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An inclusive overview of Learning Factories around the globe

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Abstract

The continuous and rapid technological advances in manufacturing brought forward by the Fourth Industrial Revolution have created the demand for a new set of specialized skills from engineers entering the workforce. Built upon the paradigm of integrating research, innovation, and education, Learning Factories (LFs) offer promising prospects in meeting this demand by providing realistic industrial production environments for the training of the new workforce. Following several cases of successful implementation in Europe, in the last years LFs are being established at an increased rate all over the world. However, due to the prominence of European LFs, the bulk of the academic literature is focused on a reduced number of institutions, while the contributions associated to newer LFs located outside Europe have a lesser presence. The present work aims to provide a comprehensive overview and discussion of LFs through analyses wider in scope with the purpose of gaining insights into the current state of LFs around the globe, the impact of Industry 4.0 on their development, and the critical factors for their successful implementation.

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1. Introduction

The term Industry 4.0, given in reference to the Fourth Industrial Revolution, was introduced by the German government back in 2011 to describe their vision for the future of industrial production driven primarily by the advanced digitalization of factories and Internet Technologies [1, 2]. In the last years a number of publications refer to technologies such as Internet of Things (IoT), Cyber-Physical Systems (CPS), Big Data (BD), Cloud Computing (CC), Additive Manufacturing (AM), Augmented and Virtual Reality (AR/VR), Cyber Security (CS), Artificial Intelligence (AI), Simulation, and Autonomous Robots as key for the materialization of Industry 4.0 [3]–[8]. The individual application of some of these technologies is not a novel concept, as they have been researched and documented for a much longer time prior to the advent of the Fourth Industrial Revolution. Industry 4.0, in contrast, is based on the simultaneous implementation of multiple key enabling technologies onto production systems [3]. In particular, CPS are considered to be the foundation of Industry 4.0, as they enable the transmission and analysis of real time data across a value chain through the integration of computational and physical entities.

As a response to the new global demands coming from the manufacturing sector due to changes brought forward by Industry 4.0, engineering education has become an important driver for the progress of the sector [9]. However, learning and teaching approaches have not developed at the same speed as technological advancements, and the traditional engineering curriculum risks to be inadequate for creating professionals with a strong multidisciplinary background and competences that meet the demands from industry. Within this frame of reference, several so-called "Learning Spaces" are being implemented in higher education institutions with the purpose of providing students a more practical training beyond the classroom. These spaces include Fabrication

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Labs or Fab Labs, Makerspaces, Learning or Teaching Factories, among others [10, 11]. In particular, the concept of Learning Factory (LF) originates as a new approach to develop tools to recreate problems found in real industrial environments, which are then addressed in an academic setting and result in the acquisition of competences [11]. LFs are replicas of multiple phases of the value chain with a high degree of realism, grounded on a didactical concept with emphasis on active learning [12]. Although the historical development of LFs goes back to the 80s, they have gained more prominence in the current context and can be considered the response of academic institutions to the challenges posed by the Fourth Industrial Revolution. In the last decade, several LFs have emerged in Europe and gained recognition from academia as well as the industry. In fact, it is through the collaboration with industrial partners that LFs have managed to build their success, as they have become hubs for the concentration and transfer of knowledge, research, and practice between academia and the industry. This is the case of the I4.0 Lab of the Politecnico di Milano, whose activities and research have inspired the present work [13].

The paper intends to provide an overview of the evolution and current state of literature surrounding the topic of LFs, to understand the impact of Industry 4.0 on their development, and to identify preliminary critical factors on their implementation. The work is, therefore, structured as follows: the research objective and methodology are outlined in section 2, while section 3 discusses the results obtained from the analyses. The last section covers the conclusion and suggestions for potential lines of research.

2. Research Objective and Methodology

The objective of the research is to identify and synthetize the existing knowledge and research on the topic of LFs by conducting a critical analysis of the extant literature and the academic community behind its production. Accordingly, the analysis is structured into two phases: first, a systematic literature review of works related to the topic of LFs, followed by a qualitative analysis of individual LFs located in several locations around the world.

2.1. Systematic Literature Review (Bibliometric Analysis)

The scope of the literature review encompasses the research activities carried out by the LFs community, the geographical origins of academic literature and its impact, as well as international and inter-institutional collaborations. Based on this, the chosen method for the analysis is bibliometrics using VOSviewer, which is a software tool that can be used to generate network maps based on bibliographic data [14]. The database used for the retrieval of articles is Scopus, chosen for its rich metadata. The relevant literature was retrieved using the keywords “learning factory” or “teaching factory”. After a number of articles were excluded on the basis of relevance and retrievability, a total of **565 articles** were included in the bibliometric analysis.

2.2. Learning Factories Analysis (Quantitative and Qualitative Analysis)

The available literature is filtered a second time. The articles of interest for this phase are only primary sources that describe either: i) the process of creation, development or implementation of a LF, or ii) projects executed within a LF that include a description of its relevant technical aspects. Furthermore, an additional literature search was conducted using the Google search engine with the purpose of retrieving sources with additional information about the identified LFs. The results were 15 additional sources (including publications not indexed in Scopus and university theses), and 56 LFs websites. As a result of examining these sources, a total of **61 LFs** were identified and included in the second phase of the analysis. This new data set is organized following a number of variables based on the state-of-the-art morphological model for the categorization and description of LFs [15], which includes attributes such as location, date of establishment, purpose, scale, and product lifecycle phases recreated; and other variables considered to be relevant for the scope of this work such as Industry 4.0 technologies in the shop floor and research topics addressed.

3. Results and Discussion

3.1. Bibliometric Analysis

Fig. 1 shows the evolution in number of authors, articles, and countries between 1995 and 2020, which is the period covered by the articles included in the dataset. With the exception of the relative plateau in 2020, which could be attributed to the temporary closure of facilities at the global scale due to the onset of the COVID-19 pandemic, the significant rise in the number of authors and countries from 2015 onwards is indicative of an increasing interest in the topic, in line with the diffusion of the “Industry 4.0” concept throughout Europe and the rest of the world after its introduction. It could also suggest a higher degree of networking between authors and institutions from different countries. In order to visualize the latter in detail, an international network diagram (Fig. 2) and a co-authorship network diagram (Fig. 3) are generated using VOSviewer.

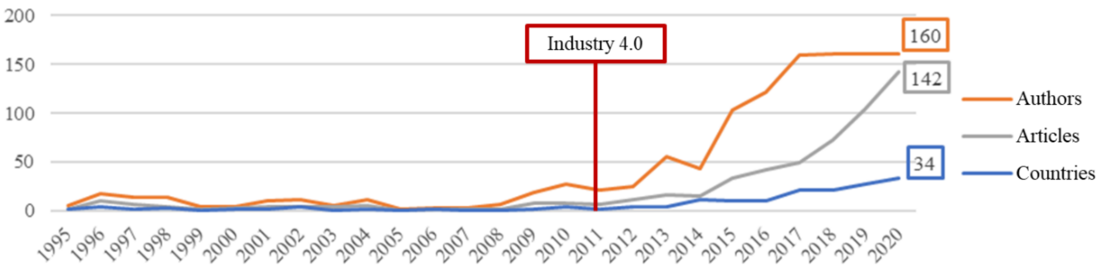

Fig. 1. Summary of research works published between the years 1995-2020.

The main bulk of research activities is conducted primarily by German authors and institutions, adding up to almost 50% of the articles included in this analysis with 244 publications. While a significant portion of these publications are authored exclusively by German academics, Fig. 2 shows that they also include collaborations between institutions from Germany, United States, Austria, Indonesia, Canada, South Africa, Greece, Italy, and others. Nonetheless, research activities -albeit localized- also take place outside of this main cluster in countries such as South Korea, Japan, Croatia, Finland, Australia and Poland.

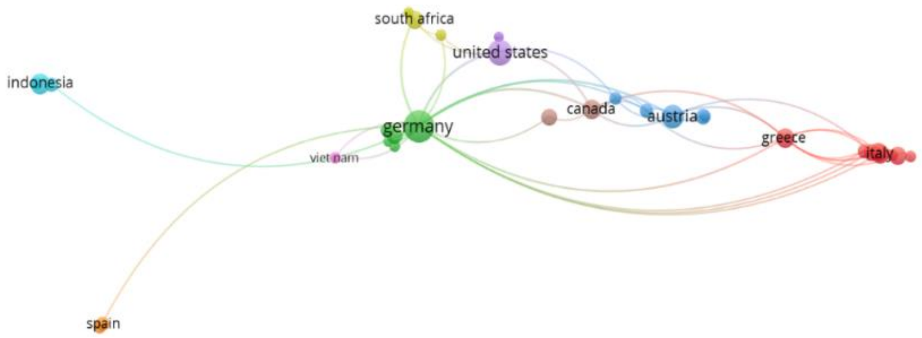

Fig. 2. International network diagram between the years 1995-2020 (countries with at least 1 publication).

Fig. 3 shows the co-authorship network diagram generated from the articles analyzed. The large cluster shown corresponds to collaborations primarily between German institutions and authors, and represent 25% of the total identified authors. However, while the metadata indicates that the sub-clusters inside have remained constant throughout the last 10 years, the number of authors entering the large cluster has steadily increased during the same period. These figures suggest the existence of a network with a relatively limited reach, especially outside Europe, that is, nonetheless, gradually expanding.

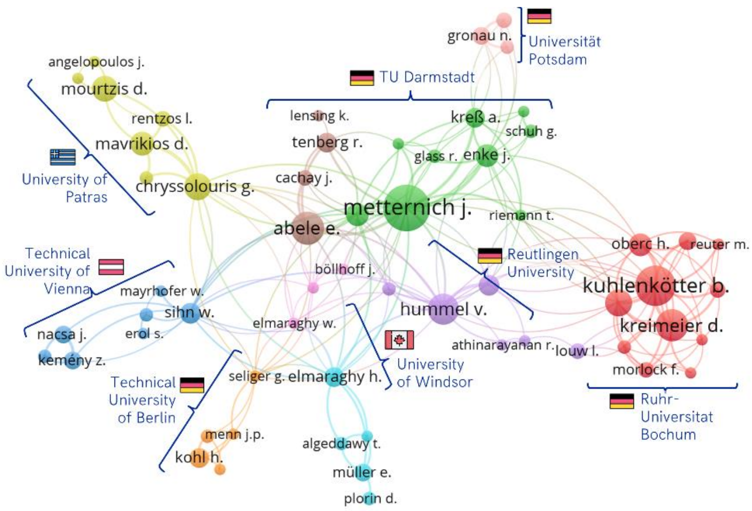

Fig. 3. Co-authorship network diagram between the years 1995-2020 (authors with at least 3 publications).

3.2. Quantitative and Qualitative Analysis

Fig. 4 summarizes the locations and establishment years of the 61 LFs included in the analysis. German LFs represent a third of the total dataset, evidencing once again their well-established presence in the LFs community and their will to communicate it to an academic and industrial audience. The considerable increase in the establishment of LFs from 2010 onwards is in line with the observations made in section 3.1. Almost 75% of the LFs included in the analysis were built in the last ten years. The majority of these facilities were built with the purpose of enhancing students' learning experience and conducting research activities. Furthermore, despite the capital expenditure involved in the creation of LFs using authentic industrial equipment, a considerable number are built as actual size representations of production environments.

Location	No.	Location	No.	Location	No.	Location	No.
Germany	21	Brazil	2	Bosnia & Herzegovina	1	Malaysia	1
Austria	3	Colombia	2			Netherlands	1
Canada	3	Denmark	2	China	1	Norway	1
Finland	3	Hungary	2	Croatia	1	Spain	1
Italy	3	Singapore	2	Greece	1	Sweden	1
USA	3	South Africa	2	India	1	Switzerland	1
				Luxembourg	1	Multiple	1
						Grand Total	**61**

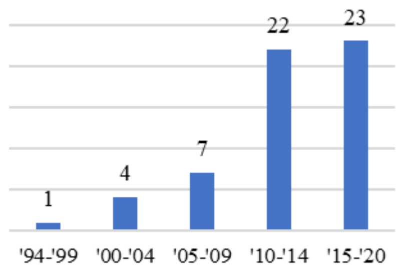

Fig. 4. Location and year of establishment of learning factories included in the analysis.

For what concerns value chains recreated in LFs, there is a clear separation between the product development and production stages: more than 80% of LFs replicate a value chain consisting of manufacturing and assembly. Furthermore, a reduced number of LFs involve stages such as planning or prototyping, while only about 20% integrate simultaneously product development and production stages within their facilities. This could be attributed to the fact that replicating a production environment requires the definition of a specific product, which could limit the effectiveness of the activities related to the product development stage.

Fig. 5 shows the main topics included in the research and educational agenda of the LFs. Lean production is approached in conjunction with Industry 4.0 by German LFs in what is referred to as "Lean 4.0" [16]. Also, in Germany, Denmark and Italy, LFs are serving as Industry 4.0 demonstration mediums for SMEs interested in its implementation. These initiatives are receiving direct support from their respective national governments. Topics such as shop floor management and process planning and control are entirely addressed in an Industry 4.0 context.

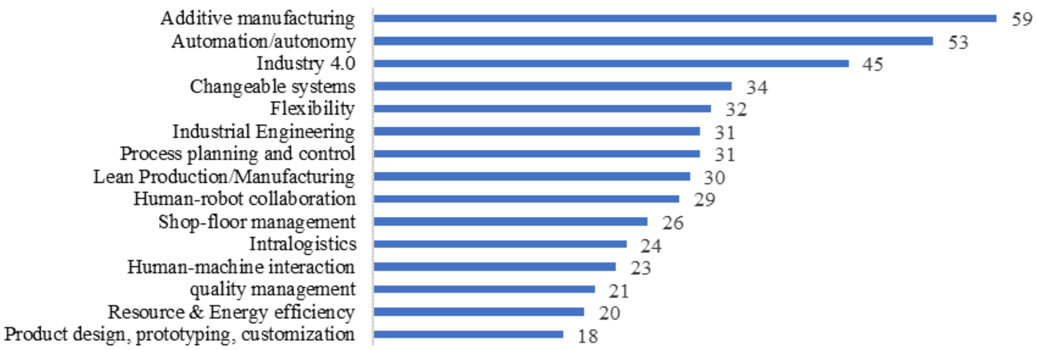

Fig. 5. Topics present in the research and teaching agenda of analyzed LFs.

Fig. 6 shows a glimpse into the physical implementation of technologies associated to Industry 4.0. Digital displays and autonomous robots have become commonplace on multiple shop floors. Displays are used as interfaces between the human and the machine, often implemented on consumer mobile devices using self-developed applications. A number of LFs develop their own tracking systems or use solutions intended for the industry. Assistance systems in the shop floor take the form of pick-by-voice and pick-by-light solutions integrated to intralogistics process. As per simulation systems, smart factories can be simulated as digital twins in 3D for virtual commissioning including not only a 3D CAD (Computer Aided Design) representation of the line but also the behavior of the line. AR/VR systems are often implemented in the assembly line and manual rework place using mixed reality on smart glasses. Also, they can be used for the explicit purpose of supporting learning [17].

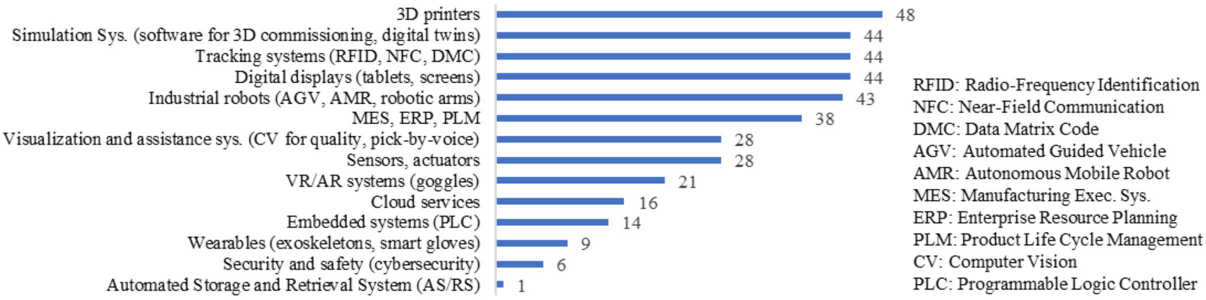

Fig. 6. Technologies associated to Industry 4.0 implemented in the shopfloor of analyzed LFs.

Industry 4.0 has fundamentally changed the manufacturing industry, and this is true for LFs as well. The LFs analysis shows that key associated technologies are implemented almost unanimously by these facilities, and that their operators are developing engineering curricula aimed to navigate these technologies hands-on while creating value based on digitalization. Literature covering the development of CPS in LFs is abundant in the analyzed data set ("Simulation Systems" in Fig. 6). Publications from newer institutions include the structured development of CPS from scratch, while the research topics and contents included in publications from more established institutions point towards the presence of an underlying interconnected environment enabling their research and teaching activities. The main objective of LFs is to bridge the gap between the industry and universities and, given that companies are welcoming Industry 4.0 solutions into their organization, it is only natural that CPS are becoming the new standard for LFs.

Beyond the characterization of LFs in terms of technical features, the articles analyzed also provided an insight into the development of LFs. Publications concerning their planning and design are able to relate the critical factors that facilitated the establishment and success of these LFs. While the specific context in which a LF is built is influenced by several internal and external factors (academic, industrial, geographical, political, economic, etc.), it is possible to identify four main factors that can be identified as determinants for a successful implementation:

- The economic support of the government in the form of funds to ensure that the LF is able to expand its technology to keep up with an ever-changing environment. In contexts where such incentives are not granted the support must be sought externally [18].
- A wide network of corporate partnerships that facilitates the procurement of hardware and software required to accurately recreate a value chain in the LF. The optimal partnership is one where the LF can give back to the corporate partners in the form of knowledge, research, and a place where new concepts can be tested. These partnerships become especially crucial for institutions that lack the funds to build a LF by themselves[12].
- An academic network for the exchange of ideas and concepts is key for newer LFs, as it grants access to the expertise of initiators already operating their own facilities. The collaboration between LFs has proven to be successful as evidenced by the implementation of LFs outside Europe [19]. This also benefits the network as a whole as the unique configuration of each LF will result in the production of unique contributions [20].
- A valuable knowledge output from students and researchers within the LF ensures its continuous development through the execution of research and projects. This requires the participation of students that are highly motivated, technology literate, aware of the importance of industry 4.0, and eager to become a driver for the development and adoption of new technologies within their institution [21].

4. Conclusions and Future Work

Through the analysis it was possible to obtain an overview of the current status of LFs around the globe, to understand the impact of Industry 4.0 technologies and to define the critical factors for their implementation. The analysis also shows the emergence of a new phase in the historical development of LFs, in which wider audiences are becoming involved in the LFs community and, as a result, the collaboration network is expected to widen as well. The transition to this phase has already started at a progressive pace, since the construction of newer LFs attracts the interest from the regional industry and governments, which ultimately results in investments and funding directed towards the creation of such facilities. As an overview of LFs with a scope wider than existing publications, the present work uncovered three points upon which future research efforts can be directed:

- A comparative analysis between LFs and other Learning Spaces. Given the prominence and success of the LF model, the absence of many other renowned engineering institutions in the list of analyzed facilities suggests the adoption of alternative Learning Spaces for the purposes of education, training and research. The literature exploring LFs and other Learning Spaces in parallel is scarce.

- An update to the state- of- the- art Morphological model for the categorization of LFs. Given the increasing adoption of Industry 4.0 technologies, the model would benefit from an update aimed to keep up with changes in the industry.
- The creation of an online database of LFs. During the process of collecting data for this work, it was observed that data related to existing Learning Industries is scattered and sometimes irretrievable. In order to foster collaboration in the network the first task should be to organize in one place the relevant data about all the institutions involved in the field of LFs beyond the known networks such as IALF and the CLF.

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