Learning Factories and Sustainable Engineering—Competencies for Students and Industrial Workforce

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Abstract—*Sustainability and the circular economy are becoming increasingly important for industry and academia. Learning factories at higher education institutions around the globe attempt to educate students and industrial workers on these topics through specially developed training modules. To successfully implement measures to mitigate issues, such as climate change, product life cycle considerations—in which different phases may require different worker competencies—are indispensable. In this context, we provide some evaluation of learning factory use cases regarding sustainability. The use cases are evaluated on product life cycle phases and respective worker sustainability and circular economy competencies. The results show that the majority of the use cases focus on the production life cycle phase; product development, product use, and end-of-life have either not or very rarely been addressed. Our general conclusions and implications relate to these findings with a recommendation that learning factories expand their training capabilities.*

Key words: Circular economy (CE), competencies, learning factory (LF), skills, sustainability, training

1. INTRODUCTION

ACCORDING to the UN Intergovernmental Panel on Climate Change, greenhouse gas emissions are increasingly and negatively affecting the climate leading to an average global temperature of 1.5 °C above preindustrial levels in 2030 [1]. In response to these findings, politicians and other stakeholders are making commitments and actions to limit global temperature rise. The International Energy Agency found that the industrial sector is responsible for 23% of all energy-related emissions [2]. These are only one of many sustainability concerns that represent future industry and company challenges [3].

However, to effectively incorporate corporate sustainability practices to address these global and local environmental issues, appropriate employee competencies and skills are required. Employee sustainability skills include the ability to critically analyze corporate effects on sustainable development and the ability to evaluate and decide on needed actions for sustainable production [4]. *Learning factories* (LFs) can support these competency developments by supporting the transformation of theory into real practice [3].

LF use real-world processes—including technical and organizational aspects—enabling action-oriented learning for trainees [5]. In addition to education, academic, and professional training, LFs use research activities, such as problem identification and solution validation [6]. LFs have proven to be effective learning environments to address sustainability challenges. Examples, which will be further described later, include LF course training modules (use cases) that help identify energy savings potentials that are 15.9% points higher compared to the nontrained group [7].

Globally fewer than 35% of LF include sustainability modules, with even fewer supporting research in this field [8]. Given this low representation, we provide insights into where and how to increase these numbers. Classification of existing use cases focusing on sustainability is developed and missing sustainability competency elements are identified. Recommendations for the LF community to increase the consideration of sustainability-related topics are presented.

2. BACKGROUND

2.1. Sustainability and the CE

Sustainability can be described as a system where consumed resources can naturally regenerate without endangering the possibility for future generations to meet their needs. One common possibility to structure sustainability is according to three simultaneously considered dimensions of environment, economy, and equity or social [9].

One viable strategy for enhancing the three pillars of sustainability is through the circular economy (CE) concept. CE is based on the following:

1) rethinking and redesigning products and services;
2) implementing the recirculation of materials;
3) regenerating natural systems;
4) reducing the generation of pollution and waste.

Together these aspects and other CE dimensions can lead to a more environmental, economic, and socially sustainable industry [10].

In CE, the whole product life cycle (PLC) must be considered to holistically evaluate and improve product sustainability. The PLC includes product development, production, product use, collection, sorting, and reprocessing [11], and sets our foundation for an evaluation of sustainability in LF.

In the first PLC phase sustainable product design—ecodesign, material efficient design, recyclable design, design for manufacturing—and the selection of materials need to be considered [12]. For the production phase, the manufacturing process and technology and associated resource consumption—electricity, fuels, auxiliary materials, and waste—and the resource efficiency within circularity are of interest [12]. In the product use and collect phases, customer product use and return need to be considered—where awareness of the environmental impact needs to be tackled. The last phase issues, such as product modularization, remanufacturability, and respective business models, need careful CE consideration [13].

2.2. Sustainability Competencies

Effectively incorporating the various sustainability and CE practices into companies requires appropriate employee skills and competencies. Sustainability competencies include the following:

1) the identification of connections between sustainable development principles and disciplinary theory;
2) critical analysis of sustainable development effects;
3) evaluation and decision making on the sustainability courses of action;
4) critical analysis of sustainability knowledge, data, and values;
5) the recognition and treatment of uncertainty in data;
6) action for change consistent with this analysis [4].

For an energy sustainability example—an integral aspect of CE—a set of competencies can consist of determining energy flows to achieve energy efficiency, detecting energetic interdependencies in production systems, and analyzing the interdependencies to identify improvement measures [14]. Those would include classical lean management competencies for the identification and reduction of waste and material inefficiency [14].

For CE competencies, an LF focuses on recycling, reusing, and remanufacturing, and a *recycling factory* concept has been proposed [15]—with a similar recommendation of waste reduction based on the lean management concept in this factory training [15]. Finally, competencies to design and implement suitable measures and evaluate their impact on the sustainability output are required [14].

2.3. Sustainability in LFs

The review of the existing literature showed several LFs that are actively researching or offering teaching modules for students and industrial workforces in energy and resource efficiency [4], [7], [14]–[22]. Energy quantification and efficiency are the major focuses [14]. Recently, social sustainability has also emerged as a concern [21]. Yet no general framework to analyze sustainability and competencies in LFs exists. Although different teaching use cases and approaches to related topics do exist, there is a lack of insight into different PLC phases in the context of sustainability within LF. Noting this need for a framework to further action in LF for sustainability, scholars from different universities that operate an LF formed a working group and bundled their knowledge and approaches to further develop structured LF use cases that are directed toward sustainability topics [22].

This article builds on these use cases for additional insights through the development of a framework for sustainability competencies across the PLC. This framework provides insights into how PLC-related sustainability competencies are relevant for industry and academic education.

3. Results

The analysis of use cases gathered from the literature and additional expert input revealed use cases that are either developed for training purposes or research activities in the LF community. The discussion of use cases in this article is along categories of the main PLC phases. Initially, 21 use cases (different teaching modules in several LF toward sustainability) were identified in [22] and were grouped together, as they describe similar teaching modules (e.g., energy monitoring). Based on this initial categorization, 16 of these 21 use cases were identified as potentially important toward CE and clustered according to the different phases of the PLC.

Using published material and various items discussed in Section 2.2, *conceptual* and *professional* knowledge sustainability competencies that could be trained were determined. These two groupings are summarized in the columns within Table 1. Conceptual competencies relate to awareness regarding the impact on PLC sustainability. Professional competencies include competencies related to fostering transparency, deriving measures, and evaluating their impact on sustainability (see Table 1). A mapping of these competencies, the use cases (LF), and the PLC dimensions are now summarized. A summary of the use cases and competencies required and their source study appear in Table 2.

3.1 Product Development Throughout the first phase of the PLC, legal requirements, costs, quality, and safety are prioritized before environmental issues [23]. Nonetheless, designers are facing increasing challenges in incorporating environmental concerns into product development [24].

As an example, material characteristics and quantities are mostly determined in the early product development phase. These early decisions play a crucial role in sustainability and circularity management across the PLC. Material efficiency focuses on the entire life cycle from raw material over production to disposal and recycling. Related LF use cases should incorporate ecodesign, or life-cycle-based product development [see, e.g., 16]. However, no product development use cases have been identified in this sample set of LF studies—which represents a strong indication of the lack of focus on these topics.

3.2 Production From Table 1, we see the majority of use cases focusing on the production stage of the PLC. A further subdivision into two groups—building and technical building systems, and machines—can be made for the production stage.

Increasing resource efficiency, and specifically energy efficiency, is the most dominant concern. Energy efficiency requires significant knowledge about managing and measuring energy usage. Therefore, several LFs offer use cases that aim to provide a transparent picture of energy usage.

Several methods (requiring skills and competencies) can be applied. Qualitative observations of processes and guided interviews with operators and management on the shop floor will be important data and knowledge acquisition skills [25]. Structured energy flow analyses, including identification of energy flow improvements and energy waste management, were important skills developed [7]. Using and applying energy monitoring systems, including postprocessing analysis and decision support capabilities, and knowing how to implement energy monitoring systems were identified as consistently provided competencies [26].

Some use cases also focus on the technology-enabled real-time energy monitoring requiring some technical skills development with emergent technology. For example, mixed reality applications that visualize normally invisible energy flows and efficiency potentials were a part of some LF programs [see, e.g., 27].

A structured evaluation of the real energy consumption serves as a basis for energy efficiency improvements. This evaluation is necessary for LF to raise awareness and exemplify improvement measure impacts on students of the teaching modules. The conventional and nonconventional machining processes may be analyzed with the process—or equipment—with more efficient energy consumption that can be defined [28].

Several use cases focus on the identification of energy wastes—such as defective products and overproduction—whose identification process is based on the lean production philosophy [29]. This type of energy flow analysis can help ensure improved energy flows within the system [7]. Operators and factory workers can be enabled to improve their energy consumption and waste reduction process performance by building competencies on real-time asset performance optimizing tools for process parameter optimization and waste reduction. In this situation, LF found that the data from multiple sets of sensors paired with machine learning algorithms can help suggest ideal set points based on the environmental and production conditions. From these data, interactive standard operation procedures provide operators with the content and level of detail to work efficiently depending on their skill level [30].

Table 1. Classification of Existing Sustainability Use Cases for LF.

		Use Cases	Conceptual Knowledge (Why)			Professional Knowledge (What)						
			Awareness Building			Transparency				Measures		Evalu-ation
			Impact of Product Development on Sustainability	Impact of Material and Energy Consumption on Sustainability	Impact of Energy Flexibility on Sustainability	Material or Energy Wastes	Material or Energy Flows	Determination of Process Efficiency	Energy Measurements	Design of Improvement Measures	Implementation of Improvement Measures	Evaluation of the Impact on Sustainability
Product Development		-	-	-	-	-	-	-	-	-	-	-
Production	Building and Technical Building Systems	1		✓		✓	✓	✓	✓			
		2		✓		✓	✓	✓	✓			
		4		✓		✓	✓	✓	✓	✓	✓	✓
		5		✓			✓		✓	✓		
		7		✓			✓		✓	✓	✓	
		8			✓		✓	✓		✓	✓	✓
		13		✓								✓
	Production machines	1		✓		✓	✓	✓	✓			
		2		✓		✓	✓	✓	✓			
		3		✓		✓	✓	✓				
		4		✓		✓	✓	✓	✓	✓	✓	✓
		5		✓			✓		✓	✓		
		6		✓			✓		✓	✓		✓
		7			✓		✓		✓	✓	✓	
		9			✓		✓	✓		✓	✓	✓
		10		✓				✓	✓	✓		
		11		✓				✓	✓	✓		
		12		✓		✓	✓	✓		✓	✓	✓
		13		✓								✓
		14		✓			✓	✓	✓	✓	✓	✓
		15		✓			✓	✓	✓	✓	✓	✓
		16	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Product Use		-	-	-	-	-	-	-	-	-	-	-
End of Life	Collection and Sorting	-	-	-	-	-	-	-	-	-	-	-
	Reprocessing	14		✓						✓		✓

Energy flow analyses can help identify energy waste. Other use cases address energy efficiency on technical building systems and production machines using industrial scale demonstrations or through the application of model scale production processes. Model scale production processes ensure better accessibility, less space, and investment compared to industrial scale learning environments [38]—although they are less realistic settings.

Energy simulations are used in some of the use cases. These simulations can analyze production environments regarding their energy efficiency, predict energy consumption, and also evaluate identified improvement potentials through fast scenario comparisons [31]. Using prediction models, insights for energy flexibility use cases can be derived and controlled via virtual reality, simulation, and scheduling [32].

Some use cases focusing on the PLC production stage have implemented general evaluation techniques for identified improvement measures. Some use cases focus on specific evaluation tools. For example, product-specific carbon footprint analysis can be implemented as a tool to show potential greenhouse gas emissions' reductions that can be achieved across different scenarios. These tools can also help support part-specific emissions tracking [33]. In either case, the LF needs to make sure that the skills and competencies are developed for general or specific tools and how to address sustainability improvements.

3.3 Use Phase and End-of-Life

No sustainability or CE training use cases were evident for the PLC product-use stage in the LF literature. The impact of the use phase is highly dependent on the user behavior and their decision on whether or not to value environmental aspects in purchase decisions. It is also linked to product development and their responsibility to consider the environmental impact of the use phase into account when designing a product.

These design and use issues are linked to the end-of-life phase. One use case could be found in the literature that tackles the end-of-life phase in an LF. The use case focused on material collection, disposal, and reprocessing. In this example, a filament-based three-dimensional (3-D) printing process is developed for closed-loop supply by sorting, shredding, and extruding the end-of-life products and using them again as a material input. The process is complemented by a learning concept especially focusing on the evaluation of the environmental impact [27]. The lack of use cases and competency building for the end-of-life phase, especially, shows a rather important gap when seeking to develop CE capacities in workers and companies.

4. Implications and Further Research Directions

There is a number of use cases for sustainability and CE-related competencies that can be taught in LF. The majority of identified use cases address energy efficiency for production machines and equipment. There are several use case practices for the identification of both material and energy waste flows. Processing efficiency determination cases and skills building use resource management or simulation models. Cases that help to derive measures for these analyses were also evident. These measures assist practitioners in improving the production material or energy efficiency in addition to supporting the needed infrastructure.

Some use cases go one step further and teach possibilities to evaluate suggested measures on the effect of production on environmental sustainability. However, when considering the entire PLC, it was found that none or only very few use cases deal with the product development, product use, or the end-of-life phases—each one of them are important phases that require significant training and competency development. These

Table 2. Legend for Matrix and Exemplary Published Use Case Studies (Competencies and Skills Focus).

Nr.	Use Case	Studies	Nr.	Use Case	Studies
1	Energy Monitoring	Eder at al. (2020)	9	Energy flexible operation of production lines	Grosch et al. (2021)
2	Part-specific CO_2	Weyand et al. (2021)	10	Cyber–physical cooling storage station	Vogt et al. (2019)
3	Real-time waste monitoring	Yen Ting et al. (2017)	11	Energy efficiency of manufacturing	Vogt et al. (2019)
4	Energy Flow	Ketenci et al.(2022)	12	Energy efficiency of production machines	Petruschke et al. (2021)
5	Mixed reality	Juraschek et al. (2018)	13	AI-based waste reduction	Ayora et al. (2021)
6	Defining the lowest energy-intensive process	Stavropoulus (2016)	14	Recycling of plastic waste for 3-D printing	Juraschek et al. (2020)
7	Energy storage systems and renewable energy integration	Schulze et al. (2019)	15	Energy simulation	Ketenci et al. (2021)
8	Energy flexible operation of climatized rooms	Sauer et al. (2019)	16	Support holistic analysis and implementation of measures in external LF	Mangers et al. (2021)

findings lead to research, education, and industry implications.

4.1 Research Implications The product development PLC phase, considers material and energy use, selection of production technologies, and product maintenance, repair, and recycling capabilities are first determined. Therefore, product development plays a crucial role in lowering the corporate environmental and sustainability impact—especially requiring new competencies for designers.

Interestingly, no published LF use cases were identified that include the product development phase. Research is needed on the awareness raising for sustainability impact on product development and defining the related competencies needed for product developers. Subsequently, new use cases should be developed, tested, and implemented in LF to address this major and critical gap in building worker and designer capacity.

Product use with a focus on sustainability and CE in LF is virtually nonexistent. New training practices for product users, especially for high energy consumption products, are needed to incorporate and build awareness for sustainability impacts and energy-efficient operations. Incorporating the use phase in product development research is another avenue for further research and development. Product designers and developers need to account for resource efficiency and foster environmental friendly usage in their product designs.

Further research should be directed toward the end-of-life phase and competency-based use cases that tackle CE-related topics, such as sorting and reprocessing technologies. The linkage of product stewardship and dematerialization competencies in product development can aid in meeting CE and sustainability targets.

4.2 Industrial Implications The industry is a valuable stakeholder in LF. Industrial practitioners can support all pillars of sustainability—employees, such as engineers and managers, need to have knowledge, skills, and competencies to handle new regulations, rising costs, or changing customer requirements. Companies need a holistic picture of the entire PLC and not limit their consideration to their own production facility. However, a majority of companies focus on environmental aspects of in-house manufacturing—a holistic perspective needs to be ingrained further.

For the economic pillar, several lean management-based concepts are available in LF that focus on the reduction of waste and costs—concepts that positively affect the company's economic situation. However, for economic sustainability, other concepts, such as CE, should be encouraged and industry support for LFs should push this future direction. Understanding the potential for "win–win" opportunities allows managers to see that the implementation of sustainable practices can lead to economic advantages in the long term.

For that purpose, industrial companies should make more use and help support the development of corresponding teaching modules in LF. As mentioned above, initial studies show that participation in LF training results in the identification of higher improvement potentials and a corresponding reduction in energy consumption [7].

4.3 Educational Implications To successfully implement a more sustainable industry, the future generation of STEM (Science, Technology, Engineering, and Mathematics) students has to experience sustainability—LFs are valuable tools for this goal. LFs allow for an action-oriented self-learning process to help build competencies and skills. Therefore, adapted curriculums in higher education institutions and more LF teaching modules toward environmental, CE, and social sustainability are needed.

The presented use cases can be used as a starting point and inspiration for the existing LFs, who might not be familiar with the topic of sustainability yet. Additionally, standardized learning modules regarding sustainability-related topics, possibly available amongst the LF community, could help in spreading the knowledge and fostering the implementation of more sustainability use cases in LFs. But as evidenced by major gaps in a number of areas, substantially, more needs to be completed in developing a broader set of educational modules and the linkage among educational institutions, LF, industry, and government are needed.

5. Conclusion

The developed matrix shows the current status of the training modules in LFs with regard to sustainability and CE. Gaps were identified regarding all other PLC phases except for production, and further research is recommended to systematically derive needed competencies and implement use cases in these fields.

Since product development has a key influence regarding the final impact of a product and, respectively, a company, special focus is recommended on this phase. Furthermore, effort should be made to address the topic of sustainability as holistically as possible in companies, taking social, environmental, and economic aspects into account equally. LFs and their owners can support this process toward sustainability by developing tailored learning modules and sharing the content amongst the community.

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