12th Conference on Learning Factories, CLF2022

# Sustainability and Circular Economy in Learning Factories – Case Studies

Astrid Weyand [a*], Sebastian Thiede[b], Jeff Mangers[c], Peter Plapper[c], Atacan Ketenci[d], Matthias Wolf[d], Vasiliki C. Panagiotopoulou[e], Panagiotis Stavropoulos[e], Gesine Köppe[f], Thomas Gries[g], Matthias Weigold[a]

*[a]Institute for Production Management, Technology and Machine Tools (PTW), Technical University of Darmstadt, Otto-Berndt-Str. 2, 64287 Darmstadt, Germany*
*[b]Chair of Manufacturing Systems, Faculty of Engineering Technology; Department of Design, Production & Management; University of Twente, De Horst 2, Building 20, Enschede, 7522 LW, The Netherlands*
*[c]Faculty of Science, Technology and Medicine, University of Luxembourg, 6 rue Richard Coudenhove-Kalergi, L-1359 Luxembourg[c]*
*[d]Institute of Innovation and Industrial Management, Graz University of Technology, Kopernikusgasse 24/II, 8010 Graz, Austria*
*[e]Laboratory for Manufacturing Systems & Automation, Department of Mechanical Engineering and Aeronautics, University of Patras, 26504, Greece*
*[f] ITA Academy GmbH, Vaalserstraße 460, 52074 Aachen, Germany*
*[g]Institut für Textiltechnik der RWTH Aachen University, Otto-Blumenthal-Straße 1, 52074 Aachen, Germany*

**Abstract**

Since the mitigation of climate change is one of the biggest challenges to face on a global scale, the topic has become more relevant also in industrial context. Learning factories have proven to be suitable environments to address and convey competencies to tackle industrial challenges in an interactive way. Hence, several learning factories are already dealing with sustainability topics in various use cases. This paper strives to present a state of the art of sustainability and circular economy in learning factories. Therefore, a classification framework is developed based on the state of the art of several learning factories and existing literature regarding the topic. This framework is then used to systematically describe the different activities regarding sustainability and circular economy that are currently ongoing in learning factories worldwide. This can be used to get an idea about the different aspects of the topic and how to address them, but furthermore also offers assistance to identify "blind spots" which could and should be addressed in learning factories in the future.


Peer Review statement: Peer-review under responsibility of the scientific committee of the 12th Conference on Learning Factories 2022.

*Keywords:* Learning factory, Sustainability, Circular Economy, Learning outcomes

## 1. Introduction

Among many other studies, the latest report provided by the Intergovernmental Panel on Climate Change (IPCC) presents alarming statistics and numbers regarding the anthropogenic climate change [1]. Politicians and other stakeholders from countries all over the world are claiming commitments and actions to meet the goals of the Paris agreement and limit global temperature rise to 1.5 degrees [2]. This also resembles in changing regulation for companies, making it necessary to develop towards sustainability. Reducing their environmental impact through increasing efficiency, substitution to renewable sources or fostering circular economy are important elements to do so. Learning factories have proven to be effective tools for developing competencies of company employees for this sort of changing requirements and new topics. Although exact and up-to-date numbers are not available yet, based on [3] and [4] for the German region, it is assumed that less than 35% of learning factories worldwide teach topics regarding sustainability, including the important aspect of Circular Economy (CE), and

* Corresponding author. Tel.: +49 6151 8229674
*E-mail address:* a.weyand@ptw.tu-darmstadt.de

even less do explicitly research in this field. Given this low representation, the paper aims at giving a deeper insight into the current state of the art. Therefore, a joint matrix of use cases is developed as base for investigation. Furthermore, missing elements to holistically tackle these topics are identified and recommendations are derived. The analysis was carried out through the members of the working group *Sustainability and Circular Economy* in the International Association of Learning Factories (IALF).

## 2. Basics

### *2.1. Sustainability*

Sustainability as a term in its current sense has existed since about 1713, when it was used in connection with forestry. At that time, it was a question of forestry whether the forest can always regrow the resources it has consumed. [5] This principle of sustainability, to consume only as much as can grow back again to not endanger the possibility for future generations to meet their needs, is still valid today. It was stated outside of forestry in the so called “Brundtland-Report” 1987. In this report, three dimensions of sustainability were defined, namely environment, economy and equity (the last one also being framed as society). [6] Whereas the Brundtland-Commission stated this three dimensions as co-equal, other sources attribute greater importance to the environmental dimension, followed by the social dimension, stating that society and economy (as part of society) can only exist in a healthy environment. [7–9] Three core strategies of sustainability are named as efficiency, substitution or consistency and sufficiency. Efficiency hereby describes the concept of resource productivity, consistency meaning reduced environmental impact by resource substitution and adopted natural resource flows and sufficiency relating to a value shift and reduced consumption.. [10,11] Another classification of sustainability dimensions was introduced with the Sustainable Development Goals (SDGs) 2015 by the United Nations [12].

### *2.2. Circular Economy*

During the last years, the concept of CE has gained the interest of scholars [13], researchers, professionals, and politicians, as a convenient solution to move away from the linear economy concept without neglecting the goals of sustainable development [14]. CE is based on rethinking and redesigning products and services, implementing the recirculation of materials, with the aim to regenerate natural systems and reduce the generation of pollution and waste [15]. The main goals of CE can be summarized as followed, according to [16]: 1) close and slow loops, 2) minimize waste and 3) sustainability. It is thus important to consider systems holistically and better connect the end-of-life with the beginning-of-life of products. Nevertheless, the economic model behind these aspects poses a challenge due to the existing barriers between the developed theories within academy and those applied and used by practitioners [17]. The broad concept of CE (currently being standardized within ISO TC 323) with its link to sustainability makes it difficult to implement and evaluate it in the development of efficient practices [18]. To overcome this burden, circular hubs are increasingly regarded as facilitators of circularity in the industry [19], which gives learning factories an important role with regard to a successful paradigm shift. One example from a CE learning factories can be found in [20]. Otherwise, the field of interest is not very much covered in the literature, which strengthen the need for this work.

## 3. Development of classification matrix

To structure the variety of approaches with which learning factories address the topics of sustainability and circular economy, a classification matrix was developed. In this matrix, the different use cases found in learning factories are analysed in different categories and subcategories. The first category to consider are the phases of the product life cycle management (PLM) with product development, production, product use, collection and sorting as well as reprocessing [21]. Since production processes are the focus of most learning factories, this subcategory was further divided into the common subsystems building, TBS (technical building services) and production machines [22]. The next two categories are energy and material. Regarding both, the topics of efficiency and substitution play an important role when it comes to sustainability (see chapter 2.1), hence they are affiliated as subcategory. For the category energy, flexibility is added, meaning the possibility to shift energy demands in times where (more) renewable energy is available. For material, circularity is also added as subcategory (see chapter 2.2). Another category is a reduced deviation of TRL (technology readiness level) to examine the progress of the different use cases. It is divided in the subcategories proof of concept, Lab/Prototype demonstrator and available in industry. The next category learning factory (LF) use scenarios examine, in which context the analysed use cases occur in learning factories, for university education, professional training, research/development and/or consultancy/engineering. At last, also the SDGs addressed with the different use cases are noted in the matrix.

## 4. Classification of learning factory use cases

### *4.1. Approach for classification*

After the classification matrix concept was developed, the members of the working group collected use cases addressed in their respective learning factories. After the wording was aligned and the use cases were specified, it could be identified that use cases are applied in multiple learning factories in similar or equivalent ways. These use cases were then combined into one. Furthermore, research was done to identify use cases in learning factories outside of the learning factories represented in the working group, based on available published literature.

### *4.2. Results - Classification matrix*

The results of the classification process are presented in Table 1. The determined categories are on top, the use cases are numbered and mentioned on the left. A full-filled circle means that the use case tackles the topic completely, half-filled partly and an empty circle means not addressed.

Table 1. Classification matrix for the identified use cases on sustainability and CE in learning factories

| | Phases of PLM | | | | | | | Energy | | | Material | | | TRL | | | LF Use Scenario | | | | SDG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Production | | | | | | | | | | | | | | | | | | | |
| Use Case Nr. | Product development | subsystem building | subsystem TBS | subsystem production machines | Product use | collection & sorting | Reprocessing | Efficiency | Flexibility | Substitution | Efficiency | Circularity | Substitution | Proof of concept | Lab/ Prototype demonstrator | Available in industry | University Education | Professional Training | Research/ Demonstration | Consultancy/ Engineering | Number |
| 1 | ○ | ● | ● | ● | ○ | ○ | ○ | ● | ● | ● | ○ | ○ | ○ | ○ | ● | ● | ● | ● | ● | ◑ | 5, 7, 9, 12 |
| 2 | ○ | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ○ | ◑ | ○ | ◑ | ○ | ● | ○ | ● | ● | ● | ◑ | 12, 9 |
| 3 | ○ | ○ | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ○ | ● | ● | ○ | ● | ● | ● | ○ | 8, 9, 12 |
| 4 | ○ | ● | ◑ | ● | ○ | ○ | ○ | ● | ◑ | ◑ | ○ | ○ | ○ | ○ | ● | ◑ | ● | ● | ● | ● | 9,12 |
| 5 | ○ | ○ | ● | ● | ○ | ○ | ○ | ● | ○ | ○ | ○ | ○ | ○ | ● | ● | ○ | ● | ◑ | ● | ◑ | 9,12 |
| 6 | ◑ | ● | ○ | ● | ● | ● | ● | ● | ◑ | ● | ● | ○ | ● | ● | ● | ● | ◑ | ● | ● | ● | 3,7,8,9,12 |
| 7 | ● | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ○ | ● | ○ | ○ | ○ | ○ | ● | ● | ○ | ○ | ○ | 7 |
| 8 | ○ | ○ | ● | ● | ○ | ○ | ○ | ◑ | ● | ◑ | ○ | ○ | ○ | ● | ● | ◑ | ● | ◑ | ● | ◑ | 7,9,12,13 |
| 9 | ○ | ○ | ● | ● | ○ | ○ | ○ | ○ | ● | ◑ | ○ | ○ | ○ | ● | ● | ◑ | ○ | ○ | ● | ○ | 7 |
| 10 | ○ | ◑ | ● | ◑ | ○ | ○ | ○ | ○ | ● | ○ | ○ | ○ | ○ | ○ | ● | ○ | ● | ○ | ● | ○ | 7 |
| 11 | ○ | ○ | ● | ● | ○ | ○ | ○ | ○ | ● | ○ | ○ | ○ | ○ | ● | ● | ○ | ● | ○ | ● | ○ | 7 |
| 12 | ○ | ○ | ● | ● | ○ | ○ | ○ | ● | ◑ | ○ | ○ | ○ | ○ | ● | ● | ○ | ● | ○ | ● | ○ | 7,9,12,13 |
| 13 | ● | ○ | ○ | ● | ○ | ○ | ○ | ● | ● | ○ | ● | ○ | ○ | ○ | ○ | ● | ● | ○ | ● | ○ | 7 |
| 14 | ○ | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ○ | ○ | ○ | ○ | ● | ● | ● | ● | ● | ● | ◑ | 7,9,12,13 |
| 15 | ○ | ○ | ○ | ● | ○ | ○ | ○ | ● | ◑ | ◑ | ○ | ○ | ○ | ● | ○ | ○ | ● | ◑ | ○ | ○ | 9,12 |
| 16 | ○ | ◑ | ○ | ● | ○ | ○ | ● | ● | ◑ | ◑ | ● | ○ | ○ | ○ | ○ | ● | ◑ | ● | ● | ● | 7,9,12,13 |
| 17 | ◑ | ○ | ○ | ● | ○ | ◑ | ● | ◑ | ◑ | ● | ● | ○ | ○ | ● | ● | ◑ | ◑ | ● | ● | ● | 7,9,12,13 |
| 18 | ◑ | ○ | ○ | ● | ○ | ○ | ○ | ◑ | ○ | ○ | ● | ○ | ○ | ◑ | ● | ◑ | ◑ | ● | ● | ● | 7,9,12,13 |
| 19 | ○ | ○ | ○ | ● | ○ | ◑ | ● | ○ | ○ | ○ | ○ | ● | ○ | ● | ● | ○ | ● | ○ | ● | ○ | 7,9,12,13 |
| 20 | ○ | ○ | ○ | ● | ○ | ○ | ○ | ● | ○ | ◑ | ◑ | ○ | ○ | ○ | ● | ○ | ● | ● | ◑ | ○ | 12 |
| 21 | ◑ | ○ | ○ | ● | ◑ | ● | ● | ◑ | ○ | ◑ | ◑ | ● | ● | ◑ | ○ | ◑ | ● | ◑ | ◑ | ● | 9, 12 |

Legend:

| Nr. | Use Case | Nr. | Use Case |
|---|---|---|---|
| 1 | Energy Monitoring | 12 | Cyber-physical cooling storage station |
| 2 | Part-specific $CO_2$-accounting | 13 | Energy efficiency of manufacturing |
| 3 | Real-time waste monitoring on shopfloor | 14 | Energy efficiency of production machines |
| 4 | Energy flow analysis | 15 | Compressed air |
| 5 | Mixed reality for energy efficiency | 16 | AI based process parameter optimization (YET) |
| 6 | Gemba walk for waste analysis | 17 | AI based waste reduction |
| 7 | Defining the lowest energy-intensive processes | 18 | Interactive standard operating procedures |
| 8 | Energy storage systems and renewable energy integration | 19 | Recycling of plastic waste for 3D Printing |
| 9 | Energy storage in flywheels | 20 | Energy simulations |
| 10 | Energy-flexible operation of climatized rooms | 21 | Supported holistic analysis and implementation of measures in external LF |
| 11 | Energy-flexible operation of production lines | | |

### *4.3. Description of use cases*

In the following, each of the identified use cases is briefly described in a general manner. For further details of implementation, the cited references can be used. The 1st use case, identified to be the most common one regarding sustainability in learning factories, is energy monitoring. It focuses on (real time) monitoring of energy consumed, potentially including post-processing analysis and decision support capabilities. It can be a necessary part for learning factories to sensitize and show the impact of specific improvement measures. Additionally, energy monitoring itself can be core of research work, for example in case of the implementation of low-cost energy monitoring systems, described in [23]. Use case 2, the part-specific $CO_2$-accounting, is used as a tool to show savings regarding greenhouse gas emissions that are possible with several measures, but it can also demonstrate how to set up a part-specific tracking in the first place [24,25]. Another use case regarding monitoring is presented in [26], where waste of production processes is monitored in real-time and used for benchmarks on the shop floor, to automatise detection of material inefficiencies. In the use case Energy flow analysis participants learn how to identify both improvable energy flows and energy wastes. This serves as a basis for energy efficiency improvements [27]. Other examples from learning factories show that mixed reality can be interesting in context of energy efficiency of production machines or also HVAC systems (heating, ventilation, air conditioning). Mixed reality increases transparency through visualising normally invisible energy flows and efficiency potentials. [28,29] Another analysis method to identify waste in the context of sustainability and circular economy is the gemba walk. By observation of processes and guided interviews with operators and management on the shop floor, non-efficient ways of working and weak points in production (e.g. too high energy consumption) can be uncovered. Based on previously mentioned analysis methods, conventional and non-conventional machining processes can be compared, and the process with the lowest energy consumption can be defined [30]. The use case can also include an additional designing process to use the least amount of energy and material for the development and creation of a product. level.

To achieve carbon neutral manufacturing through renewable energy supply, but also to ensure a successful energy transition, energy flexibility of manufacturing process and systems is important. The is addressed in learning factories in different forming. Use case 8 is dealing with energy storage systems and renewable energy integration into manufacturing systems. This involves several storage options for different energy carriers but also appropriate technologies, methods and tools to design and control the manufacturing system as such. To demonstrate the important interaction of all elements, different setups are established. [31] A specific form of storage system is shown in the use case of energy storage in flywheels. There, the innovative concept of flywheel energy storage is combined with other types of storages such as a battery for research and education purposes [32]. To examine the energy flexibility potential of industrial indoor climate control, a modified climate room can be used. In this demonstrator, thermally active wall elements serve as cooling units as well as energy storage, a conventional air handling unit is installed as reference case [33]. Energy flexibility in production lines is also depicted in learning factories. This can be achieved for example by adapting production schedules towards energetical optimization [34] or operate the industrial energy supply systems with optimized control algorithms [35]. To facilitate the understanding of influencing factors and the derivation of improvement measure regarding heating and cooling, use case 12 is dealing with a cyber-physical cooling storage station. The developed system based on small scaled equipment allows to experience the interaction of thermodynamic processes, industrial sensors and industrial automation in order to derive more efficient solutions. [36] Energy efficiency is also pursued for manufacturing, In use case 13, the energy and material efficiency is determined via the Design for Assembly, via statistical process control and via scheduling. Energy flexibility is controlled via VR, simulation and scheduling [37]. Additionally, to manufacturing in general, use case 14 is addressing the energy efficiency measures possible on production machines, either by industrial scale demonstrators like in [38], or by the development of model scale production processes. Latter ensures better accessibility, less space and investment compared to industrial scale learning environments. [39] Compressed air is another topic covered within learning factories, showing not only methods to identify leakages or the economic influence of those, but also how to optimize the compressed air system in general. Furthermore, with a real-time asset performance optimizing tool for process parameter optimization and waste reduction, operators and factory workers can be enabled to improve their process performance regarding energy consumption and waste reduction. Data from multiple sets of sensors are paired with machine learning algorithms that suggest ideal set points based on the environmental and production conditions. [40] Most processes still require manual operation. Therefore, interactive standard operation procedures provide operators with the exact content and level of detail to work efficiently depending on their skill level. Material demand plays a crucial role towards sustainability and circularity is a key concept to address related challenges. In this context, use case 19 is dealing with the recycling of plastic waste for 3D printing. The use case consists of a modular process chain for treating end-of-life plastic products/parts in order to extrude printable filament for further use in 3d printing processes. Therewith, deeper understanding of technological opportunities but also limits can be gained. [41] Energy simulations are needed for some of the use cases already mentioned above, but due to its importance are mentioned as separate use case as well. Simulation models are used to analyse production environments regarding their energy efficiency, predict energy consumption [42] and also to evaluate identified improvement potentials through fast scenario comparisons as exemplarily described in [43]. To enable a holistic view with regard to the product life cycle and to understand the interaction between the individual product states, the last use case addresses an external learning factory. After a theoretical lecture and a practical group exercise within the topic of value stream mapping at the university, students have the possibility to deepen their gained knowledge through respective analyses at companies in the context of their bachelor- or master theses. This is done with the aim to analyse interrelated cross-company value streams, to teach aspects of circularity and sustainability throughout the complete lifecycle of products [44]. These external learning factories complement the learnings of the students with real-life industrial experiences.

### *4.4. Discussion of results*

Looking at the use cases and their respective classifications, several notable aspects occur. What is striking, though not surprising if one considers the general focus of most learning factories, is that all use cases tackle the topic of production and production machines in specific. In contrast to that, life cycle phases like product development, product use, reprocessing as well as collection & sorting are hardly addressed yet. Furthermore, most use cases deal with the topics regarding energy, specifically energy efficiency. That is also visible in the SDGs addressed, where SDG 12 (responsible consumption and production) is mentioned the most, followed by SDG 9 (Industry, Innovation and Infrastructure) and SDG 7 (affordable and clean energy). Use cases regarding material resources are hardly represented, especially not in the context of circularity or substitution. Since the life cycle perspective and the holistic view of supply chains is crucial to raise all potentials to lower the environmental impact of industry, it is a clear recommendation focusing on addressing these topics in learning factories in the future. Furthermore, the application of more use cases for consultancy as well as professional training should be aspired, to reach industry directly.

## 5. Conclusion and Outlook

The developed classification matrix marks a starting point to systematically address topics regarding sustainability and circular economy in learning factories. Showing the variety of possible use cases, it can serve as inspiration for learning factories not active in the field yet to start addressing aspects of the topics as well. Therefore, the matrix needs to be updated prospectively to include upcoming use cases or use cases not included in this version due to lack of available information. Furthermore, the tackled categories of the use cases may change due to further development, that also need to be updated in the matrix prospectively. The IALF working group might provide a suitable infrastructure to organize these update process.

## Acknowledgements

The authors like to thank the IALF for providing the network and infrastructure for the working group *sustainability and circular economy in learning factories*.

## References

[1] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2021: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report, Cambridge University Press (2021).
[2] United Nations Climate Change Conference, COP26: The Glasgow Climate Pact (2021)
[3] E. Abele, J. Metternich, M. Tisch, Learning factories: Concepts, guidelines, best-practice examples. Springer (2019).
[4] M. Sudhoff, C. Prinz, B. Kuhlenkötter, A Systematic Analysis of Learning Factories in Germany - Concepts, Production Processes, Didactics. Procedia Manufacturing 45 (2020) 114–120.
[5] H.C.v. Carlowitz, Sylvicultura Oeconomica, Oder Haußwirthliche Nachricht und Naturmäßige Anweisung Zur Wilden Baum-Zucht, Braun Verlag (1713).
[6] United Nations World Commission on Environment and Development, Our Common Future (1987).
[7] J. Robinson, Squaring the circle? Some thoughts on the idea of sustainable development, Ecological Economics 48, 4 (2004) 369–384.
[8] Office of Sustainability, What is Sustainability?, University of Maine (2021) https://umaine.edu/sustainability/what-is-sustainability/, accessed on 27.12.2021.
[9] M.S. Cato, (2012) Green economics: putting the planet and politics back into economics, Cambridge Journal of Economics 36, 5 (2012) 1033–1049.
[10] A. Grunwald, J. Kopfmüller, Nachhaltigkeit, Campus-Verlag (2006).
[11] N. Schäpke, F. Rauschmayer, (2014) Going beyond efficiency: including altruistic motives in behavioral models for sustainability transitions to address sufficiency, Sustainability: Science, Practice and Policy 10, 1 (2014) 29–44.
[12] United Nations, THE 17 GOALS | Sustainable Development (2015) https://sdgs.un.org/goals, accessed on 27.12.2021.
[13] R. Merli, M. Preziosi, A. Acampora, How do scholars approach the circular economy? A systematic literature review, Journal of Cleaner Production 178 (2018) 703–722.

[14] J. Kirchherr, D. Reike, M. Hekkert, (2017) Conceptualizing the circular economy: An analysis of 114 definitions, Resources, Conservation and Recycling 127 (2017) 221–232.
[15] Ellen Macarthur Foundation, Towards the Circular Economy: Economic and business rationale for an accelerated transition (2013).
[16] J. Mangers, M. Minoufekr, P. Plapper, S. Kolla, An Innovative Strategy Allowing a Holistic System Change towards Circular Economy within Supply-Chains. Energies 14, 14 (2021) 4375.
[17] M.V. Hernandez Marquina, P. Zwolinski, F. Mangione, Application of Value Stream Mapping tool to improve circular systems, Cleaner Engineering and Technology 5 (2021) 100270.
[18] M. Geissdoerfer, P. Savaget, N.M. Bocken, E.J. Hultink, The Circular Economy – A new sustainability paradigm?, Journal of Cleaner Production 143 (2017) 757–768.
[19] M.F. Mogos, S.S. Vildåsen, J. Sørumsbrenden, D. Powell, Rethinking Circular Business Models: The Role of the Learning Factory, in A. Dolgui et al., Advances in Production Management Systems, Artificial Intelligence for Sustainable and Resilient Production Systems. Springer International Publishing (2021) 402–410.
[20] J.A. Pascual, C. Pimentel, M. Mateo, I. Hoyuelos, J. Matias, A.M. Gento, A Learning Factory for Remanufacturing: A New Configuration at Valladolid Lean School, Proceedings of the 6th European Lean Educator Conference, Springer International Publishing (2020) 1–10.
[21] H. Cao, P. Folan, Product life cycle: the evolution of a paradigm and literature review from 1950–2009, Production Planning & Control 23, 8 (2012) 641–662.
[22] C. Herrmann, C. Schmidt, D. Kurle, S. Blume, S. Thiede (2014) Sustainability in manufacturing and factories of the future. International Journal of Precision Engineering and Manufacturing - Green Technology, 1, 4 (2012) 283–292.
[23] M. Eder, A. Ketenci, E. Auberger, M. Gotthard, C. Ramsauer, Integration of low-cost digital energy meters in learning factory assembly lines, Procedia Manufacturing 45 (2020) 202–207.
[24] J. Hagen, L. Büth, J. Haupt, F. Cerdas, C. Herrmann, Live LCA in learning factories: real time assessment of product life cycles environmental impacts, Procedia Manufacturing 45 (2020) 128–133.
[25] A. Weyand, S. Schmitt, L. Petruschke, G. Elserafi, M. Weigold, Approach for Implementing New Topics in Learning Factories – Application of Product-specific Carbon Footprint Analysis, Proceedings of the Conference on Learning Factories, SSRN Journal (2021).
[26] N.G. Yen Ting, T.A. Yee Shee, L.J. Sze Choong, Internet of Things for Real-time Waste Monitoring and Benchmarking: Waste Reduction in Manufacturing Shop Floor, Procedia CIRP 61 (2017) 382–386.
[27] D. Khripko, H. Dunkelberg, D.L. Summerbell, J. Hesselbach, Energy Efficiency and demand side management: A case study of a holistic energy concept in polymer processing, Procedia Manufacturing 21 (2018) 702–709.
[28] M. Czarski, Y.T. Ng, M. Vogt, M. Juraschek, B. Thiede, P.S. Tan, S. Thiede, C. Herrmann, A Mixed Reality application for studying the improvement of HVAC systems in learning factories, Procedia Manufacturing 45 (2020) 373–378.
[29] M. Juraschek, L. Büth, G. Posselt, C. Herrmann, Mixed Reality in Learning Factories. Procedia Manufacturing 23 (2018) 153–158.
[30] P. Stavropoulos, C. Giannoulis, A. Papacharalampopoulos, P. Foteinopoulos, G. Chryssolouris, Life Cycle Analysis: Comparison between Different Methods and Optimization Challenges, Procedia CIRP 41 (2016) 626–631.
[31] C. Schulze, S. Blume, C. Herrmann, S. Thiede, Energy Storage Technologies to foster Energy Flexibility in Learning Factories, Procedia Manufacturing 31 (2019) 330–336.
[32] P. Mouratidis, B. Schubler, S. Rinderknecht, Hybrid Energy Storage System consisting of a Flywheel and a Lithium-ion Battery for the Provision of Primary Control Reserve, 2019 8th International Conference on Renewable Energy Research and Applications (ICRERA), IEEE (2019) 94–99.
[33] A. Sauer, E. Abele, H.U. Buhl (2019) Energieflexibilität in der Deutschen Industrie: Ergebnisse aus dem Kopernikus-Projekt Synergie. Fraunhofer Verlag.
[34] B. Grosch, T. Kohne, M. Weigold, Multi-objective hybrid genetic algorithm for energy adaptive production scheduling in job shops, Procedia CIRP 98 (2021) 294–299.
[35] T. Kohne, H. Ranzau, N. Panten, M. Weigold, Comparative study of algorithms for optimized control of industrial energy supply systems, Energy Inform 3, (2020) 1.
[36] M. Vogt, B. Uhlig, K.S. Sangwan, C. Herrmann, S. Thiede, Implementation of a cyber-physical cooling storage station in a learning factory, Procedia Manufacturing 31 (2019) 142–147.
[37] G. Chryssolouris, D. Mourtzis, P. Stavropoulos, D. Mavrikios, J. Pandremenos, Knowledge Management in a Virtual Lab Collaborative Training Project: A Mini-Formula Student Car Design, in A. Bernard, S. Tichkiewitch, Methods and Tools for Effective Knowledge Life-Cycle-Management., Springer Berlin Heidelberg (2008) 435–446.
[38] L. Petruschke, G. Elserafi, B. Ioshchikhes, M. Weigold, Machine Learning Based Identification of Energy Efficiency Measures for Machine Tools Using Load Profiles and Machine Specific Meta Data, MM SJ 2021, 5 (2021) 5061–5068.
[39] A. Kaluza, M. Juraschek, B. Neef, R. Pittschelllis, G. Posselt, S. Thiede, C. Herrmann, Designing Learning Environments for Energy Efficiency through Model Scale Production Processes, Procedia CIRP 32 (2015) 41–46.
[40] R.V. Ayora, N. Praß, Grafischer Ansatz zur Energieoptimierung durch künstliche Intelligenz, in D. Trauth et al., Monetarisierung von technischen Daten, Springer Berlin Heidelberg (2021) 297–315.
[41] M. Juraschek, L. Büth, S. Thiede, C. Herrmann, 3-CYCLE—A Modular Process Chain for Recycling of Plastic Waste with Filament-Based 3D Printing for Learning Factories, in K.S. Sangwan, C. Herrmann, Enhancing Future Skills and Entrepreneurship, Springer International Publishing, (2020) 79–87.
[42] B. Dietrich, J. Walther, M. Weigold, E. Abele, Machine learning based very short-term load forecasting of machine tools, Applied Energy 276 (2020) 115440.
[43] A. Ketenci, M. Eder, M. Ritter, C. Ramsauer, Scenario-based Simulation for Energy Optimization in Learning Factory Environments, Proceedings of the Conference on Learning Factories, SSRN Journal (2021)
[44] J. Mangers, M. Minoufekr, P. Plapper, Value Stream Mapping (VSM) to Evaluate and Visualize Interrelated Process-Chains Regarding Circular Economy. in A. Dolgui et al., Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems, Springer International Publishing (2021) 534–542.