A Literature Survey of Energy Sustainability in Learning Factories

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***Abstract*—Commercial competence to satisfy customer demands requires companies to provide the necessary skilled engineering staff and fight against time to achieve that. Learning Factories (LF) aim to provide training and education so that the manufacturing facility can respond to its production aims. However, the implementation of learning factories concept is taking different styles especially with the rise of Industry 4.0. On the other hand, sustainability concerns are becoming more serious and need to be fulfilled due to the recent climate changes. In this paper, a literature survey of the recent developments in this field is conducted with regards to energy sustainability. In particular, an analysis of the pedagogical aspect in terms of the applied learning theories, curriculum design and learning environment is explored. Further, some critics based on the analysis are put forward, and some research topics are suggested in relation to both the pedagogical and technical aspects.**

***Index Terms*—Learning factory, Industry 4.0, sustainability, energy, pedagogy, training, education.**

I. Introduction

A. Learning Factory: Concept and Brief History

Learning Factory (LF) is defined as an idealised replica of value chain sections in which formal/informal learning can take place [1]. Therefore, it can be called a “Teaching Factory” [2]. To refer to a system as a Learning Factory, it should possess a real learning environment including realistic production processes [3], and this learning environment can be physical (machines, assembly, logistics etc.) or digital (planning, modelling, simulation etc.) [2].

The term “Learning Factory” appeared for the first time in the United States of America (USA) when the National Science Foundation (NSF) awarded a consortium led by Penn State University a grant to establish a “learning factory” [4]. In its course of historical development, LF witnessed three distinctive waves based on documented research literature [5]. The first one 1986-2004, the second 2004-2011 and the third from 2011 to the current time.

Although the term implies educational purposes, LF can be used for research and apprentices training like the ETA (Energy efficiency, Technology and Application centre) in Darmstadt [6]. LF is both an organisation that interacts with the inner and outer influences, and a teaching environment where people receive training on specific methods and procedures [7]. Therefore, LF’s main deliverables can be technological and/or organisational (if research focused), or developing the participant competencies (if focused on teaching and training) [4]. On the national level, LF also helps overcoming the gap between engineering graduates number and the needed number of skilled staff in industrialised countries [8].

In the automation field, Pittschellis [9] exemplifies different types of LF. The first one is the Modular Production System (MPS) which is a simplified copy of the automated production line that teaches automation principles, sensors, industrial networking etc. Another type is the process learning factory which focuses on the process optimisation rather than the technology in the domains of lean production, logistics and energy efficiency. A third type considers the gamification/competition in terms of the fulfilment of orders based on preassigned priorities.

B. Motivation

The LF concept was found before the introduction of Industry 4.0. Therefore, it is necessary to identify the progress made so far in terms of the most studied themes and the weaknesses to be overcome. Particularly, the energy research field needs further investigation as the world recently suffered significant climate changes. The conventional learning and teaching concepts are not yet modified to communicate methods of energy efficiency advancement [6]. From this perspective, teaching and learning is the first step to plant sustainability concept in the future staff. Besides, as the world witnesses a great shift in technologies, the manufacturing environments are changing and the staff training methods should be upgraded to achieve the transfer of a greater amount of knowledge proportional to the technological change. Figure 1 shows the number of publications in the LF field in general compared to the number of publications about energy in the LF context. The data are obtained from Scopus database using the keywords ‘Learning Factory’ and ‘Energy’ in April 2020. It is clear that the research in LF is growing and getting increased importance, however, energy research is not given enough attention yet. Another point is that sustainability by nature has a social dimension and education involves a psychological/social dimension which makes establishing the relation easier.

The audience this paper addresses includes: the researchers in engineering education in general and energy sustainability education in particular; management levels who supervise training and plan training strategies; higher education institutions willing to emphasise energy sustainability education in their engineering curriculum and LF researchers.

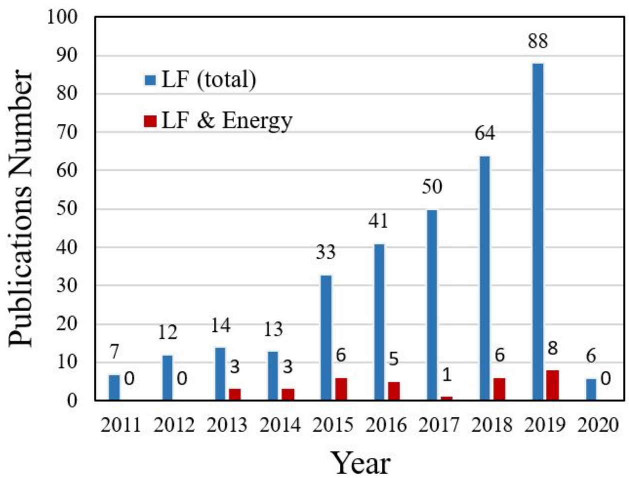

Fig. 1. LF recent publications number (source: Scopus)

C. Sustainability and Energy in LF

Promoting sustainability should take place in line with education. Integrating the Green Factories in Higher Education ascertains the students' awareness of energy and resources efficiency prior to their career start [10]. Resources efficiency is also linked to the lean management that is part of the training delivered in LF [11]. Broadly speaking, any activity/ process that do not add value is waste, and trainees should be aware of waste types [7]. This includes energy and other resource, but energy obtained from fossil fuel suffers price fluctuations and impacts the climate. Energy waste is classified under the fundamental objectives in LF [12]. Therefore, the trend is either to control the consumption or to replace it with the renewable. Solar power is one example of using renewables in LF [8], [13]. Energy in the LF context can be recognised as a unifying theme that connects science, mathematics and engineering together [14]. Transferring energy efficiency related knowledge is challenging due to the non-visibility of energy flows and the interdisciplinary knowledge it requires [12]. Consequently, LF should offer the students the chance to learn how to achieve energy transparency and efficiency [15], then how to detect energetic interdependencies in production systems, and subject them to an analysis that yields potential improvement measures [16].

It should be noted that the majority of the sustainable LFs in this study are located in Germany due to the fact that Germany phased out the nuclear power plants. Therefore, with the transition to renewable energy sustainable manufacturing becomes a must.

Fig. 2. Word cloud of the analysed literature

D. Paper Contribution and Structure

This paper analysis the current available literature concerned with energy sustainability in the LF context. The aim is to identify the aspects that were given attention and some future trends with direct relation to pedagogy and Industry 4.0.

An analysis of the most frequent words in the literature mentioned above (obtained from Scopus database) was performed in order to identify the themes that drive the energy related research in LF context. The word cloud gives and overview of this analysis (Figure 2). The size of the word's font indicates a higher frequency, thus a strong link to the major theme. It is not surprising to see the words: 'learning', 'energy', 'manufacturing', 'production', 'factory/factories' and 'system' occupying the centre and having a strong representation as they are the topic of the analysed research works. Then, it can be noticed that the words 'efficiency', 'process', 'machine', 'data', 'knowledge', 'training' come next in representation power. Therefore, themes will be constructed using the logical connections between these terms.

In the following, Section II addresses the pedagogical aspects in LF in terms of the layout, learning environment and teaching design. Section III discusses the technological aspects especially the ones related to Industry 4.0 and proposes some open research questions concluded from the analysis, then Section IV concludes the paper.

II. Pedagogy in Learning Factory

Taking another look at the word cloud in Figure 2, it can be seen that the technical aspect occupies the scene, whereas the pedagogical concepts are less represented, which reveals the need of further work on this aspect. LF relies mainly on the principals of learning-by-doing with a shorter theoretical training [7]. Nevertheless, helping the trainee gain a new competence is the heart of LF didactics. The competence can be technical, social or methodological. Thus, the teaching process has to be analysed in order to validate the current practises and establish the basis of the future ones.

A. Layout of Learning Factory

The analysed literature features many learning factories in different countries. The “Die Lernfabrik” in Braunschweig Technical University is composed of three labs: Research Lab, Experience Lab, Education Lab [8], [17]. The topics of focus are: energy & resource efficient manufacturing, urban production and Industry 4.0. Another example is The Ostfalia Learning Factory which is divided into: Lean Lab, NiFaR, Smart Production Lab, FabLab 38 and digifab [11]. So the layout differs according to the planned training. In this vein, [18] considers the learning factory as a modular product where various learning modules can be integrated in the holistic learning module-set. These modules are derived from the competences’ profile.

In terms of hardware, the ‘Smart Learning Factories’ are equipped with a great number of sensors and networked machines to generate big data and make use of it [14]. For the software, [19] envisions a LF learning environment that corresponds to a continuous improvement approach. This environment is equipped with software tools for data acquisition and visualisation of multiple parameters and indicators. It should be noted that LF is not limited to automation applications but can include manual workstations according to [20] where an energy saving potential up to 65% is reported.

B. Learning Environment

Developing learning environments for energy efficiency is a challenging task. Therefore, the designer of the learning environment is an energy efficiency expert engineer [12]. Learning environments are classified into four types based on the intended purpose [12]:

- Fascination: aims at dragging attention with an easy to understand content that is focused on a single aspect and triggers a wow effect.
- Sensitisation: sheds the light on an important issue, and the wow effect is attributed to the content.
- Analysation: aims to develop a deeper understanding of the content by testing some parts of the training course.
- Transformation: relies on putting the course content into action and industrial practice.

Regarding the architecture of the learning environment, a multi-level architecture is introduced in [15]. The levels are hardware level, communication level and service level. On the hardware level, a modular production system provided with data acquisition system and energy meters is installed to enable energy transparency. Such an architecture is a mini scale of the Digital Factory one. A similar architecture with the digital technologies is utilised in [14] where production operation energy consumption data can be collected using real-time data collection system (Andon). A methodology of building the content and physical structure of the learning environment is provided in [18]. To deepen the trainees understanding, a method called LEGO® SERIOUS PLAY® is deployed where trainees build metaphorical representations of the studied concepts.

In these digital learning environments, there is a possibility to plug different tools/functions in the IT hardware/software infrastructure. “Google Alerts” tool is used to simulate global monitoring activities in [21]. A digital research diary was developed in [22] to organise student’s work systematically, promote self-awareness and make the the student’s work transparent to the teaching staff. The digital tool ETA-Wiki (energy efficiency wiki platform) is developed in [6]. ETA-Wiki is accessible through mobile terminals and provides a digital handbook that learners can access whether they are at workshops or at home.

C. Learning Theories

After surveying the literature, Table I summarises the learning theories and styles applied in LF.

TABLE I
TABLE I: LEARNING THEORIES IN SUSTAINABLE LF

Learning Theory	**Ref.**
Life long learning	[6]
Learning by doing	[7], [9]
The constructivistic learning theory	[9]
Constructivist didactics	[11]
Action-oriented learning	[12], [18]
Game-based learning and simulation games	[16]
Problem-oriented interaction, reflexive self-education	[18]
Energy-bingo	[23]
The “playful” approach	[24]
Research-based learning	[17], [25] [22]
Dale’s cone of experience (Figure 3)	[23]
Hands-on and try-out approach	[26]

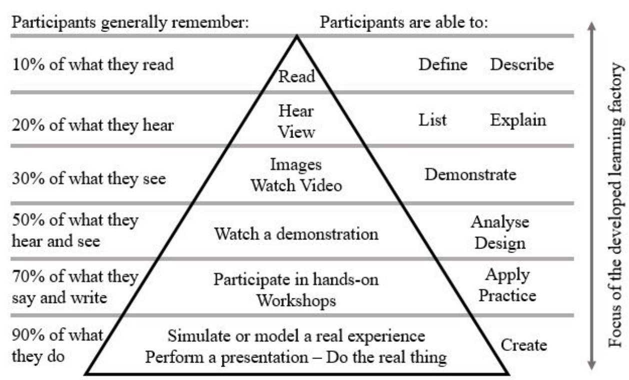

Fig. 3. Dale’s cone of experience [23], [27]

It can be noticed that there is a clear focus on research-based learning, and this is justified in [22] where it is attributed to Humbdolt’s vision who believes that university is a research institution whose mission is to pass knowledge and discuss it critically.

D. Teaching Objectives

As LF has a competences' profile to fulfil in terms of providing training and necessary knowledge, the surveyed literature provides different teaching objectives. These objectives affect the following curriculum design that is a structured based on the objectives and the layout & learning environment. However, the learning environment/layout can be modified to suit certain teaching intended objectives. The objectives are classified as follows:

- Trainee related objectives: continuous motivation and effective contextualization of the actual work environment [6]; creating the motivation required to engage people in energy efficiency [12].
- Energy quantification objectives: energy flows and energy measurement, energy transparency and digitalisation benefits to energy transparency [15].
- Operational objectives: teaching the concept of agility in terms of its processes and structure (integrated with energy) [21]; operation analysis to address energy efficiency [17]. It should be noted that the operational objectives serve as energy/resources sustainability enabler.
- Sustainability/Energy awareness: the awareness of energy waste in manufacturing [23]; enabling the trainees of recognising the energy efficiency potentials of various transportation technologies (e.g. automated guided vehicles, conveyor belt) [26]; developing consciousness of energy and material consumption, and training the trainees on increasing resources efficiency in both the product and production facility [20]; lean management for material efficient production [11]; sensitising trainees for the achievable energy and resources efficiency with focus on logistics and facilities [18].
- Optimisation related objectives: to impart optimisation measures [12]; design and optimisation of resource-efficient production processes, the optimisation of effort-benefit ratio [28].

E. Curriculum content

In harmony with the objectives and the available teaching/training resources, the curriculum is designed. The curricula included in the revised literature are reflections of the objectives classified in the previous paragraph. Table II summarises the major topics with their objectives themes.

It is quite logical to see the theme of energy quantification dominating due to that all the industrial practices can be utilised to achieve reduced energy consumption by making use of all the human and technological resources. In continuation to this, once the quantitative aspects are assigned, it becomes possible to move to the optimisation phase. On the other hand, there is a clear absence of the topics related to the trainee which should be given more attention.

Another important point is the variety of the disciplines in the courses in addition to the fact that the deliverers should possess significant experience in order to qualify the trainees to gain the required competences.

TABLE II
TABLE II: MULTIPLE CURRICULA CONTENTS AND THEIR THEMATIC OBJECTIVES

Ref.	Objectives theme	Major topics
[28]	Energy Quantification Operational Objectives	Measures of process improvement, sensors and their connectivity, norms (e.g. DIN ISO 50001) and Key Performance Indicators (KPI), effort-benefit ratio
[17]	Energy Quantification Operational Objectives	KPIs and energy efficiency of cooling process
[24]	Awareness Energy Quantification	KPIs, Lean management and industrial engineering, the 5S method and value streams
[21]	Operational Objectives	Agility and risk assessment
[15]	Energy Quantification	Energy transparency
[14]	Energy Quantification Optimisation	Energy & sustainability module with the topics: Energy monitoring, management and optimisation, energy IoT and renewables.
[22]	Energy Quantification Operational Objectives	Energy efficiency in production engineering
[26]	Energy Quantification Awareness Operational Objectives	Energy storage technologies, demand side management, energy flexibility assessment strategies.
[26]	Energy Quantification Operational Objectives	Automatic Guided Vehicles (AGVs) ecological and economic benefits
[11]	Awareness Operational Objectives	The reality of the manufacturing industry practices, resources efficiency

F. Assessment methods

Assessment has two directions: the learner/trainee assessment of the course and the assessment of the trainee/learner by the end of the course.

Regarding the first direction, learners' feedback was recorded in [23] after experiencing an actual use case and testing their ability to acquire the component energy consumption. Furthermore, some peer-feedback took place in the form of the discussion about energy consumption optimisation and the best approaches to achieve that. Evaluation results of the training are shown in [15]. In this evaluation, the trainees express their satisfaction on a scale 1-5. Similarly, [11] states that participants experience was positive. In [18], the participant rated the teaching methods/tools on a grade 1-6 with 1 being very good and 6 being very bad. Then, two month after finishing the training, the trainees emphasised the positive impact of learning factory event. Additionally, external observers evaluated the training usefulness. The motivation importance is stressed in [18] (following to the training), and [22] notices the students' increased motivation accompanied with improved examination results compared to the last semesters.
However, it is not clear how the satisfaction is linked to the curriculum training goals. Additionally, the feedback of the companies that hired the trainees is indicated only in [18].

For the second direction, [18] defines the delta analysis where the training effectiveness is evaluated by comparing the targets defined before the training and the achieved transfer after it. Students have to complete courses and energy challenges to gain Energy Systems Credentials in [14]. A paper-based self evaluation of participants, and evaluation of the social and methodological competences is conducted in [18]. To automate this partially, [16] suggests having an intelligent learning management system capable of evaluating individual learning processes to allow (semi-) automated controlled learning processes.

III. Discussion and Suggestions

The pedagogical aspects were analysed in the previous section. This section is dedicated for some technological aspects in LF taking into account the recent changes due to the rise of Industry 4.0.

A. Adaptation of Industry 4.0

Simulation was used as a part of the learning environment in many reviewed studied. Without previous training, teams composed of two members assemble cars in several rounds of simulation" in [24]. Discrete event simulation environment is provided in [26] so that multiple scenarios can be tested in order to evaluate different efficiency measures and choose the more resources efficient one. Also, scenario-based simulations are introduced in [29]. In [18], participants showed good satisfaction with simulation as a knowledge transfer method.

Also for Virtual Reality (VR), [6] puts forward the use of a VR application to assist the trainees. Also, [14] proposes a framework of the Smart Learning Factory in which Augmented/Virtual reality technologies are planned to be into action.

Industry 4.0 constitutes a challenge to companies in terms of human resources development [15]. Further, [15] shows caution about digitalisation as the learners become more attracted to the software interface, and degrade their competency of method-based acting, applied measurement and analysis questioning. However, there is a great potential of increasing sustainability. Once the infrastructure of Industry 4.0 and its enablers is established, this infrastructure can be shared with the education/training institutions. The following step is the design of sustainability requirements plan in general and energy sustainability in particular. The concepts of energy and resources efficiency in LF are still shallow, and have not been applied in a digitalised production system so far [15]. The authors suggest a framework of harmonising the education/training process with Industry 4.0 technologies to support Energy Life Cycle (ELC) in the manufacturing facility (Figure 4). ELC includes energy generation/conversion on-site, utilisation in production/manufacturing and building services, monitoring for the purposes of modelling, standardisation and finally multi-level optimisation. These ELC stages should establish the basis of analysis. Then, the pedagogical and technical aspects are tailored based on the required competences. The abundant data collected with Internet of

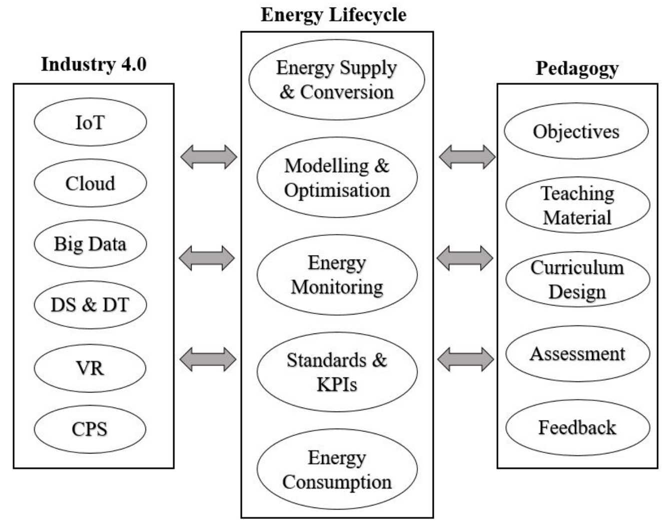

Fig. 4. A framework of energy sustainability education in LF

Things (IoT) can be stored in the Cloud. Next, processing the Big Data allows creating the Digital Twin (DT) and Digital Shadow (DT). Thus, it becomes visible to visualise the performance in VR and build the Cyber-Physical System (CPS).

Data availability is not limited to the equipment, the trainee's performance can be recorded, analysed and modelled as well. The aforementioned tools serve this purpose, this way, the training time can be estimated and the cost of training courses can be predicted while, on the pedagogy side, objectives can be more precise, learning environment more flexible and assessment more authentic.

B. Scalability of Industrial Processes

In [19] learning environments are classified into: model scale and industrial scale, then their pros and cons are presented. One reason for scaling the industrial processes is to ensure that the students can work self-guided safely [8]. However, this raises the questions " What is the degree of scalability to be considered in designing sustainable LF?" and "How can the modelling/simulation capabilities affect the scalability measures or replace scaled equipment/processes?".

C. Sustainable LF as an Exchangeable Model

The suggested LF models should be exchangeable at the national strategic planning levels. Examples of the information to be contained in this model can be: the relation between the level of automation, the contribution of renewable energy and the staff trained to develop equipment to be more sustainable. The scalability of this model should also be tested and verified. As sustainability is a general demand, sustainable industrial models should be exchangeable even if commercialised.

D. Leadership and Change Management

Social and personal competences such as leadership skills are getting more importance in the light of recent changes towards smart manufacturing and Industry 4.0 [18]. According to [26], employees from different hierarchy levels take the training in LF. Therefore, it can be concluded that some of the trainees have proven leadership which in turn can be invested in triggering more sustainable polices/practices. Moreover, special training/courses should be designed to those in the position of decision making. 'Sustainable leadership' is briefly mentioned in [24], however, it should include the shift to sustainable technologies/strategies especially with the Industry 4.0 revolution.

E. Evaluating the Learning Theories' Impact

The learning theories applied in sustainable LF were discussed earlier. However, it was not possible to measure the impact of those learning theories/practices. Although some researches investigated the learners impression, more methodological approached should be followed by using statistical techniques and design of experiment principles.

IV. Conclusion

The current work introduced an analysis of learning factories that focus on sustainability in general and energy in particular. The analysis touches on the technological aspect in terms of Industry 4.0 digitalisation revolution, and concentrates on the pedagogical consideration such as learning theories, learning environment and curriculum design. The authors provide a framework that shows the synergy between the technological and pedagogical aspects of modern LF. This framework constitutes the basis of various future research directions. Furthermore, some futuristic research proposal were put forward to improve the current status of sustainable learning factories.

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