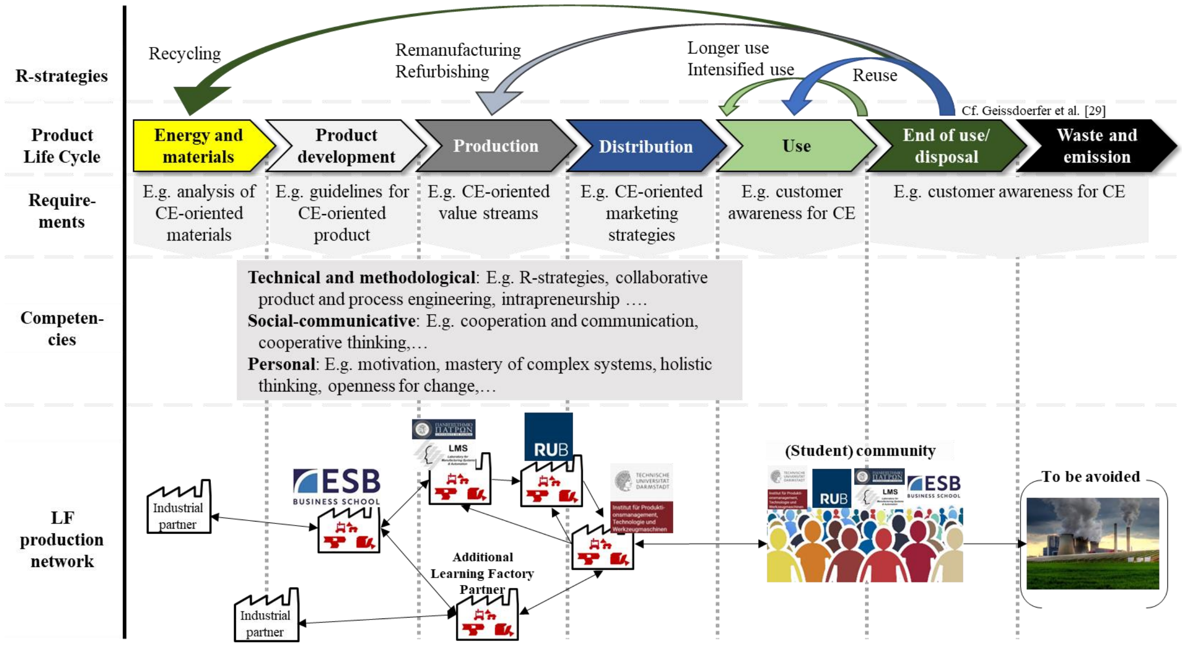

Fig. 1. Approach of the "Cross Learning Factory Product Production System" for circular economy

The CLFPPS approach visualized in figure 1 considers the affected product life cycle phases following Geissdoerfer et al. [29], relevant competencies, the R-strategies, and the comparison with the infrastructure available in the LFs. In this way it is shown how the LFs might organize a common production network to realize circular product life cycles. The developed CLFPPS approach provides an overview of the levels of consideration of the production system and required content details to be investigated. These will include among other things the necessary content-related further developments to cover the competency requirements, as well as the structural and process-related change and expansion needs of the LFs. Specific competencies have to be identified based on requirements that can be derived from the product life cycle and the R-strategies, e.g., for the production of CE-capable products methods are needed to design CE-oriented value streams. The core idea of the developed approach is that through a synergetic networking of their learning modules and socio-technical infrastructures, the LFs form a CLFPPS with a common (smart) product which has to be defined. This common product and its components should be kept in the value cycle, taking into account the R-strategies. To achieve a circular value creation process, a targeted linking of LF environments and industrial partners with specific know-how (e.g. in the area of industrial scale material recycling) is to be realized in addition to the content-related focal points of the LFs. Each LF will take the lead, according to its focus topics, for certain processes, product components and certain product life cycle phases of the joint product as well as for the didactically prepared transfer of the learning/teaching content to students and into industrial networks. The components of the common product will be developed, manufactured and kept in a circular product life cycle in a distributed value stream network. The concept for the transfer of the required competences involves the combination of onsite (hands-on) training modules and remote (online) training modules which are provided and shared by the involved LF and industry partners for joint student courses and industry trainings. For example, the Technical University of Darmstadt might provide a teaching module using the virtual reality (VR) factory environment for location-independent training of the value stream mapping method. The other partners might provide training modules on smart product service systems (Ruhr-Universität Bochum), additive manufacturing in context with CE (University of Patras) and autonomous control of intralogistics systems to achieve flexible material flows in the factories (Reutlingen University). Within the CLFPPS, bidirectional value creation flows (assembly, disassembly, reverse logistics, etc.) of the product are to be realized and tested following the CE approach. For this purpose, the production network of the LFs serves as a safe test bed without the risk that production losses (in contrast to industrial pilot tests) lead to loss of revenue. By using the student community of the LFs, valuable usage data can also be generated with the help of a joint smart product. This data can provide information about the product use and circularity of the products, which can then be used, for example, in the area of refurbishing (product upgrading for a better fit to the customer requirements).

5. Conclusion

The cooperation of LFs within a CLFPPS for CE offers great potential for universities and companies to specifically meet challenges of the CE by researching models for the realization of CE capable production networks and corresponding competency requirements. The developed approach is intended to set a starting point for further research within the LF community on the topic of CE. The synergetic networking of production environments into CE value networks and the development of corresponding teaching concepts and modules are the topics that can be mapped and researched in a CLFPPS. The described approach also provides a basis for content-related networking with other IALF Working Groups (e.g. Sustainability and CE in Learning Factories) to derive and detail the required competencies for CE to be addressed in LFs. This fosters the joint development of specific training modules and thus show possibilities for cooperation (also with regard to EU research projects).

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