G Model
CIRP-1702; No. of Pages 24

ARTICLE IN PRESS

CIRP Annals - Manufacturing Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Learning factories for future oriented research and education in manufacturing

Eberhard Abele (1)[a,*], George Chryssolouris (1)[b], Wilfried Sihn (1)[c], Joachim Metternich[a], Hoda ElMaraghy (1)[d], Günther Seliger (1)[e], Gunilla Sivard[f], Waguih ElMaraghy (1)[d], Vera Hummel[g], Michael Tisch[a], Stefan Seifermann[a]

[a] *Institute of Production Management, Technology and Machine Tools (PTW), TU Darmstadt, Germany*
[b] *Laboratory for Manufacturing Systems and Automation (LMS), University of Patras, Greece*
[c] *Institute of Management Science (IMW), Vienna University of Technology, Austria*
[d] *Intelligent Manufacturing Systems (IMS) Centre, University of Windsor, Canada*
[e] *Department of Machine Tools and Factory Management (IWF), TU Berlin, Germany*
[f] *Department of Production Engineering, KTH Royal Institute of Technology, Stockholm, Sweden*
[g] *ESB Business School Reutlingen, Germany*

ARTICLE INFO

Keywords:
Learning factory
Education
Training
Manufacturing research
Competence development

ABSTRACT

Learning factories present a promising environment for education, training and research, especially in manufacturing related areas which are a main driver for wealth creation in any nation. While numerous learning factories have been built in industry and academia in the last decades, a comprehensive scientific overview of the topic is still missing. This paper intends to close this gap by establishing the state of the art of learning factories. The motivations, historic background, and the didactic foundations of learning factories are outlined. Definitions of the term learning factory and the corresponding morphological model are provided. An overview of existing learning factory approaches in industry and academia is provided, showing the broad range of different applications and varying contents. The state of the art of learning factories curricula design and their use to enhance learning and research as well as potentials and limitations are presented. Conclusions and an outlook on further research priorities are offered.

1. Introduction

1.1. Motivation

Manufacturing remains a key wealth generating activity for any nation. In Europe alone, manufacturing accounts for more than 21% of the Gross Domestic Product (GDP) [157]. In order to reflect this importance, the promotion of manufacturing excellence will be a strategic target in the years to come.

Manufacturing itself faces rapid advances in production related technologies, tools and techniques. Thus, manufacturing enters a new era, where blue-collar workers and engineers will need novel life-long learning schemes to keep up with these advances. Manufacturing education is regarded as a major driver to build the required new generations of 'knowledge employees' in manufacturing [168] (Fig. 1).

However, manufacturing teaching and training have neither kept pace with the advances in manufacturing technology, nor with the demands from the labor market. The current practice is deficient in providing manufacturing employees with a continuous delivery of engineering competencies and a strong multi-disciplinary educational and training background. In fact, traditional teaching methods show limited effectiveness in developing employees' and students' competencies for current and future manufacturing environments [58]. In addition, the lack of soft skills has been widely recognized by employers [289].

To effectively address the emerging challenges in manufacturing education and skill demands, the educational paradigm in manufacturing needs to be revised. Modern concepts of training, industrial learning and knowledge transfer schemes are required that can contribute to improving the performance of manufacturing [12,65,168]. These new concepts need to take into account that: (a) manufacturing as a subject cannot be treated efficiently in a classroom alone [65,158,246], and (b) industry can only evolve through the adoption and implementation of new research results in industrial operation [246].

Fig. 1. Changing competence profiles in manufacturing.

* Corresponding author.

http://dx.doi.org/10.1016/j.cirp.2017.05.005
0007-8506/© 2017 Published by Elsevier Ltd on behalf of CIRP.

Please cite this article in press as: Abele E, et al. Learning factories for future oriented research and education in manufacturing. CIRP Annals - Manufacturing Technology (2017), http://dx.doi.org/10.1016/j.cirp.2017.05.005

More specifically, new learning approaches are needed to:

- allow training in realistic manufacturing environments,
- modernize the learning process and bring it closer to the industrial practice,
- leverage industrial practice through the adoption of new manufacturing knowledge and technology, and
- increase innovation in manufacturing by improving capabilities of young engineers, e.g. problem solving, creativity and systems thinking capabilities. Talent based innovation is identified as the number one driver for manufacturing competitiveness [81].

Collaboration between academia and industry is crucial. Producing knowledge through research, diffusing knowledge through education as well as using and applying knowledge through innovation (the "knowledge triangle") is the appropriate approach [72]. Universities and industrial training facilities are confronted with the challenge to identify future job profiles and correlated competence requirements, and they have to adapt and enhance their education concepts and methods. Especially, innovative learning environments must be able to react to the mentioned challenges in an interdisciplinary manner. In the last years, learning factories as close-to-industry environments for education and research have proven to be an effective concept addressing these challenges (Fig. 2).

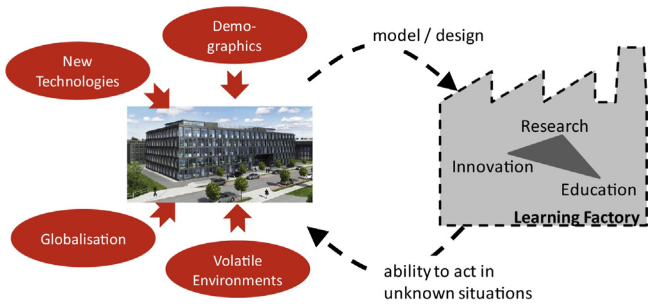

Fig. 2. The learning factory as a model of a real factory—incorporating the three poles of the "knowledge triangle" [11].

1.2. Historic background

In 1994, the National Science Foundation (NSF) in the US awarded a consortium led by Penn State University a grant to develop a "learning factory". This is when the term "learning factory" was first coined and patented. It referred to interdisciplinary hands-on senior engineering design projects with strong links and interactions with the industry. A college-wide infrastructure and a 2000 sqm facility equipped with machines, materials and tools was established and utilized to support hundreds of industry-sponsored design projects since 1995. The program was recognized nationally and received the National Academy of Engineering's Gordon Prize for Innovation in Engineering Education in 2006. This early model of learning factories emphasizes the hands-on experience gained by applying knowledge learned at the culmination of engineering education to solve real problems in industry and design products to satisfy identified needs [166,189]. Another less famous, more industry-focused approach was established in the late 1980s in Germany with the "Lernfabrik" (German for "learning factory") for a qualification program related to Computer Integrated Manufacturing (CIM) [245]. In the early 2000s, the teaching factory concept has also gained major interest, especially in the US, resulting in a number of educational and business pilot activities [23,89]. The concept of the "teaching factory" has its origins in the medical sciences discipline, and, specifically, in the paradigm of the "teaching hospital", namely, the medical school operating in parallel with a hospital, providing students with real-life experience and training. Drawing the parallel between the medical profession and manufacturing, the "teaching factory" concept referred to the integration of real industrial practice with manufacturing education and training. At California Polytechnique, the teaching factory makes use of state-of-the-art industrial grade production equipment, computer hardware and software [23]. It includes (a) a functioning "real" factory hardware environment, and (b) a production planning and control center to provide the decision making and communication functions, which act as an integrated system by utilizing state-of-the-art communication networks. The activities of the joint academia–industry initiative "Greenfield Coalition" concentrate on an application of the teaching factory concept in the Center for Advanced Technologies [89]. This "Factory as a Campus" environment combines a precision machining enterprise, producing car parts for GM, Ford, Daimler-Chrysler and their suppliers, state-of-the-art educational technology (Distance Learning, Interactive TV, Online Courses) and time-tested tutoring, mentoring, and lectures.

In the last decade learning factories have been implemented more and more predominantly in Europe [10,214,314]. Learning factories were set up in many variations aiming to improve the learning experience in several areas of application [10]. The Institute of Production Management, Technology and Machine Tools (PTW, TU Darmstadt) implemented in 2007 one of the first facilities of this new wave [8]. Complete value streams of real products, from raw materials over machining and assembly to shipment, are mapped. During the last years, several other learning factories were established with other content-related foci and physical manifestations. An overview of the broad learning factory variety is given in Section 3.

Together with the "1st Conference on Learning Factories" in Darmstadt in 2011 [6] the Initiative on European Learning Factories was established. The learning factory concept progressed leading to a joint Europe-wide collaboration. Additionally, in 2014, a Collaborative Working Group on "Learning factories for future-oriented research and education in manufacturing" (also short: CIRP CWG on learning factories) was started within CIRP in order to:

- organize learning factory related research globally,
- form a joint understanding of terms in the field,
- gather knowledge on the global state-of-the-art of learning factories,
- strengthen the link between industry and academia in this topic, and
- provide a comprehensive overview of the basics, the state-of-the-art as well as the future challenges and research questions in the field leading to this keynote paper [7].

The great potential of learning and teaching factories contributed to the steady growth of the community. Fig. 3 shows the number of yearly indexed documents on Google Scholar for the last thirty years for the terms "learning factory"/"Lernfabrik", and the term "teaching factory" including respective plural forms.

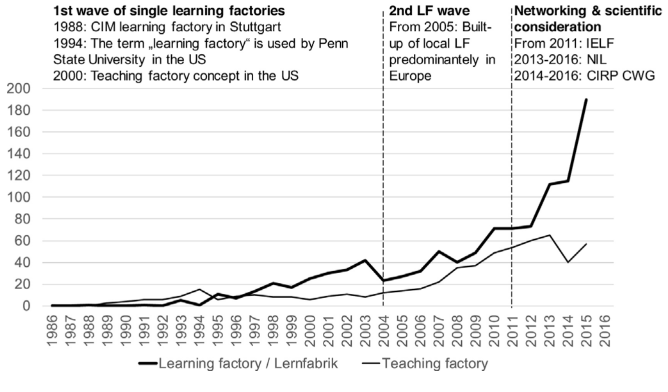

Fig. 3. Historical development of learning factory approaches and the number of indexed documents on Google Scholar regarding learning and teaching factories [298].