Learning factories for future oriented research and education in manufacturing

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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.

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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.

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).
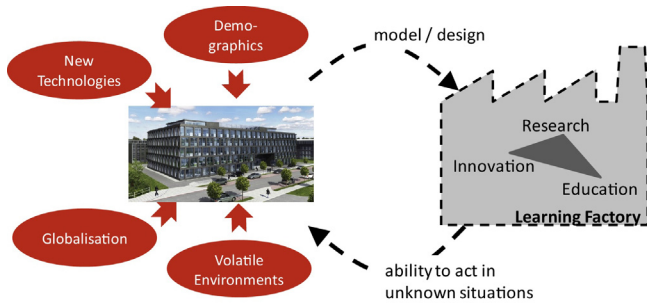

Fig. 2. The learning factory as a model of a real factory—incorporating the three poles of the "knowledge triangle" [11].

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.
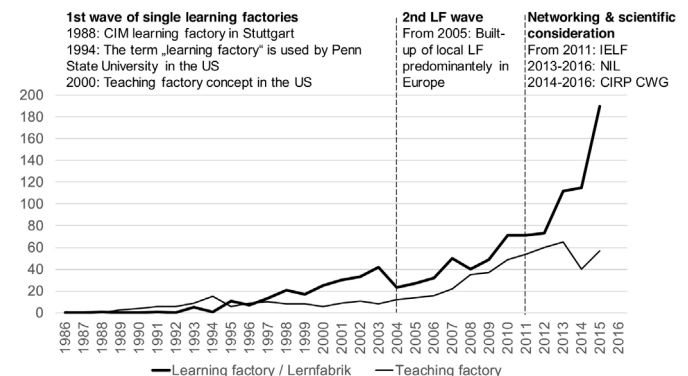

Fig. 3. Historical development of learning factory approaches and the number of indexed documents on Google Scholar regarding learning and teaching factories [298].

Documents using the terms: (a) with a strongly negative connotation criticizing over-formalized schooling, (b) with regard to the learning organization, and (c) to a machine learning approach were excluded from the results.

1.3. Relevance

In the economic context, several studies revealed the positive relationships between educational quality and individual incomes, as well as between educational quality and economic growth [34,126,135], highlighting the fact that the human capital is key to growth. Each year of schooling has been reported to increase the long term economic growth by 0.58 percentage points [135]. Furthermore, skills shortages are reported to have a negative effect on innovation performance [289]. Forecast studies show a considerable shift in labor demand: By implying that future jobs will become even more knowledge- and skill-intensive [61], a larger number of skilled workers will be required, and even future skill shortages and gaps for certain job functions are expected [309].

From an educational point of view, learning factories will contribute substantially to the continuous supply of well-prepared young manufacturing engineers and to the continuous update and upgrade of the intellectual capital of the industry's workforce in accordance with the challenges discussed previously. Other advantages of learning factories described in literature are positive effects on:

- students' attitude and on culture [30]
- interdisciplinary and soft skills [131,158,183,202,223,312]
- the quality of research, innovation, and technology transfer [59,104,131,246]
- the public image of the manufacturing industry [10,65].

2. Basic definitions and types of learning and teaching factories

Increasing speed of innovation requires a tremendous enhancement of learning and teaching productivity. Learning factories contribute to improving the latter by using a learning-centered approach instead of a traditional, unidirectional teaching-centered one. This new perception requires discussing principles in the fields of learning and working, learning goals, learning cycles and motivational approaches. Current conducive learning approaches in production technology are presented.

2.1. Definition of learning

"Learning involves acquiring and modifying knowledge, skills, strategies, beliefs, attitudes, and behaviors. People learn cognitive, linguistic, motor, and social skills, and these can take many forms" [264]. Learning is a process that builds on and making connections to existing knowledge and experiences. Due to learning, changes implemented in organisms can be seen as relatively permanent [259]. According to Kirkpatrick, learning is "[. . .] knowledge acquired, skills improved or attitudes changed due to training" [176]. Learning is classified into planned formal and mostly incidental informal learning. In informal learning processes, both implicit and experience-based learning occur [80]. In the middle of formal and informal learning, the term non-formal learning is used to describe a great variety of loosely structured learning situations [105].

2.1.1. Learning theories
Depending on the view on the learning process, different learning theories can be applied as conceptual frameworks. In the following, the behaviouristic, the cognitivist, and the constructivist learning theories are presented.

2.1.1.1. Behaviouristic learning theory. The learning psychological approach of behaviorism assumes that the behavior of people is affected by consequences and not by internal cognitive processes

[276]. In this approach, three major learning processes can be identified: classic conditioning (stimuli are associated with reactions) [227,276], operant conditioning (learning through reward and punishment) [276,293], modeling (learning by observing the actions of others) [32].

2.1.1.2. Cognitivist learning theory. Shortly after the ideas of the empirical psychological approach to explain learning by behaviors emerged, an opposite group was formed that intended to explain the exact cognitive processes of thinking inside the learner that lead to a specific behavior [221]. This area has been blanked out as a "black box" by behaviorism. The new learning theory is called cognitivism. An overview of the development of the cognitive approach is given by Refs. [73,138,287].

2.1.1.3. Constructivist learning theory. Both, behaviorism and cognitivism (also referred to as objectivism) base the learning processes on a learner-external reality which the mind of the learner is processing. In contrast, in the theory of constructivism the reality is determined by the individual learner's experiences [164]. Depending on the context, an objectivist as well as a constructivist view on learning can be beneficial [164] for learning factories.

2.1.2. Competencies
The competence concept leads to frequent confusion and misinterpretation [207,271]. Short [271] articulated the following normative conceptualizations of competence approaches:

- performance or behavioral approach, that treats competences as specific, job-related, measurable behaviors ignoring underlying attributes,
- generic approach, in which competence includes underlying attributes (knowledge, capability of critical thinking, etc.) and is considered a general attribute neglecting specific application contexts, and
- holistic approach, that integrates the above approaches and, therefore, conceptualizes competencies with knowledge, skills, attitudes, performances, etc. in specific professional application contexts.

In holistic approaches the terms "competency" and "competence", used in a distinguished manner, see e.g. [258,288], are significantly influenced by linguistics [64] and psychological [322] approaches. Competencies are context-specific dispositions, with use of knowledge and skills [108], to take self-organized, creative actions in open and complex situations [107]. Fig. 4 illustrates the relations between knowledge in a narrow sense, qualification, and competency [150].

The European Parliament defined **knowledge** as the "outcome of the assimilation of information through learning. Knowledge is the body of facts, principles, theories and practices that is related to a field of work or study" [108]. This also includes autonomous reflection on empirical experience or known preliminaries.

Skills are the "ability to apply knowledge and use know-how to complete tasks and solve problems." Within the European Qualifications Framework, "skills are described as cognitive (involving the use of logical, intuitive and creative thinking) or practical (involving manual dexterity and the use of methods, materials, tools and instruments)" [108].
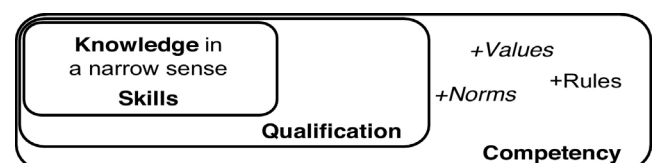

Fig. 4. The relation of knowledge in a narrow sense, skills, qualification, and competency [150].
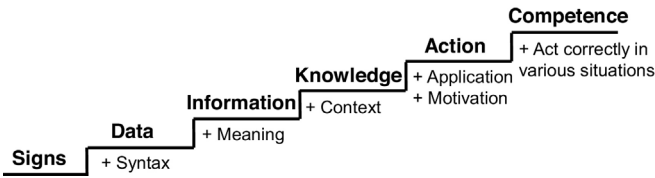
Fig. 5. North's knowledge stair [224].

Bloom et al. [44] also consider the term skills to be closely connected to the term ability and define abilities and skills as "that the individual can find appropriate information and techniques in his previous experience to bring to bear on new problems and situations. This requires some analysis or understanding of the new situation; it requires a background of knowledge or methods which can be readily utilized; and it also requires some facility in discerning the appropriate relations between previous experience and the new situation." They classify skills within the context of a learning process, across the following levels: [44,65]

- observation and replication of actions
- task reproduction from instruction or memory
- reliable execution independent of help
- adaptation/integration of expertise to meet requirements
- automated, unconscious management of activity

The link between knowledge, skill, and competence is illustrated by the knowledge management related North's Knowledge Stairs (Fig. 5). Competencies can be further divided into competency classes. Erpenbeck and Rosenstiel [107] distinguishes four classes of competency:

- Socio-communicative competencies are the used when working in groups and describe the capacity to communicative and cooperative self-organized action; facets of this class are e.g. communication, cooperation, conflict management, and leadership abilities.
- Technical and methodological competencies contain mental and physical abilities to self-organized (professional and technical) problem solving using expertise and suiting methods; facets of this class are e.g. expertise application and acquisition as well as analytic, methodical, and problem solving abilities.
- Personal competencies can be summarized under the ability to act self-reflexively; examples are reflectivity, adaptability, and the unfolding of motivation.
- Activity and action competencies describe the holistic capacity to the selection and application of self-organized actions; examples are abilities to work independently, implement plans, and perseverance.

2.1.3. Learning goals, objectives and outcomes

Learning goals or learning objectives are typically used to define the intention of an educational activity [21]. Goals on the one hand usually define the big intention behind a programme or course, objectives on the other hand specify those goals in more detail [21,303]. Learning processes need educational goals [303]. The educational scientist Bloom differentiates in his taxonomy of learning goals between

- cognitive (recall or recognition of knowledge) [44,24],
- affective (interest, attitudes, values, the development of appreciations and adequate adjustment) [182],
- and psychomotor (neuro-muscular coordination) [78] domains.

They are further detailed in Table 1. Learning outcomes further specify the learning objectives by defining measurable, observable behaviors [33]. Learning outcomes can have subject-, teacher-, and learner-related facets [93]. Gosling and Moon define the learning outcome as "a statement of what a learner is expected to know,

Table 1
Learning goals in the cognitive [24,44], the affective [182], and the psychomotor domain [78].

Domains and learning goals		Description
Cognitive	Remember	Retrieve relevant knowledge from long-term memory
	Understand	Construct meaning from instructional messages, including oral, written, and graphic communication
	Apply	Carry out or use a procedure in a given situation
	Analyze	Break material into its constituent parts and determine how the parts relate to one another and to an overall structure or purpose
	Evaluate	Make judgments based on criteria and standards
	Create	Put elements together to form a coherent or functional whole; reorganize elements into a new pattern or structure
Affective	Receiving	Being aware of or attending to something in the environment
	Responding	Showing some new behaviour as a result of experience
	Valuing	Showing some definite involvement or commitment
	Organization	Integrating a new value into one's general set of values, giving it some ranking among one's general priorities
Psycho-motor	Characterization	Acting consistently with the new value
	Observing	Active mental attending of a physical event
	Imitating	Attempted copying of a physical behaviour
	Practicing	Trying a specific physical activity over and over
	Adapting	Fine-tuning. Making minor adjustments in the physical activity in order to perfect it

understand and/or be able to demonstrate at the end of a period of learning" [122]. "Defining the learning outcomes enables both the teacher and student to see what a student is expected to have achieved, and what progress he/she made with regard to his/her qualification goal" [270].

2.2. Forms of work related learning

Dehnbostel [80] distinguishes between three types of work related learning, (a) the work-connected, (b) the work-bound, and (c) the work-based learning. In work-connected learning, the learning and working places and processes are separated but in close proximity, so that learning does not necessarily occur while performing a working task. In work-bound learning, the learning and working places and processes become identical, in that the work places are expanded by learning opportunities and infrastructure. This is commonly referred to as learning within the process of working or learning by doing. Finally, work-based learning occurs, when the working and learning places are completely separated and no working or value creation task is professionally executed, e.g. in learning factories. Work-bound solutions have the highest potential for combining work and learning productivity. Table 2 shows different existing and innovative work related learning approaches.

Table 2
Work related competency development approaches [18].

	Work-based learning	Work-connected learning	Work-bound learning
Established approaches	• Training workshops • Training centers • Practice firms • Learning factory • Self-learning programs	• Quality circle • Workshop circle • Learning station	• Training station • Guiding text method • Instruction • Informal learning by doing in a real work process
Innovative approaches (exemplary)	• Location-independent (remote) learning factories using ICT equipment and blended learning • Virtual learning factories with dynamic adaptation to target group needs • . . .	• Process-oriented, virtual learning stations for demand based methodical support • . . .	• Ad-hoc skills development during the work process • Learning tools (e.g.exoskeleton) • . . .

2.2.1. Experiential learning

Kolb defines learning as follows: "learning is the process whereby knowledge is created through the transformation of experience" [181]. The experiential learning concept based on this
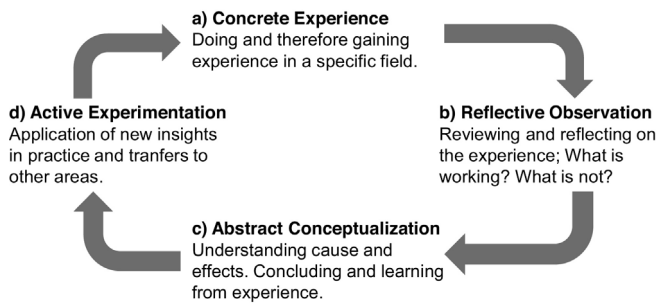
Fig. 6. Kolb's experiential learning cycle [181].

understanding can be carried out without a teacher and relies on the meaning-making process of the learner's experience. It refers to a learning process in which knowledge is gained through the inherent transformation through the stages of: (a) **a concrete experience**, (b) **observation and reflection**, e.g. what is working or failing, (c) **abstract conceptualization**, e.g. the understanding of the cause-effect relationship, the interpreting, analyzing of events or even first ideas of improvement, and finally (d) **active experimentation**, when the learner puts considerations into practice and can even translate the new understanding into predictions [181]. Experiential learning methods like project-based learning, simulations and case studies have been beneficial in developing cognitive skills for engineering students, especially when combined with other active learning methods in a single course [74]. Fig. 6 shows Kolb's learning cycle.

2.2.2. Active and action-oriented learning

Active learning neglects the passive transmission of information and instead focuses on the engagement of learners analyzing, applying, manipulating and evaluating ideas. Thereby, the understanding of concepts is promoted, as opposed to the mere reproduction of information [74]. It "involves students in doing things and thinking about the things they are doing" as defined by Bonwell and Eison [50] and is stimulated by methods such as visual-based instructions, writing, cooperative learning, debates, role playing, games and peer teaching.

A sub-type of active learning with focus on the learner's active integration via own actions is referred to as action-oriented learning. It aims at improving conceptual knowledge, which enables the understanding of cause–effect relationships as a prerequisite for problem solving. The action-oriented learning process is designed in a way that learners have to deal with complex problems independently while teachers assume the role of moderators. The appropriate learning environment is characterized by a high degree of fidelity to the actual working context, e.g. simulations, role play, virtual reality and learning factories [58,193]. This form of learning is to be understood in the context of the activity theory, which postulates conscious learning emerging from activities and not—as commonly believed—forerunning it [165].

2.2.3. Games to increase motivation

Educational Games are structured forms of play, designed with the purposes of facilitating learning, the acquisition of knowledge, skills, values, beliefs or habits. They can assist the user in understanding certain subjects or concepts, or support him in learning or improving skills by involving the own actions of the learner [124].

Learning approaches considering game elements with a serious purpose behind [84] can be classified in *Gamification* and *Serious Games*. Serious games are defined as games with an "explicit and carefully thought-out educational purpose" [14]. They "are not intended to be played primarily for amusement. This does not mean that serious games are not, or should not be, entertaining" [90]. "Gamification is the use of game design elements in non-game contexts" [84]. Serious games and gamification are used in order to increase the motivation of learners.

2.3. Morphology and typology of learning factories

Models and approaches in the field of learning factories published in the analysis of Plorin [233] are divided into the categories:

- use case description [31,41,46,96,109,116,119,153,169,185,186,191, 223,246,268,281],
- learning module generation [31,102,313],
- competency-based teaching [2,41,45,46,57,153,223,232,260,313],
- outcome measurement [57,58,119,130,296,297], and
- structural conception of learning factories [246,280,295,299,308].

This section deals with the models which are classified under the structural conception of learning factories. In recent years, numerous models have been published to categorize and describe learning factories [155,246,280,295,314]. They mostly focus on technical aspects and have a rather weak coverage of the didactical dimension. The models essentially use the heuristic approach of morphological analysis to facilitate a feature-based delineation of learning factories. The morphological analysis [331,332] is especially useful for describing complex systems like learning factories as it is able to integrate also a large number of relevant features and characteristics and their potential attributes without compromising its usability [211].

Therefore, a holistic as well as generic description of learning factories in general is achieved, while a particular, existing institution can be specified in detail at the same time. The description model allows a simplified illustration of correlations between all conceptual options and the actual design of the specific, analyzed learning factory [299].

A relatively compact morphology for learning factories is shown by Ref. [295]. It illustrates a variety of typical learning factory parameters resulting from a survey that was conducted at ten universities that are members of the Initiative on European Learning Factories (IELF).

A description model based on a morphological box, which includes three content dimensions: operation model, target group/metrics and equipment is offered [280]. The model supports describing framework conditions of a learning factory and also contains supplemental information that does not primarily concern the actual capability building process. An additional model from [279] focuses on the description of didactical aspects of learning factories. It also makes use of the morphological technique, systemizing the objectives of teaching processes and the respective learning contents, the design of the learning scenario and the entire surrounding organizational framework.

The classification tool for learning factories developed by Wagner et al. [314] retrieves dedicated information on the changeability of learning factories through a decision table. It is able to differentiate between parameters of first and second order. While first-order parameters test if a certain change-enabler is valid for a certain learning factory, the second-order parameter describes technical realization of this particular change-enabler.

In general, the different systematization approaches contain various learning factory features or characteristics with different attributes. Often the identified characteristics are structured in groups or dimensions depending on their similarity. Table 3 gives

Table 3
Existing morphologies, typologies, and classifications of learning factories.

	Focus of morphology/typology/ classification	Groups of characteristics (Dimensions)	Characteristics
[314]	Classification scheme for the changeability of different learning factories	5	N/A
[295], [155]	Morphologic description of learning factory key characteristics	1	11
[280]	Detailed description model on learning factories	3	25
[279]	Morphology focusing on didactical aspects inside LF	6	40
[299]	Comprehensive description model for learning factories based on the dimensions of the CIRP definition on LF	7	59

an overview of characteristics and groups of characteristics of the different approaches. Also the focus of each description model is named.

Both, new research results in the context of higher education as well as emerging technologies, have a continuous impact on teaching methods and training needs, and learning factories are advancing further accordingly. Therefore, description models for learning factories need to be evolved or even expanded continually. That is why the CIRP CWG on Learning Factories together with the project Network of Innovative Learning Factories (NIL), mutually developed and validated a multi-dimensional description model [299]. It fulfils three major purposes: [299]

- Providing orientation and guidelines in designing and establishing a new learning factory,
- serving as a tool for delineation of existing ones, and
- working toward a standardization of the learning factory concept.

The description model developed within the CIRP CWG on learning factories represents an academic consensus on the contained features and characteristics and is founded on the definition and the dimensions of learning factories as identified in Refs. [10] and [3]. It consists of 59 single characteristics and their respective attributes. The characteristics are clustered into seven categories: Operating model, purpose and targets, process, setting, product, didactics, and metrics. The categories are further described in Fig. 7. In addition, the usefulness of the morphology
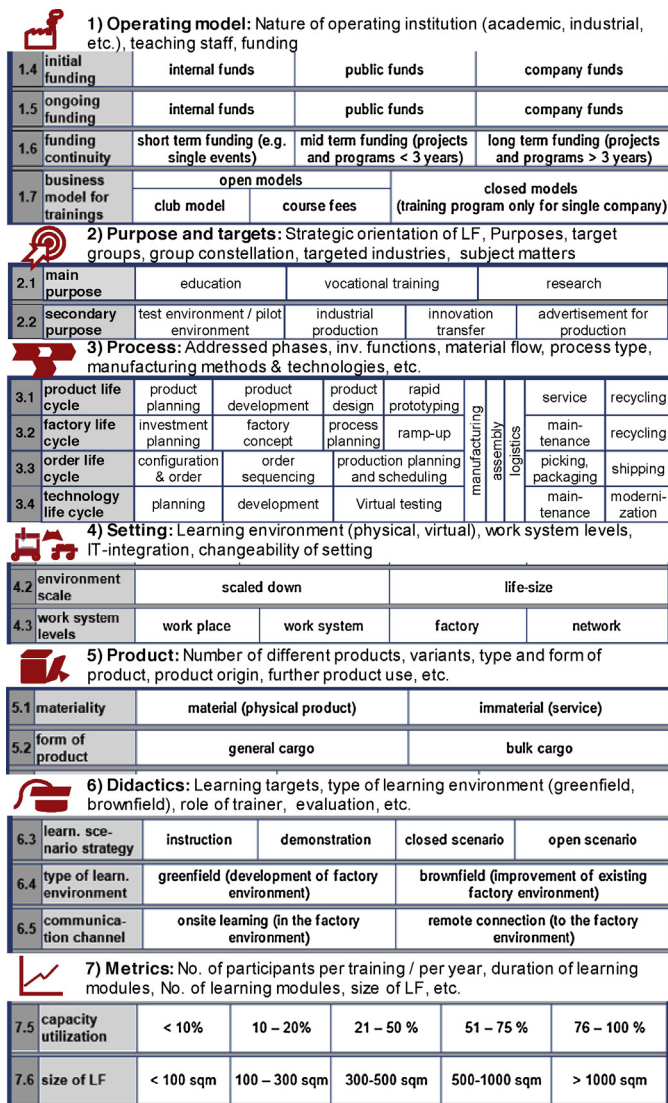

Fig. 7. Extract of the LF morphology shown in Ref. [299].

was confirmed in several qualitative interviews with industrial and academic learning factory experts outside the CIRP-community.

Furthermore, the morphology is also used as a basis for the development of a quality system for learning factories, here inter alia the requirements of various stakeholders are derived from the morphological structure, see also Ref. [103].

Furthermore, a web-based application that allows operators of existing learning factories to present their concept with the help of the described morphology is established [205]. The platform serves as an information database for those who try to identify facilities with specific desired features and thereby enables new contacts and partnerships for all stakeholders of the learning factory community (access under: Ref. [194]).

2.4. Definitions and related conclusions

Since the emergence of the first learning factories, a number of various implicit and explicit definitions were formulated. The early definitions are largely based on descriptions of single existing learning factories, in the 2010s a comprehensive scientific discussion took place.

The first known definition of a learning factory by Ref. [166] describes a facility for product and process realization that can be used for academic education. Additional key factors include active participation of trainees and an agile environment. Abele et al. [13] base their definition on principally the same assumptions, but emphasize the need for closeness to reality of all aspects of such a facility in an authentic simulation. The teaching factory concept of Chryssolouris et al. [65,68,210] connects the real factory with the classroom using advanced information and communication technologies (ICTs) for bi-directional knowledge exchange. The result of an investigation of more than 25 learning factories, Wagner et al. [314] fortify the postulation of authenticity and changeability of the factory environment and claim the suitability of learning factories for different target groups as well as the purpose of test and transfer of theoretical knowledge to the industry. With the intent to identify a methodical approach for developing action-oriented, competency-based learning factories, the definition of Tisch et al. [295] focuses on a systematic configuration of the learning environment. The members of the Initiative on European learning factories [156] agreed on a comprehensive definition with regard to realistic processes and the didactical concept. Sihn (2014) referenced in Ref. [210] differentiates between physical and virtual settings of learning factories and includes both types in his definition. Further definitions cover partial aspects (see [183], or Tracht (2014) referenced in Ref. [210]). Fig. 8 gives an overview on

	Purpose	Process	Setting	Product	Didactics	Operating Model
Jorgensen et al. (1995) [155]	◐	◕	◑	○	◕	○
Abele et al. (2010) [13]	◑	◑	◑	◑	◕	○
Chryssolouris et al. (2014) in [195]	◑	◔	◑	◕	○	○
Wagner et al. (2012) [291]	◑	◔	◑	◑	◑	○
Tisch et al. (2013) [275]	◑	◕	◕	○	◕	○
Initiative on European Learning Factories (2013) [145]	◑	◔	◕	○	◕	○
Sihn (2014) in [195]	◕	◔	◑	○	◑	○
Kreimeier et al. (2014) [172]	◑	◑	◑	◑	◑	○
Tracht (2014) in [195]	◕	◑	◑	○	◔	○
CIRP CWG [3]	●	●	●	●	●	●

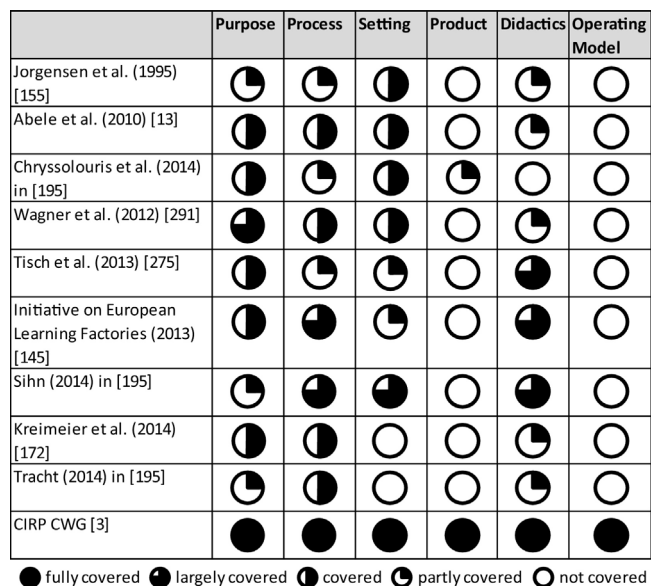● fully covered ◕ largely covered ◑ covered ◔ partly covered ○ not covered

Fig. 8. Overview on the scope of existing definitions for learning factories.

the scope of the various definitions related to the dimensions developed in chapter 2.3.

Based on this, a comprehensive and generally accepted definition was agreed within the CIRP CWG [10] and published in the CIRP Encyclopedia [3]:

"A learning factory in a narrow sense is a learning environment specified by

- **processes** that are authentic, include multiple stations, and comprise technical as well as organizational aspects,
- a **setting** that is changeable and resembles a real value chain,
- a physical **product** being manufactured, and
- a **didactical concept** that comprises formal, informal and non-formal learning, enabled by own actions of the trainees in an on-site learning approach.

Depending on the **purpose** of the learning factory, learning takes place through teaching, training and/or research. Consequently, learning outcomes may be competency development and/or innovation. An operating model ensuring the sustained operation of the learning factory is desirable (Fig. 9).

In a broader sense, learning environments meeting the definition above but with

- a setting that resembles a virtual instead of a physical value chain, or
- a service product instead of a physical product, or
- a didactical concept based on remote learning instead of on-site learning

can also be considered as learning factories." (see Fig. 10)

In general terms, the primary purpose of learning factories is "Learning" in a "Factory" environment [314]. While there is broad consensus that this includes academic education of students or further education of industrial employees [10], other groups can also be targeted. Furthermore, learning through the identification of research gaps, the implementation of research results [267] or the transfer into a quasi-realistic environment [188,260] need to be covered as purposes.

The processes within a learning factory should be close to reality [8,158,295]. As a single machine or a single workplace do not represent an authentic factory, the processes covered need to comprise multiple stations [10,294]. A pure technical process (i.e. a technical demonstrator) is not equivalent to a learning factory. Organizational aspects need to be included.

A major benefit of learning factories is the possibility of experiential learning [131,143,189,235]. In order to facilitate this type of learning, the setting of a learning factory should be changeable and can be accommodated to the needs of the trainees [295]. A physical setting [8,166] is accounted a learning factory of the narrow definition, while a virtual setting (i.e. computer-simulated, virtual factories) [235,250,274,275] falls under the
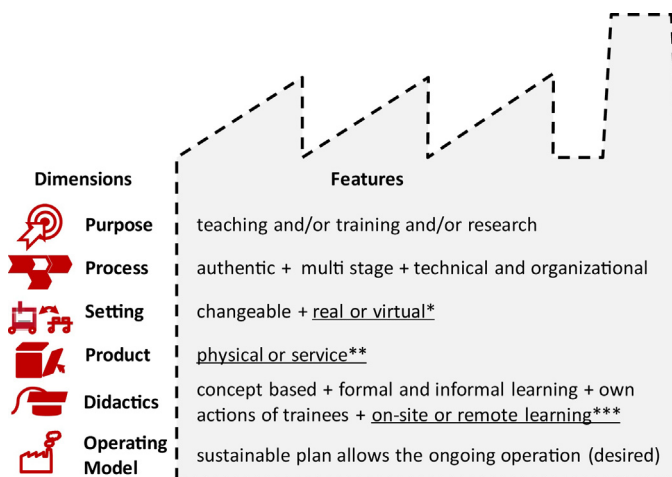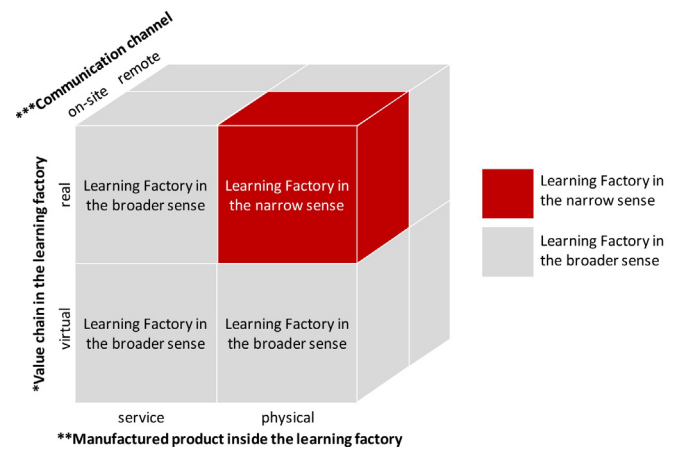

Fig. 10. Learning factories in the narrow and in the broader sense [10].

broader definition [3]. Similarly, learning factories that make use of a physical product are learning factories in the narrow sense, whereas those with service products, see e.g. [132], are attributed to the broad sense.

Regarding didactics, there needs to be a concept including formal and informal learning. A mere facility provided for self-designed learning [180] (i.e. Learning Center [231] or Learning Space [167]) is not a learning factory. The didactical concept specifies what is learned by whom and how [10]—or more generally and comprehensively "Who should learn what, from whom, when, with whom, where, how, with what and for which purpose" [161] (literal translation according to Ref. [329]). Trainees have the freedom to create own implementations through individual physical and intellectual activities [58,131]. A learning factory with physical presence of trainees in the factory environment versus the use of a remote connection via ICT [204,247] distinguishes narrow from broad definition.

3. Overview of existing learning factories

Learning factories have become widespread in recent years, particularly in Europe, and have taken many forms of facilities varying in size, scope, function, and sophistication aiming to enhance the learning experience of students and industrial trainees in one or more areas of manufacturing engineering knowledge.

Learning factories are more and more used as test areas for research. Various surveys [10,187,214,295,314] are known to have documented and introduced fractions of these learning factories. In the following paragraphs several existing learning factories are presented and classified by their thematic core focus.

3.1. Learning factories for production process improvement

Learning factories for production process improvement deal with lean methods and principles, like value stream analysis and design, just-in-time, line balancing, problem solving or job optimization.

PTW at TU Darmstadt started one of the early implementations of process learning factories (CiP, Center for industrial Productivity) in 2007 [8]. It consists of nine machine tools and two assembly lines used for training in industrial engineering and in particularly lean manufacturing methodologies (Fig. 11). A pneumatic cylinder is manufactured in a close-to-reality production environment, representing a holistic, multi-stage value stream [211]. The learning factory also serves as a testbed for revealing research gaps and for the implementation of research results [267].

The Learning and Innovation Factory (LIF) for Integrative Production Education at Vienna University of Technology is an interactive, hands-on education and research center of several institutes to make methods and tools for production optimization comprehensible to students and industry employees [158]. Methods of lean management in logistics, in order fulfillment and

Fig. 9. Key characteristics of learning factories.

Fig. 11. The learning factory CiP at TU Darmstadt [238].

administration are integrated. As an application-oriented product a slot car in 1:24 scale is used.

The activities of the LPS Learning Factory at Ruhr University of Bochum are characterized by the interfaces between human beings, technology and organizations. The LPS operates a pilot factory in which the theoretic concepts developed are implemented and technology demonstration and transfer to industry are promoted [41].

The learning factory LSP for streamlined products and production management, operated by the Institute for Machine Tools and Industrial Management (iwb, TU Munich), focuses on Lean Production principles [198].

In close cooperation with various companies at a nearby industrial park, the Lean Lab at NTNU in Gjøvik deploys a learning factory mainly for teaching flow production, line balancing and workplace design [302].

Although users of university-based learning factories are generally not limited to university or college students, and company employees are often trained in courses offered using learning factories located in educational institutes, several industrial companies have established learning factories by themselves, particularly providing the technologies and knowledge most relevant to their business.

An example is the Chrysler World Class Manufacturing Academy in Michigan, USA [304] which features both full scale physical learning factory facilities for experiential learning related to their required manufacturing competencies as well as supportive on-line learning courses that can be accessed remotely by their employees.

In 2012, the BMW learning factory VPS (Value-Oriented Production System) Center was opened in Munich, Germany, with interactive learning stations that help to visualize the VPS/LEAN principles [146]. The VPS Learning Factory concept is currently rolled out globally to each BMW production site.

Company Kärcher pursues a similar strategy for teaching process improvement methods to its employees: The Kärcher Learning Factory was prototyped in 2013 in Germany and has been exported to all global Kärcher sites, individually adapted to typical product(s) manufactured at the given site [291].

The MOVE academy of the automotive, industrial and aerospace components supplier Schäffler disseminates its lean philosophy using a learning factory with real drilling, deburring, quality assurance, assembly, and logistics processes [36,141].

Together with academic and industrial partners, the consulting company McKinsey & Co. developed a global network of learning factories on several topics [132].

In 2014, Bayer and TU Berlin built up a learning factory for process optimization integrating also social topics, e.g. worldwide participation in value creation or health and safety in factory environments [142].

3.2. Learning factories for reconfigurability, production and factory layout planning

Various learning factories are dealing with reconfigurability related to production and factory layout planning.

The learning factory for advanced Industrial Engineering (aIE) at the Institute of Industrial Manufacturing and Management (IFF) (University of Stuttgart, Germany) is focused on the link between digital production planning and implementation of the physical models in the laboratory [154]. This transformable production platform comprises standardized and mobile plug and play modules for assembly, coating, inspection, transportation and storage, and is capable of re-configuration into different layouts. It was designed and implemented by Festo Didactic and uses a product with many variants to demonstrate aspects of production planning and control and order processing [35,87].

A similar integrated learning factory, the first of its kind in North America, was set up at the Intelligent Manufacturing Systems (IMS) Center (Windsor, Canada) in 2011 [96]. It includes a modular and changeable assembly system (iFactory) which consists of robotic and manual assembly stations, computer vision inspection station, Automated Storage and Retrieval System (ASRS) and several material handling modules. It is integrated with a design innovation studio (iDesign), process and production planning tools (iPlan), 3D printing facility and dimensional metrology CMM (Coordinate Measuring Machine) facility. Its structure is similar to that at University of Stuttgart, but with different foci including: (a) developing enablers of change in manufacturing, (b) manufacturing systems learning which integrates products design with systems configuration design and co-evolution of products and systems development, and (c) products design, customization, personalization and prototyping (see Fig. 12).

The IFA learning factory at the University of Hannover offers a wide span of trainings on lean thinking, factory layout planning, ergonomics, workplace design and production control [119,268,312]. Additionally, there is a virtual representation of the learning factory environment in operation for educational purposes. The IFA as well as other learning factory facilities are also used as support and enabler in the context of change management concepts with main focus on the human factor within the work environment [86,88,241,312].

The "Mini-Factory" at the University of Bolzano was set up in 2012 in order to enhance practice-orientation in engineering education. A pneumatic cylinder and a camp stove oven serve as realistic products [203].

At KTH XPRES Lab a digital factory is developed for the purpose of supporting cross-disciplinary organizational learning and decision making when designing manufacturing systems [275], see Fig. 13. The XPRES Lab uses virtual representations of the

Fig. 12. The modular and reconfigurable learning factory at the IMS center, University of Windsor, Canada [306].
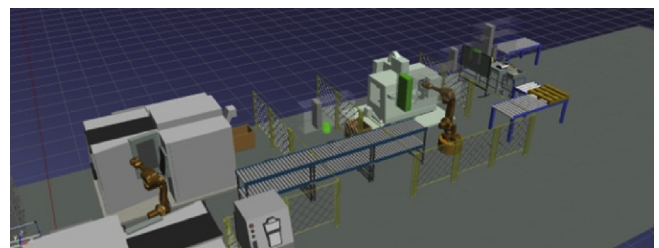

Fig. 13. The virtual learning factory XPRES at KTH.

physical learning factory. For a more detailed view on digital and virtual learning factories see also Section 5.2.5.

3.3. Learning factories for energy and resource efficiency

Learning factories for energy and resource efficiency deal, among other things, with the relation between energy and resources consumption and the production output in order to develop and test related optimization strategies and measures, such as modern metering technologies or KPI monitoring software.

In 2016, PTW at TU Darmstadt opened a greenfield-factory (ETA-factory), which integrates several interdisciplinary approaches to reduce the energy consumption as well as the CO_2-emissions of industrial production processes (Fig. 14). Machinery and the building shell interact with each other. The ETA-factory is used mainly for research and demonstration, but also for education [4].

iwb at TU Munich has established a learning factory for energy productivity, involving several machining, hardening and handling processes of a real industrial product [242].

Ruhr-Universität Bochum also operates a learning factory for Resource Efficiency [184].

The main focus of the "E^3-Factory" at Fraunhofer IWU in Chemnitz is energy research in car body powertrain production using realistic processes and data. The environment serves as teaching and prototyping lab as well as for upscaling and technology transfer [240,283].

Fig. 14. The learning factory ETA at TU Darmstadt [239].

3.4. Applied teaching factory concept

The teaching factory concept is based on the knowledge triangle notion aiming to seamlessly integrate its three cornerstones: education, research and innovation [67,204]. In the context of the KNOW FACT project led by the University of Patras, the teaching factory concept is implemented as a non-geographically anchored learning "space", which is facilitated by advanced digital technologies and high-grade industrial didactic equipment [68]. It facilitates the communication and interaction of teams of engineers and students or researchers, working on real-life problems and engaging actual facilities at the industrial and academic sites. On that basis, it operates as a bi-directional knowledge communication channel bringing the real factory to the classroom and the academic lab to the factory [246,247] (Fig. 15).
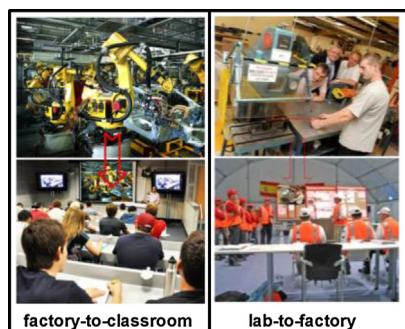

Fig. 15. Teaching factory sessions for factory-to-classroom and lab-to-factory knowledge communication.

3.5. Learning factories for Industrie 4.0

In recent years more and more learning factories also address the topics digitization of production, Internet of Things or the German Industrie 4.0, e.g. see Refs. [106,260,290,317]. Learning factories in this area are focusing today more on research and technology transfer than on education and training. Those learning factories are therefore discussed in detail in Section 6.2 "Use cases of Research and Innovation factories".

Industry today experiences massive problems transferring and implementing the demonstrated Industrie 4.0-ideas [215]. Thus it is consensus in literature that for the future industry requires well-educated personnel that is capable of understanding complex interdisciplinary connections, adapting, and designing all facets of cyber-physical production systems, see e.g. Ref. [15,16,237, 290,317]. Here, learning factories are exceptionally well suited to enable the potential to interdisciplinary thinking and acting of today's and future manufacturing engineers (regarding inter alia manufacturing, information technology and communication sciences), see e.g. Ref. [123,237,268,290,317].

3.6. Learning factories related to other topics

3.6.1. Learning factories for sustainability

The learning factory at TU Braunschweig (Die Lernfabrik) comprises a research lab, an experience lab and an education lab. It focuses on sustainability in manufacturing, addressing several topics [45,145]. Also the joint learning factory of Bayer and TU Berlin addresses next to typical lean topics challenges of sustainable manufacturing regarding the economic, the environmental, and also the social dimension [142]. In order to develop the right mindset and behavior in this broad field of sustainable manufacturing, learning factories have to address topics that are located in the so far comparatively less illuminated area of the social dimension. For the role of manufacturing regarding this dimension see also Ref. [285]. Additionally, in this matter learning factories can be enriched by the use of learning conducive artefacts, which convey their functionalities to the user automatically. The so-called learnstruments [115] aim at increasing learning efficiency and expand the awareness for the environmental, economic, and social perspective of sustainability. The concept of learnstruments has been implemented in several use cases [149,208,217,218,220].

3.6.2. Learning factories for product emergence processes

The learning factory in Vienna focuses on a learning module for students with the goal to experience activities in the product emergence process by understanding the life-cycle of a product and related processes [158,273].

3.6.3. Learning factories for logistics optimization

With the goal of realistic teaching and research in the logistics area, ESB Reutlingen created a learning factory focusing on various logistics concepts [153].

3.6.4. Learning factories for management and organization

The learning factory for management and organization at Ruhr-Universität Bochum teaches topics of change management and worker's participation in an industrial setting [183].

3.6.5. Learning factories for business administration

In its Capability Center in Munich, McKinsey & Co. established a learning factory for business administration. Realistic bank offices, call centers and a mortgage factory including the corresponding administrative processes were created [132].

3.6.6. Learning factories for automation technology

Starting in the 1980s, the company Festo Didactic uses learning factory concepts in the field of students' education for automation basics, PLC-technology, industrial networking or the use of sensors [232].

The above overview cannot be considered complete. There is a broad variety of learning factory application fields which is constantly expanding. In order to keep track of the developments, a database for listing and classifying all existing learning factories was developed within the CIRP community, see Section 2.3.

4. Learning factories curricula: from target-specific goals to a systematic operational methodology

4.1. Introduction to didactical and methodical basics

Didactics (in English the plural form is used to distinguish the term from the pejorative "didactic", which has a connotation to oversimplified teaching [265]) is the science of teaching and learning in general [92,329] regarding all forms of learning at all levels [329]. The term "didactics" has its origin in the Greek language (didáskein) and literally means "teaching". Didactics is focused on organized forms of teaching–learning processes [249]. From a didactic perspective, two crucial fields of action in teaching–learning processes are identified [178,249]:

a Intentions, goals and contents
b Methods and media

Didactics in the narrow sense includes the first field of action. The second one is referred to as "methodology". When talking about didactics in the wide sense, the "methodology" is a sub-discipline of didactics [249]. Fig. 16 visualizes the terminology of didactics.

Traditionally, didactic systems are often understood with the simple framework of the didactic triangle with the interrelated corners teacher, student, and content, see e.g. Ref. [54,152]. Beyond that, in the field of didactics it is hard to define the international state of the art since different regional circles of authors can be identified that hardly refer to each other [174]. As a result, many approaches and theories were developed completely separately. In literature two important mainstreams can be identified: [329]

- **General didactics**, with main influences coming from German-speaking countries having its roots going back to the ancient world. For further elaboration on the history of General Didactics see e.g. Ref. [26,329].
- **Instructional design**, which is the American way of instruction planning and organization going back to the 1920s. For further elaboration on the history of Instructional Design, see e.g. Ref. [243,272].
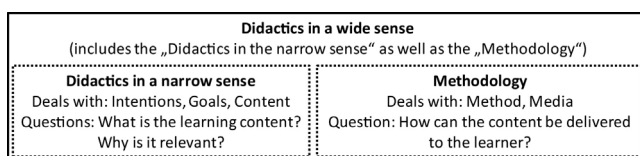

Didactics in a wide sense (includes the „Didactics in the narrow sense" as well as the „Methodology")	
Didactics in a narrow sense Deals with: Intentions, Goals, Content Questions: What is the learning content? Why is it relevant?	**Methodology** Deals with: Method, Media Question: How can the content be delivered to the learner?

Fig. 16. Terminology of didactics and methodology.

4.1.1. Approaches and models of general didactics

For the didactics in the narrow sense, Klafki [178] delivered substantial input to the content-related preparation of teaching with his "bildungstheoretische Didaktik" (which could be translated according to Ref. [53] to "didactics theory on the education of the cultivated mind") and later critical-constructive didactics. According to Klafki [178], relevant learning content can be identified and legitimized following five basic interrelated questions, extended by two additional questions in a newer edition more related to the methodology [179].

- What is the **exemplary relevance** of the content?
- What is the **current relevance** to the learner?
- What is the **future relevance** for the learner?
- How is the content **structured thematically**?
- How can the success of learning processes be **verified**?
- How is content opened up to the learner (**accessibility**)?

- How can the content be **structured methodically** regarding a sequence of learning processes?

A second important, more learning-centered, approach from the General Didactics is given by the so-called "Berliner Modell" [140], and based on this the "Hamburger Modell" [262]. Both approaches address didactics in a wide sense. Central decision fields of the "Berliner Modell" are intention, content, method, media, as well as their interrelations having the personal and socio-cultural preconditions and consequences in mind. For a detailed description of the "Hamburger Modell" see Ref. [262].

In the 1960s and 1970s the discussion of those models was influenced by curriculum studies that criticized the state of the art in General Didactics and in particular the reckless selection of learning contents [329]. Robinsohn [252,253] criticized primarily the subject-specific content selection and put in his Curriculum Theory a multidisciplinary curriculum in the center, which is oriented to the realities of the learners. Here, a connection between the General Didactics and international curriculum studies is established. Today, General Didactics and Curriculum Studies (for an overview see for example [230]) exist both in separate worlds, while also efforts to combine General Didactics and Curriculum Theory can be identified [151].

4.1.2. Approaches and models of instructional design

Strong influences in the rise of Instructional Design (ID) in the 1960s were the behaviorist psychological learning theory [276], Blooms taxonomy of cognitive learning goals [44], and the cybernetic systems theory approach [325]. Instructional Design puts more emphasis on the methodology part with systematic linear design processes, and addresses the determination of learning content. As early protagonists in ID Glaser [118] (introduction of the term), Mager [199] (operationalization in measurable objectives), and most influential Gagné [113] (ID as a scientific discipline) can be named.

One well-known approach, which is based on Gagné [113], is given with the Dick and Carey model for "The Systematic Design of Instruction" [85]. The model is (one of) the most influential models of the ID domain [329]. In today's models of ID the following general structure of subtask can be identified: "1. Conduct a needs analysis; 2. Determine if need can be solved by training; 3. Write learning objectives; 4. Conduct task analyses; 5. Identify the types of learning outcomes; 6. Assess trainees' entry skills and characteristics; 7. Develop test items; 8. Select instructional strategies for training; 9. Select media formats for the training; 10. Pilot test instruction before completion; and 11. Do follow up evaluation of training" [329]. "ADDIE" (Analysis, Design, Development, Implementation, Evaluation) is often used as an overarching ID conceptual framework [216,226].

With the general shift from behaviorist theories to cognitive theories, a shift in the field of ID is also recognized to create possibilities for reflective thinking using "free learning environments" [110]. Also the shift to the constructive learning theory in general led to new ID models, e.g. Ref. [134,163,326]. This last shift initiated an ongoing controversy between objectivism (behaviourist and cognitive learning theory) and constructivism in ID, see e.g. Ref. [85,164]. Today, both objectivist and constructivist ID approaches are in application [329]. One popular approach in higher education didactics that brings together the constructivist theory and the outcome-based alignment of learning is the "Constructive Alignment" concept by Ref. [42,197]. In this concept the teaching–learning activities as well as the assessment measures at the end or during teaching courses are aligned to intended learning outcomes [42,43].

4.2. Process of analyzing and configuring a learning factory

Learning factories are complex systems that contain various interrelated concepts and elements. In order to provide a holistic
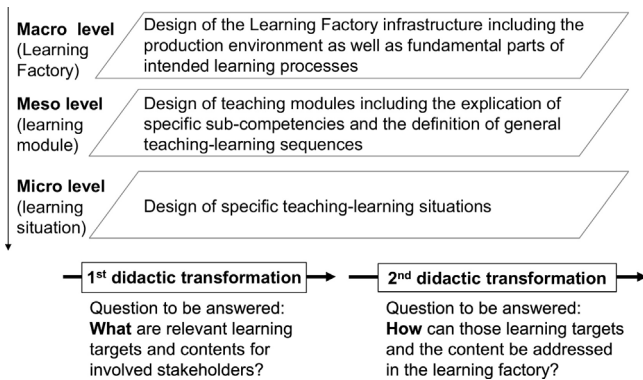
Fig. 17. Conceptual design levels of learning factories [294].

Table 4
Overview on LF design approaches.

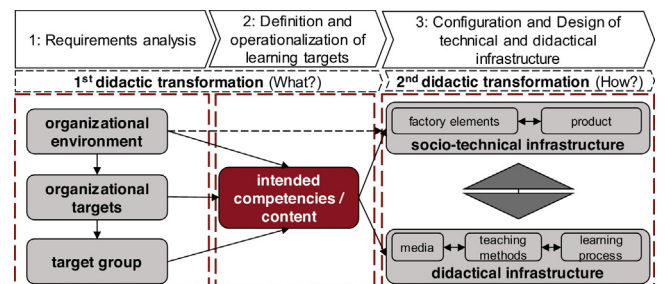| Approach	Design object	Focus	Description
Reiner [241]	LF	Training	Generic three step approach
Riffelmacher [250]	Digital and physical learning environment	Training	Development of a learning environment for high variant assembly systems. No design approach derived
Tisch et al. [294,295]	LF, learning modules, learning situations	Training, education	Holistic learning factory design approach on three conceptual levels
Wagner et al. [315,316]	LF product	Research, education	Product design for learning factories
Doch et al. [91]	LF	Training	Generic four step approach
Kaluza et al.[169]	Scaled-down learning environment	Equipment	Approach to develop scaled-down learning equipment for resource efficiency
Plorin et al. [234]	Adjustment of learning env., learning modules	Training	Iterative approach for the adjustment of learning environments

Fig. 18. From context-specific requirements to the configuration of the learning factory [294,295].

structure for the learning factory concept in general, three conceptual levels of learning factories are defined: [294]

- The Macro level "Learning Factory" includes the learning environment, the learning factory program, and the general didactic approach
- The Meso level "learning module" includes the teaching-learning situations and the preparation of the environment for the specific content
- The Micro level "learning situation" includes specific problems and tasks used inside a learning module.

Fig. 17 depicts the three conceptual levels of learning factories. Following this and depending on the addressed design level, learning factory design approaches address different design objects, namely: learning environments, learning modules or learning situations. Depending on the design level and the specific design objectives addressed, learning factories are seen as Ref. [294]:

a) an idealized replica of real manufacturing environments (factory perspective): Several publications describe the learning factory as a model of a real factory environment, e.g. Ref. [91,169,234,294],
b) a complex learning environment (learning perspective): Several approaches design learning factories as a complex learning environment [9,241,250,294,295]
c) a combination of a) and b)

According to perspective c) learning factories are seen as a learning environment for and a model of socio-technical systems. In order to design and configure the entire learning factory including learning modules, it needs to be designed with its didactical, social and technological implications in mind [294].

For the learning factory development, several linear, sequential, and generic approaches were proposed. Reiner [241] describes the use of learning factory concepts as a part in a lean transformation and therefore uses a generic three step approach: "Requirements", "Development and construction", "operation and use". Doch et al. [91] use similar sequential phases for the development: Requirements analysis, conceptualization, design and implementation (Table 4).

Since competency development is generally seen as a learning factory key objective [2,13,159,203,241,279,294,295], targeted competencies crucially influence the design process. In the context of competency-oriented learning factory design, Tisch et al. [295] define a holistic approach in two major transformations. The first transformation consists of the analysis of targeted sectors, goals, target groups, and the definition of intended competencies and learning contents, i.e. question of didactics in the narrow sense. Based on the results of the first transformation step, the second transformation defines learning media, didactical methods used as well as value creating processes inside the factory [9,295], i.e. the methodology. Fig. 18 gives an overview of the two transformations.

Furthermore, a description of the learning factory design over the three conceptual design levels including several case studies are provided in Ref. [294]. The approach is also used in further case studies, see e.g. Ref. [9,102,190]. Also another approach based on a reference model consisting of structure, design, integration and quality assurance models for the realization of learning factories for factory planning and operation is recognized [233].

Some approaches focusing on (parts of) the second didactic transformation, for example product development for learning factories is addressed. It is discussed that, in contrast to normal factories, learning factory products are defined in a way that the overall learning factory objectives are achieved [211,315,316]. In general, two ways of finding a suitable Learning Factory product are recognized [211,294,315]:

- Industrial products available on the market are chosen (and possibly simplified didactically) with the intention to complete the learning factory configuration (targets, technical system, etc.)
- Learning factory products are designed individually to complement the learning factory configuration.

Fig. 19 compares the traditional product design process (a) with possible learning factory product design processes (b, c).

Additionally, several approaches dealing with specific design questions are recognized. Kaluza et al. [169] describe an approach to design scaled-down learning factory environments. Here, the focus lies on the exact modeling of the technical system in order to make sure that the scaled-down setting has the same characteristics (regarding energy efficiency in this case) as the life-size equipment. Also, it is mentioned that existing approaches focus on the design of learning factories for education and training. A procedure for designing research and demonstration factories is missing [116]. Tvenge et al. [302] see potential in the use of learning factories by opening it to a broader approach like the modern workplace learning framework [137], which allows learning in a continuous, on demand, autonomous, social, and on-the-go manner.
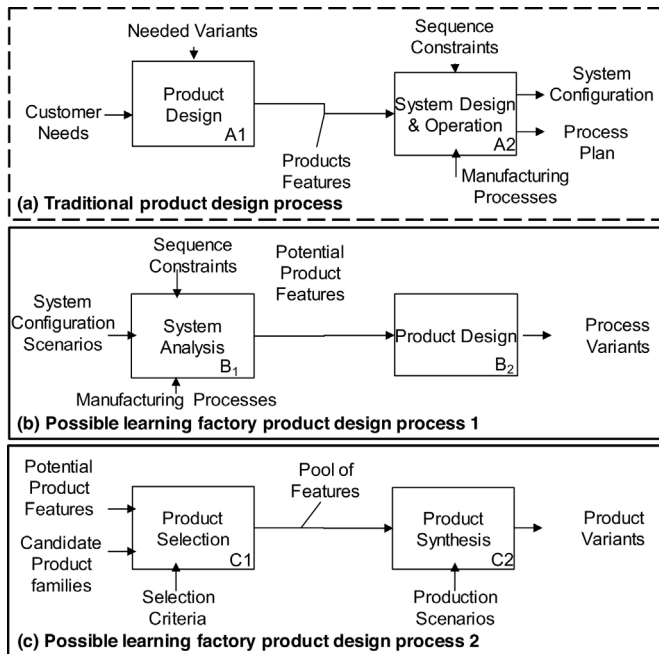
Fig. 19. Comparison of traditional product design process and product design process for learning factories [315,316]).
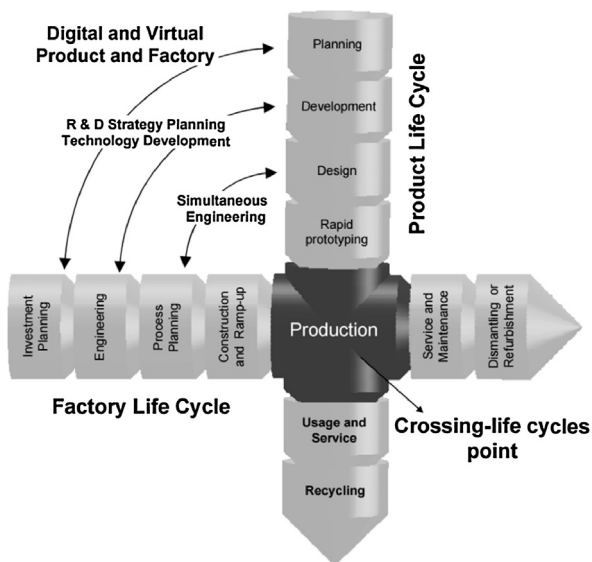

Fig. 20. The product and factory life cycle as a framework for learning factories [228].

In this context, it is important that decisions on the produced product and the mapped processes are interwoven. A decision in the area of the product always affects the production processes and vice versa. This interdependence can also be visualized with the interaction between factory and product life cycle, see also Ref. [228] and Fig. 20.

5. Enhanced learning in learning and teaching factories

5.1. Evaluation of learning success

In this section, the state of the art of learning success evaluation in learning factories is described and available measuring approaches and techniques are discussed. A last section describes how learning success is measured in learning factories today.

5.1.1. Learning outcomes and learning success

Learning environments and systems are arranged in a way that after completing the learning process, individual learning outcomes should be noticeable [222,266]. A major issue regarding the use of learning factories is whether differences in the students' and practitioners' learning outcomes can be documented. In order to start answering this question, intended learning outcomes of learning factories are defined. The sound measurement of learning success requires learning objectives based on which results can be evaluated [245]. The more precisely these objectives are formulated, the more accurate is the assessment of the actual success [196]. Generally, for individual learning outcomes a distinction is made between [310]

- **Knowledge:** Underpinning theory and concepts as well as tacit knowledge arising through experience of performing specific tasks are included.
- **Skills:** Usually describe a level of performance regarding accuracy and speed in performing specific tasks
- **Competence:** The terms competence or competency are used inconsistently in literature [327]. The concept is derived from psychological [322] and linguistic [64] approaches and describes the ability to self-organize including motivational aspects [107].

Different levels of learning outcomes are further described in different cognitive [24,44], affective [182], and psychomotor [78] learning outcome taxonomies, see also Section 2.1.3.

5.1.2. Factors influencing learning success

Learning success is influenced by two key factors: The first and most important factor is the learner including the attitude toward teacher, situation, and content [40]. Second, the learning situation needs to be linked to the requirements of the learning targets [236]. This includes factors like the learning environment, the attitude and behavior of the teacher, the didactic concept [40], or the structure of the learning situation [100].

5.1.3. Learning success measurement

Learning measurement can be defined as the determination and the extent of certain traits, characteristics, and behaviors associated with a learner [206]. Evaluation of personal development measures controls the quality as well as the success of the different phases of the training process and as a result allows the improvement of quality [278]. The widespread CIPP-Model appropriately defines four fields for evaluation of programs and institutions, in the fields: Context, Input, Process, and Product [284]. This section focuses on the product (or also output) phase of the training process. For this phase, Kirkpatrick [177] presents a model that is most observed in practice [277]. In this model, four levels of learning success are defined: reaction, learning, behavior, and results. In the context of this paper the focus is on evaluation of the learning level. In Fig. 21 the learning success evaluation is classified based on the CIPP and the Kirkpatrick model. Additionally, goals, questions, methods, and indicators of the evaluation are defined for each level.

Any form of science-based learning success measurement must meet the three quality criteria validity, objectivity, and reliability [40]. From a practical point of view, other criteria like economy, equality of opportunity [100], manageability, transparency [148], differentiability, or a sensitivity to change [55,70] are also relevant.

5.1.3.1. Measurement techniques and forms of evaluation.
Generally, none of the forms of learning success measurement is fundamentally superior or inferior to others, but rather better or less suiting in specific arrangements [229]. In literature, amongst others, the following systematizations (apart from the Context–Input–Process–Product Model) of techniques of learning success measurement can be identified: [70]

- **Subjective** vs. **objective** evaluation: Subjective evaluation facilitates a fast and simple way of evaluation, although due to the strong dependency on the evaluator (and therefore a limited validity), more and more evaluations are carried out on the basis of objective measurement criteria [70]. A relatively low
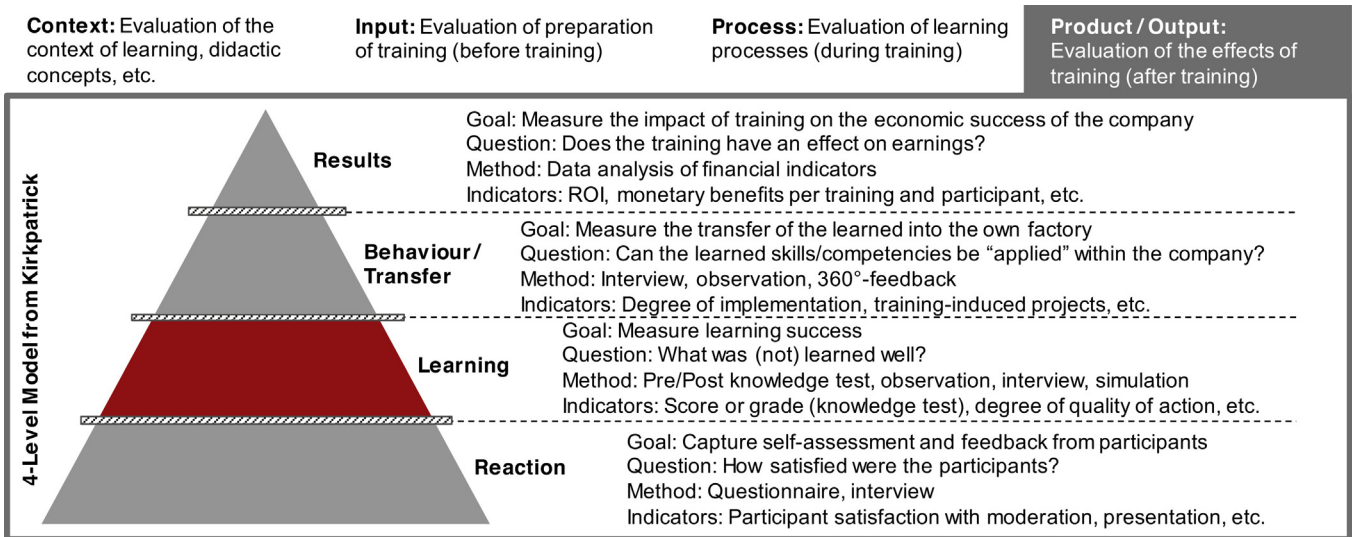
Context: Evaluation of the context of learning, didactic concepts, etc.

Input: Evaluation of preparation of training (before training)

Process: Evaluation of learning processes (during training)

Product / Output: Evaluation of the effects of training (after training)

4-Level Model from Kirkpatrick

Results
Goal: Measure the impact of training on the economic success of the company
Question: Does the training have an effect on earnings?
Method: Data analysis of financial indicators
Indicators: ROI, monetary benefits per training and participant, etc.

Behaviour / Transfer
Goal: Measure the transfer of the learned into the own factory
Question: Can the learned skills/competencies be "applied" within the company?
Method: Interview, observation, 360°-feedback
Indicators: Degree of implementation, training-induced projects, etc.

Learning
Goal: Measure learning success
Question: What was (not) learned well?
Method: Pre/Post knowledge test, observation, interview, simulation
Indicators: Score or grade (knowledge test), degree of quality of action, etc.

Reaction
Goal: Capture self-assessment and feedback from participants
Question: How satisfied were the participants?
Method: Questionnaire, interview
Indicators: Participant satisfaction with moderation, presentation, etc.

Fig. 21. Evaluation possibilities in the training process according to Ref. [297] based on Refs. [22,39,117,177].

correlation (.389) between subjective and objective ratings is recognized [49].

- **Open** vs. **closed** evaluation: In open evaluations potential answers or reactions of learners are not limited (e.g. open questions). Response options in closed evaluation are intentionally predefined (e.g. multiple choice questions).
- **Self** vs. **external** evaluation: In self (or internal) evaluation learners reflect on the actual learning success, see e.g. [196]. Potential problems of self-evaluation is discussed by Harris and Schaubroeck [136]. In external evaluations, other persons as the learner evaluate learning success.
- **Summative** vs. **formative** evaluation: In summative evaluation only final results are compared with postulated goals (accountability). Formative evaluation accompanies learning processes with evaluations allowing also changes in current learning activities (improvements) [76].
- **Direct** vs. **indirect** evaluation: In indirect evaluation multiple measurements are conducted (e.g. pre-/post-tests), and the differential value is seen as an indirect indicator of change. In contrast, the direct evaluation aims directly at the change, e.g. with a direct, subjective question to learning progress [70].
- **Quantitative** vs. **qualitative** evaluation: Quantitative evaluation focuses on what is learned, here e.g. questionnaires can be used. Qualitative description methods aim at a differentiated exploration and understanding of learning and transfer processes.

5.1.4. Practical learning success evaluation

In literature, the forms of assessment are divided into behavioral, generic, and holistic approaches [121,207].

While competencies are not directly observable [107,127,139], they are revealed through single performances in specific problem situations (behavioural approach). Those specific performances are observable [64,127]. Practical learning success evaluations enable the rating of those performances in the process of problem identification or solving [148]. Various such performance-oriented assessments are used in general, and also in learning factories [58,129,148,296,297]. In those evaluations, scenarios with complex problem situations unknown to the learner are created, and the learner's actions (performances) to solve those problems are evaluated [297]. For the performance evaluation, multiple observation channels ought to be used [100]. Observation and evaluation should be separated [229]. Potential problems of performance evaluations are discussed in [100].

Additionally, in contrast to the behavioral approach, knowledge elements which are a crucial basis for competencies [107,139,292] and other underlying traits, such as critical thinking, can be partly queried. This is known as the general approach [292]. Problems of the general approach are discussed in Ref. [121].

In combination, the knowledge- and performance-oriented evaluation of learning success allow a goal-oriented evaluation from two perspectives and, therefore, enables better and more robust evaluation results (holistic approach) [121,292].

5.1.5. Learning success evaluation in learning factories

In recent years, some evaluations of knowledge-oriented, performance-oriented or hybrid knowledge- and performance-oriented learning success evaluations were performed [58,296,297]. However, many more evaluations are needed to foster scientifically sound results.

In the next years, more large-scale longitudinal and cross-sectional studies should be conducted to investigate the learning success in learning factories. This way, the large conceptualization, construction, and operation effort may be justified. This allows wider dissemination and associated enlarged opportunities of the learning factory concept in general.

Apart from the evaluation of learning success, for multidimensional assessment of the learning factory system a maturity model based on the description model containing the learning factory design levels and dimensions [103,294,299] is currently in development, see Refs. [101,103].

5.2. Digital, virtual, and hybrid learning factories

5.2.1. Digital and virtual learning factories

Due to the trend of the digitization of production facilities and processes, virtual and digital learning factories earned increased attention in the context of production education [62,128,132,175,321]. Thus, the spectrum of learning areas in learning factories is continuously expanding.

Besides a physical learning environment, a learning factory can consist of a digital and virtual environment for providing added value for the education of the production of the future. Digital and virtual learning factories are used for the training in similar research fields of conventional physical learning factories. Students' tasks are more focused on planning and simulation activities [321], such as factory layout planning, front-loading, concurrent engineering, virtual commissioning or human ergonomics evaluation.

A digital learning factory maps all processes, products and resources of a real learning factory in a digital model. It is an environment integrated by computer and information technology (IT) as well as data models representing the link between various IT-tools.

Virtual learning factories enhance digital learning factories by providing visual software tools and infrastructure, such as human interfaces, to enable the visualization of digital models. As

industrial virtual factories, a virtual learning factory incorporates visualization of data, for example through virtual reality or augmented reality technology for the digital simulation of operations at factory level, mainly used for virtually planning the layout and processes of a learning factory, simulating tasks or evaluating alternative designs prior to the start of production [66]. Virtual solutions enable the verification of all conflict situations before the real implementation of factories and the design of optimized solutions [153].

Virtual environments are used with the motivation to increment the quality of teaching [200] and are considered an important strategic mean to enable education in the manufacturing domain [201]. In literature, various training approaches using virtual production environments can be identified [1,60,63,82, 83,112,120,201,225,318]. Also the use of virtual environments in combination with physical learning factory approaches is common [234,235,250,251].

5.2.2. Software tools for digital and virtual learning factories

Different software tools are available on the market. The applications are important enablers to create digital factories. However, for providing a digital or virtual learning factory, special emphasis has to be given to the didactic concept, which is usually not integral part of the software itself.

Tools, such as TaraVRbuilder [286] or VisTable [310] are programs that allow visualizing, analyzing, and optimizing 3D virtual production environments without advanced knowledge in programming or CAD. Both tools provide libraries with an extensive number of objects from buildings, machinery and robotics, logistics systems, etc. VisTable supports static scenario planning, material flow analysis, optimization of assembly lines and space utilization (Fig. 22). In comparison, TaraVRbuilder simulates processes and enables the creation of dynamic virtual production and logistics systems as well as planning for "Industrie 4.0" applications.

Fig. 22. Exemplary virtual factory; visTable®touch Software [311].

Three dimensional (3D) experience [77] by Dassault Systèmes is a combination of previously separated tools, such as Catia, Delmia, Simula and Enovia. It aims at the integration of product-, resource-, layout- and process planning, which allows not only to develop virtual products but also to build a virtual manufacturing environment. Additionally, the simulation of different scenarios can be conducted directly in a virtual factory. Due to the fact that operating with this tool requires advanced skills in CAD programming, introduction to the application is required.

5.2.3. Fusion and integration of hybrid learning factories

Various characteristics of digital learning factories make them act as a strong supplement for the physical learning experience since they provide more flexibility and freedom in experimenting. Therefore, it is essential that the digital learning factory represents the real learning factory in all of its relevant processes, activities and resources. The system can be simplified and modeled for the purpose of digital simulation. Both physical and digital environments can support the adaptability and the improvement of the respective environments [94,219]. If the level of fusion and integration of the physical, digital and virtual components has reached a high maturity, the concept of a so-called hybrid learning factory is realized (Fig. 23). A hybrid learning factory faces the challenge to bridge different data sources in a robust and reliable way, to remove media breaks within real and virtual worlds, in order to create one (seamlessly) merged world.

Another perspective about the collaboration and integration of physical, digital and virtual learning factories indicates that digital environments have contributed to the education approach of learning factories by providing an alternative for building those factories with real equipment. Thus, educational concepts exist which exclusively perform in a digital or virtual learning environment without physical production infrastructure [132]. Digital factories have a bigger scope without strict limitations since their experimental field can be extended to a more holistic view [195]. The simulation of an increased number of scenarios and turbulences can be provided [250]. The expansion of value chain related processes, such as the supply chain, can be executed by computer aided models. Operating with digital systems offer high analysis speed and the simulation of long-term, frequented repeated periods without the need of teaching staff and costs for resetting the plant [323]. Physical learning factories require pre-defined and limited learning scenarios due to high investment and operating costs of preparing a production facility with real machines and equipment limit the setup and operation. In comparison, building up a digital learning factory requires investment into IT infrastructure and efforts for its implementation, i.e. programming and integration.
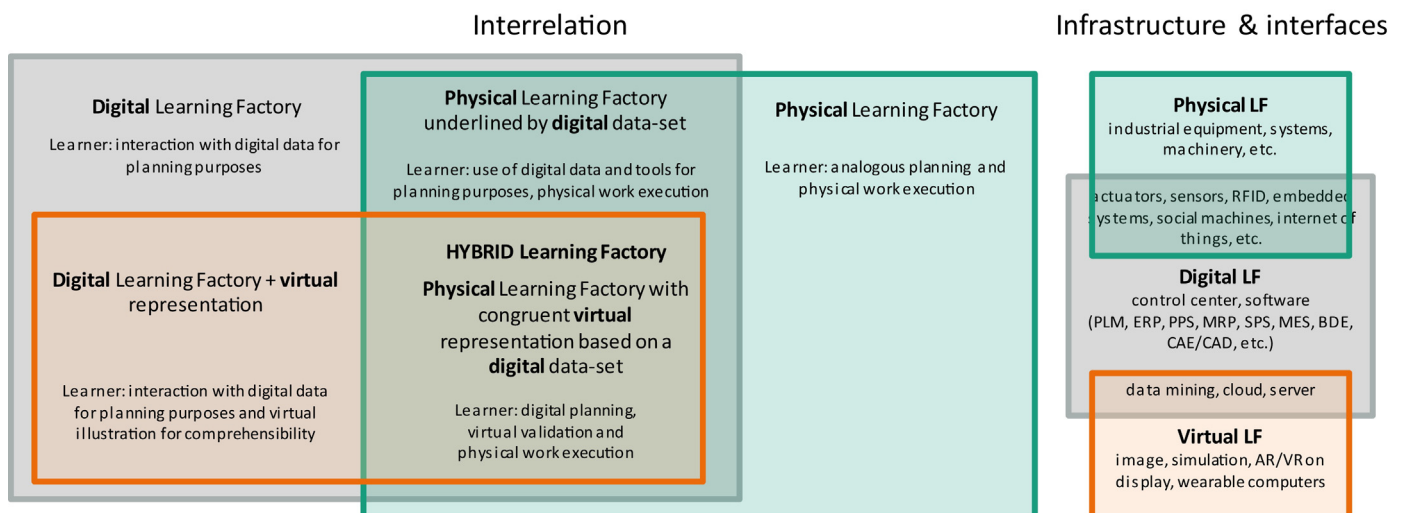

Fig. 23. Physical, digital, and virtual learning factory concepts.

5.2.4. Use cases of digital and virtual learning factory

At KTH XPRES Lab, a digital factory is developed for the purpose of supporting cross-disciplinary organizational learning and decision making when designing manufacturing systems. A new concept vehicle and the digital factory of its manufacturing system are part of the lab. It will exemplify how digital models of product, manufacturing processes and factory are visualized and integrated to clarify interdependencies and support a holistic decision making. Digital manufacturing is performed in terms of machining simulation in the machining section, and flow simulation in the layout section. In the real XPRES lab, the upright is machined in a 5-axis machining center. Learning is supported by not only modeling and visualization, but also by hands-on experience through the simulation of a what-if scenario of the effects of changes in each domain and in the whole system [275].

The ESB Logistics Learning Factory (LLF) at Reutlingen University is a training and innovation instrument to gain professional action competence in the field of the design and optimization of cyber-physical production and logistics systems including the ergonomic evaluation of these systems [153]. The LLF has a virtual representation identical with the physical learning factory that was created in Dassault Systèmes' "3DEXPERIENCE" software, consistently integrating product, resource and process design as well as simulation in one platform. The virtual model serves as a complement to the physical environment and allows students to test and validate system designs and system changes virtually before their implementation in reality (Fig. 24).

In the virtual learning factory of McKinsey & Co. participants from all over the world meet in an authentic 3D virtual factory [132]. Together they observe the virtual execution of production processes to detect and discuss optimization possibilities. Through the so-called "go–see–do" training activity, the concept of experimental learning is realized. Participants experience the transformation of suboptimal states to best practice through self-directed improvement identification and implementation. The training curriculum, that addresses core lean topics, management infrastructure, as well as mindset and behavior, guarantees a consistent, customized implementation.

Festo offers modular production (MPS) and advanced learning systems to create tailored solutions for universities, vocational schools and manufacturers. Since these systems are supported by the virt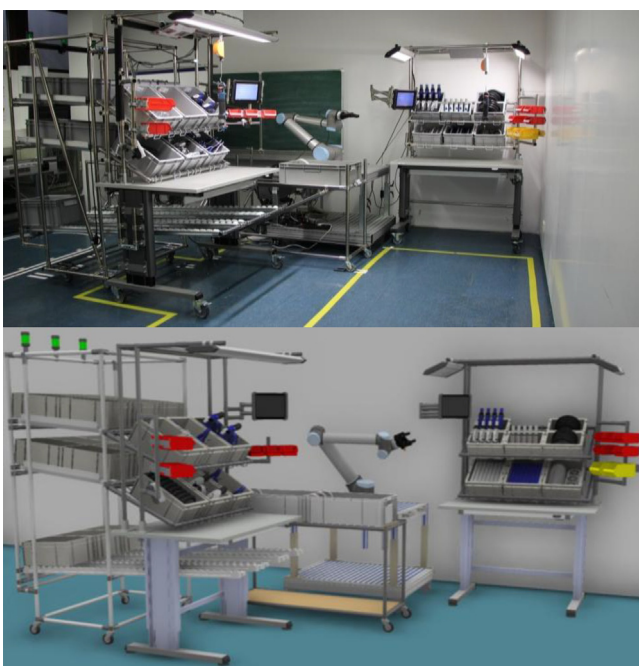ual platform CIROS VR [69], users benefit from opportu-nities to plan, simulate and optimize factory components and their interactions virtually.

6. Enhanced research in learning and teaching factories

Applied sciences like production engineering strive for the creation of practically utilizable knowledge. Research topics typically emerge from questions coming up in industrial practice [305]. Fig. 25 shows the interaction of empirical experiences and theoretical research.

However, any direct interaction of research and industrial daily operations brings hardly controllable risk of interference with basic factory stability. Furthermore, the complexity and the costs for transferring research results directly to industrial production can be considerably high, especially for SMEs that predominantly do not have their own research infrastructure and academic experts from various research fields. Learning factories can provide a significant potential for research and for demonstration and innovation transfer.
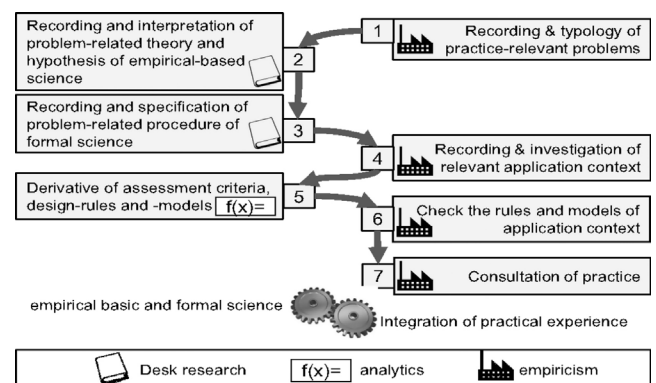

Fig. 25. Research process of applied sciences [261] on basis of Ref. [305].

6.1. Potentials of an extended learning factory approach

A concept for involving learning factories as research enablers in the research process is presented by Seifermann et al. [267] and shown in Fig. 26. In this approach it is described how research problems can be identified and solutions tested and verified neutrally with the help of the physical model learning factory at reduced costs and complexity compared to reality.

This research approach can be illustrated with the help of the example of cellular manufacturing activities at the process learning factory CiP [267]. From the problem identification [37] over the evaluation of general economic application fields and efficiency evaluation [38,209,212], gains in flexibility [213], and examination of quality issues caused by multiple clampings [47,48], to enabling concepts for cellular manufacturing like low cost automation approaches [266] can be developed, tested and validated in learning factories. Independently from the general research process, learning factory environments are often used as validation environments, see e.g. Ref. [27,28,56,57,172,173,301].

Furthermore, today, companies face the challenge of having access to latest technologies and related know-how. Learning factories offer a great potential for demonstration and innovation transfer. Learning factories provide application-oriented innova-tion and technology platform that enable development and research until market maturity of products, production technolo-

Fig. 24. Real assembly environment and its virtual model of the ESB Logistics Learning Factory (LLF).

Fig. 26. Learning factory as research enabler according to Ref. [267].

gies, and production processes as well as the subsequent transfer of those innovations is facilitated.

6.2. Use cases of research and innovation factories

A number of research, innovation and demonstration factories are presented in the following.

The Industry 4.0 Pilot Factory (I40PF) in Austria serves both as a research platform and a teaching and training environment with regard to a human-centered cyber-physical production system for "high-mix and low-volume" (lot-size 1). It is based on the "Learning and Innovation Factory for Integrative Production Education" (LIF) from the Vienna University of Technology. The I40PF provides access to Industrie 4.0 competencies and equipment, such as intelligent assembly technologies, digital assistance systems with augmented reality technologies on wearable devices and collaborative robotic systems [106].

The learning factory of the Intelligent Manufacturing Systems (IMS) Center at the University of Windsor (Figs. 12 and 27) supports the innovative research conducted at the institute and has proven to be an effective test bed for developing and demonstrating new technologies, tools, methods and advanced research concepts in systems engineering. Research results are assessed in the learning factory and demonstrated to academia and industry. Exemplary research topics contain: (a) strategies for product variety management [97]; (b) types and metrics of manufacturing systems complexity [98]; (c) co-evolution and co-development of products and their manufacturing systems inspired by biological evolution [99]; (d) new applications of Max-Plus Algebra in modelling and simulation of manufacturing systems [269]; (e) design synthesis of manufacturing and assembly systems and optimum system granularity [20] to identify optimal product and process platforms; (f) manufacturing systems layout complexity modelling and metrics [95] modular product–multi platform configuration [133] to customize product platforms where either assembly and/or disassembly to improve responsiveness to changing orders; and (g) assembly systems synthesis and master assembly sequence generation using knowledge discovery [170].

The Department of Factory Planning and Factory Management at the Chemnitz University of Technology operates the Experimental and Digital Factory (EDF). The facilities provide networked laboratories for innovation, CAD, ergonomics, usability and biometry, as well as a project house. The EDF is used as a research and teaching environment for changeability with regard to product, process and resources. A testing environment for equipment manufacturers is included [314].

Also located in Chemnitz, the Fraunhofer IWU uses the "E^3-Factory" for research in car body powertrain production with a focus on energy. Prototypes are introduced and tested before being transferred to the industry [283].

On 1600 sqm, the Demofabrik Aachen features small-scale production of marketable products with a high vertical range of manufacture. This includes sheet metal forming, joining of automotive body structures and a manual assembly section. The process chain as well as individual production steps represent authentic industrial requirements in terms of complexity level and quality specifications [260]. It is integrated in the Enterprise-Integration-Center that features additionally an ERP-innovation-lab, a service-science-innovation-lab and a smart-objects-innovation-lab for digitization, simulation and visualization of complex production systems.

The research and teaching factory of the Cal Poly State University includes a functioning real factory, and a production planning and control center to enable the decision making and communication functions, which act as an integrated whole, by utilizing state-of-the-art communication networks. The learning and manufacturing environment combines a precision machining enterprise, producing car parts for GM, Ford, Daimler-Chrysler and their suppliers, state-of-the-art educational technology, such as distance learning, online courses, and time-tested tutoring, mentoring and lectures. Industrial projects that take place in the teaching factory provide students with the integration of learning experiences into a contextual setting, where emphasis is given to the competency and effective application [65].

The Advanced Manufacturing Institute (AMI) at Kansas State University (KSU) operates a full service engineering and manufacturing facility, located at an industrial park [29]. The concept involves students to provide services in designing and developing new solutions for industrial clients and complement their academic education with the hands-on real engineering practice. Thus, an extended teaching factory paradigm has been realized with the aim to effectively integrate education, research and innovation activities within a single initiative involving industry and academia [67,300].

A SmartFactory at the Technical University of Kaiserslautern aims to model the intelligent industrial plant of the future [330]. It is modifiable and expandable (flexible), it links any number of components from different suppliers (networked), enables the independent execution of contextual tasks by components (self-organizing), and emphasizes the user friendliness of the systems (user-oriented).

The Process Learning Factory CiP at TU Darmstadt is used for research in two different ways: (a) research on the topic "learning factories" [4,5,58,102,294,295,297,299] (b) research on various topics in the area of Lean Production, i.e. Refs. [17,56,57,130,147, 209,212,213,254–257,266].

7. Conclusion and future research priorities for (inter)national programs

7.1. Potentials and limits of learning factories

Based on the learning factory morphology (Section 2.3 and Ref. [299]) the main and secondary purposes of learning factories can be identified. Especially for the main purposes (education, training, and research) as well as for the secondary purpose (test/pilot environment) learning factories offer a high potential. Potentials of learning factories are derived and discussed in Section 7.1.1. Additionally, in Section 7.1.2 limiting factors of learning factories are identified and possible concepts to overcome those limits are derived.

7.1.1. Potentials of learning factories

In this section the potentials of learning factories are identified regarding education and training. Potentials of learning factories for research and innovation transfer are discussed in Section 6.1.

In didactics, psychological, and learning design literature, aspects of the methodical modelling of successful learning processes are discussed intensely, see e.g. constructivist learning environments [163], situated learning [192], active learning [162], or problem-based learning [51]. In order to create effective learning, it is advantageous if learning environments and learning modules can address these orientation concepts. Fig. 28 gives an
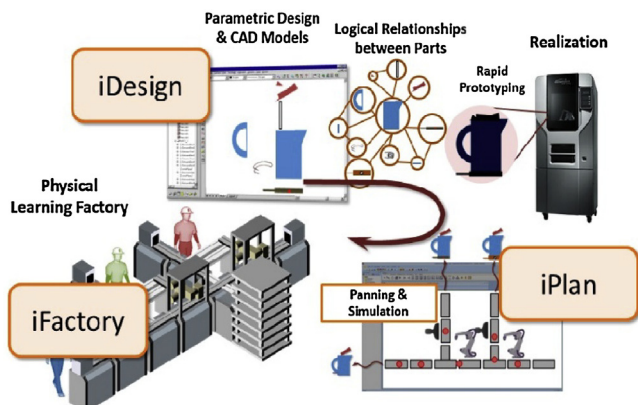

Fig. 27. Integrated products and systems design, planning and control demonstrated in the learning factory environment at the IMS center, University of Windsor [94].

Aspects of methodical modelling	Learning factory as a learning system
Contextualization, situated context [163,192]	Partial model of real factory provides a rich learning context
Activation of learner [50,162]	Generation and application of knowledge in the learning factory (learner active phases)
Problem solving [51]	Solving of real problem situations in the learning factory
Motivation [79]	Motivation by the reality character and the possibility to act hands-on immediately.
Collectivization [125]	Self-organized learning in groups is a suitable model in learning factories
Integrate thinking and doing [19]	Alternation of hands-on phases in the learning factory and systematization phases
Self-regulation [263] and self-direction [114]	External as well as self-controlled learning processes are enabled – depending on the prerequisites

Fig. 28. Aspects of methodical modelling of successful learning processes and the possibilities in learning factories [298] based on Refs. [19,50,51,79,114,125, 162,163,192,263].

overview of the most important aspects to enable effective competency development as well as the extent learning factories are able to address them.

With regard to formal learning oriented toward work processes, two learning process approaches are distinguished in general:

- Information assimilation: Where content (e.g. methods, experiences of others) is first theoretically derived/explained and then afterwards applied and tested [71].
- Experiential learning: Where the application is seen as basis for theoretical understanding of content [181].

Advantages and disadvantages of learning process types have been discussed intensively in the literature [71,171,328]. Fig. 29 shows how in production-related education and training both types of learning processes, i.e. information assimilation and experiential learning, may profit from integrating the learning factory concept.

Additionally, the process of learning is often described as a feedback process [25,111,248,282], in which actions of the learner alters the surrounding system (real world). As the real world changes, it gives the learner information about the system, consequently, with this new information the learner gets a revised understanding of the surrounding system and the decisions he or she makes to bring the real world closer to the underlying goals [282]. Action and cognition cannot be separated from each other [222], since the understanding leads actions, and actions update the understanding [52,75,320] as visualized in Fig. 30. In organizational learning literature the direct link between "information
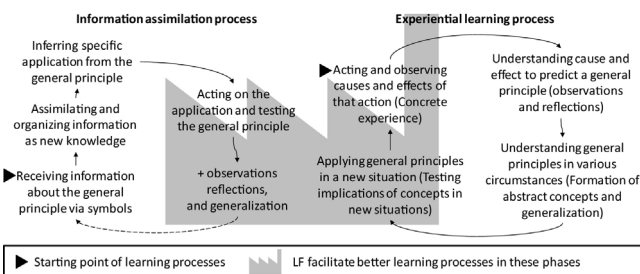

Fig. 29. The role of learning factories in learning processes [298].
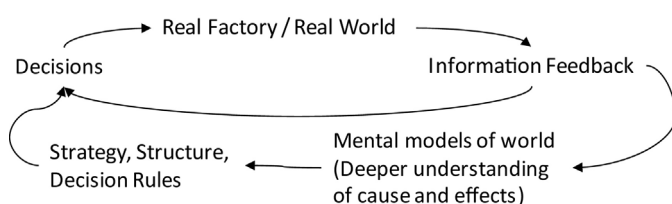

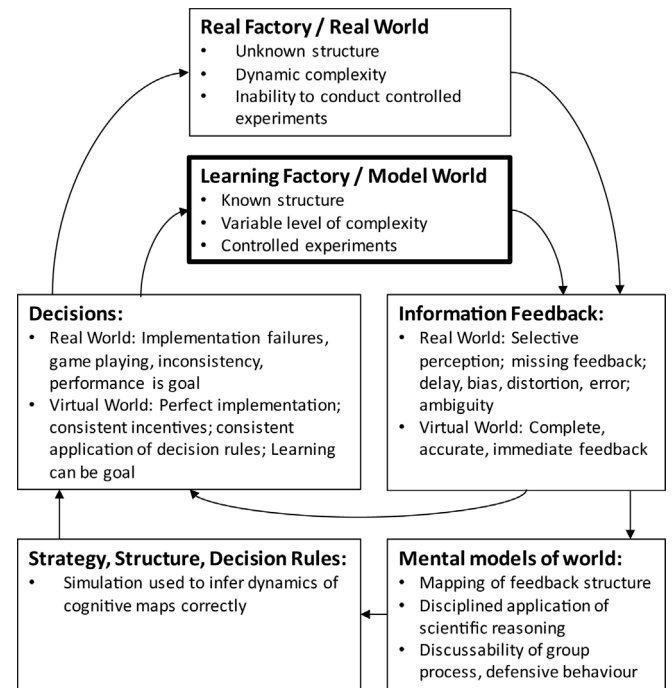Fig. 30. Learning as a feedback process according to Ref. [282].

Fig. 31. Extend the learning loops with the help of learning factories as virtual worlds, according to Ref. [282].
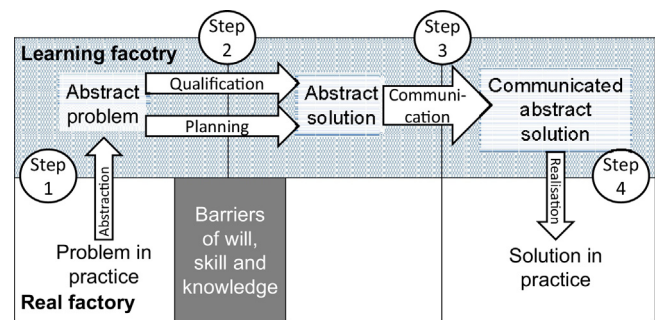

Fig. 32. Learning factories in change management [88].

feedback" and "decision" is named "single-loop learning", the indirect link from "information feedback" over a change in the "mental models of the world" is named "double-loop learning" [25].

Having this feedback loop in mind, in the manufacturing domain learning factories can serve as a kind of "virtual world", see Ref. [282], which provides high quality feedback by experiencing industry-relevant transformation processes and problem situations in advance. In this manner, learning factory concepts expand the learning feedback cycle. Fig. 31 visualizes the expanded feedback process and shows the benefit of learning factories, having a virtual world installed where the focus can be on learning and not on the performance of the factory.

Therefore, learning factories can be used to facilitate organizational change processes [88]. In a survey with managers in Austria, Switzerland, and Germany the resistance of employees is identified as the most important reason why change projects fail [144]. Sources for employees' resistance barriers of will and barriers of skill/knowledge can be traced [88,244]. Fig. 32 shows a learning factory concept to overcome those barriers by abstracting the problem in the learning factory, qualify, plan, and find a solution in the learning factory, and as a last step transfer the solution to the real factory environment [86,88].

7.1.2. Limits of learning factories

For the learning factory concept as it is implemented today, several limitations can be identified. In the following sections the limits of learning factories are systematized in limits regarding

- the resources needed for learning factories
- the mapping ability of issues in learning factories
- the scalability of learning factory approaches
- the mobility of learning factory approaches
- the effectiveness of learning factories

7.1.2.1. Limited resources. The conceptualization, building, and operation of learning factories are resource intensive tasks. Various resources from suitable personnel to appropriate equipment, corresponding space, facilities, high quality content and knowledge are needed. Any missing resource in building and use of the learning factory can be a show stopper. Accordingly, for the sustainable operation of learning factories not only a model is needed that continuously ensures financial, but (just as important) also human and content/thematic sustainability [299]. Fig. 33 identifies exemplarily the most relevant resources needed over the lifecycle of a learning factory.
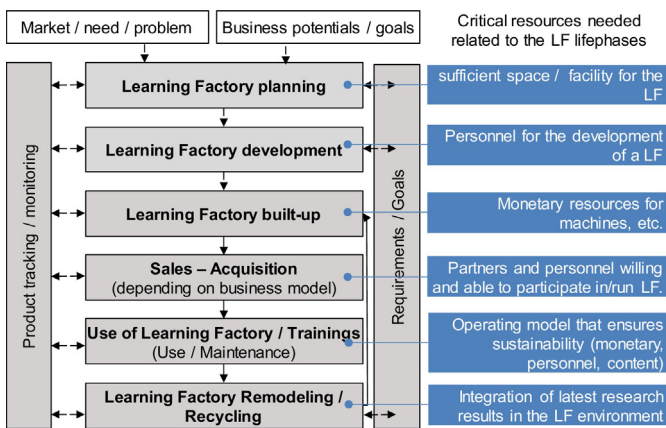

Fig. 33. Required resources over the learning factory lifecycle [298], lifecycle similar to general product lifecycle according to Ref. [307].

7.1.2.2. Limited mapping ability. As a model of the real factory, learning factories map the setting and the processes of industrial environments. In this context a single learning factory is not able to provide a suitable, general environment for all challenges in academia and industry. Single learning factories have to focus on specific topics (**content- and object-related mapping ability issues**) [11], in this context an approach for the interconnection of learning factory sites is proposed [319].

Furthermore, in theory, learning factories may focus on problems and challenges on all factory levels, from work place up to a whole factory network, see e.g. Ref. [324]. Especially, on the top factory level "factory network" **space- and cost-related mapping ability issues** occur obviously. Although, single learning factory approaches are identified that especially address problems of global factory networks [191].

Additionally, the learning factory concept reaches limits when feedback cycles based on the actions of participants would take too long to be completed naturally and there is no possibility of using a "fast forward"-like simulation in order to shorten the feedback cycle. Of course, those limits depend on the duration of the learning module. Examples for action fields with long feedback cycles are supplier development, product development, maintenance plans etc. In those cases, learning factory trainings can be created but feedback cycles on the action of learners either need to be simulated or would not be completed (**time-related mapping ability issues**). Examples for immediate feedback cycles are standard lean topics like line balancing, 5S or SMED.

7.1.2.3. Limited scalability. Compared to other education concepts, the scalability of the learning factory concept is strongly limited. For example in a lecture, one lecturer may teach without problems up to 500 learners or more. Most learning factory concepts need one to two trainers for up to 15 trainees. Furthermore, the capacity

of the facility is a limiting factor. Often only one class at a time can take place in learning factories. One approach in this matter is the e-learning integration in learning factories [190].

7.1.2.4. Limited mobility. Physical learning factories are built at fixed locations; they are not mobile and only regionally available. Approaches addressing this limit can be identified, e.g. Ref. [203].

7.1.2.5. Limited effectiveness. Learning factories are built in many cases with the aim of competence development. Often it is not checked if learning approaches are effective. In order to achieve effective learning factories, goals must be considered in the design as well as in the evaluation phase.

In order to overcome the identified limits of learning factories the following suggestions are considered helpful [298]:

- Systematic approaches to design LFs of any kind.
- Virtual learning factories that are less resource consuming and allow a scalability and mobility of the LF approach.
- Concepts using ICT equipment to enable a location independent operation of the learning factory.
- Methods to measure competence-oriented learning success.
- Network of learning factories to overcome the problem of a limited scope of single facilities.

7.2. Outlook: challenges and opportunities

In recent years, learning factories have been established in manufacturing education and research as promising learning and innovation platforms. This paper provided a scientific overview of the global state of the art of learning factories in academia and industry. Considering the novelty of the topic, the paper revealed a fair and sound maturity level. Still, in the coming years, significant challenges remain to be faced by the learning factory concept: Industrial practice, i.e. manufacturing technology, industrial settings, engineering problems etc., is changing rapidly, the pace in which production systems evolve has significantly increased over the last decades, and many new technologies and approaches have been introduced in operations. The learning factory concept has to keep pace with these changes in order to be up to date or even proactively innovative in the years to come.

Moreover, manufacturing technologies vary widely. The paper showed that dedicated learning factory facilities are in general limited to certain application domains. Approaches to networked learning factories combining synergies on different contents and foci, or the use of ICT-equipment to increase the scale of a learning factory setting should be explored. Advanced digital technologies and high-grade industrial didactic equipment might emerge as supporting opportunities and valuable tools. This could even potentially facilitate the establishment of non-geographically anchored learning factories.

Although digital learning factories can be considered as an effective learning tool, they lack physical interaction and teamwork qualities that are present in physical learning factories [128]. While in digital learning factories it is possible to filter external influencing factors that may be not relevant for learning scenarios, such as machine noise or air temperature, physical learning factories provide these authentic experiences and in addition they simulate uncertainties, such as machine failure, tool fracture or human errors.

In future production scenarios, IT skills are needed to be able to cope with the modeling of complex processes and the cross-domain integration of different systems [160]. Academic education is forced to enable a proper understanding of engineering as well as computer sciences at the same time. Therefore, in digital learning factories, students additionally gain knowledge in IT through working with digital models, using simulation software, manipulating and analyzing data or design interfaces between cyber and real world.

7.3. Future research

The opportunities mentioned above result in future research priorities. Future research work includes the definition of new business models facilitating education and training through a learning and teaching factory network. The availability of learning content and resources is a major limitation in the training delivery process. The structuring and launch of a learning factory network may enable an efficient allocation of demand and supply.

Physical, digital and virtual learning factory concepts are complementary. Since each learning factory type offers individual advantages, a fusion and integration in a hybrid learning factory environment is potentially very beneficial. Future research is required on how physical, digital and virtual learning factories can collaborate and on how higher and advanced education can be improved through these hybrid learning factories.

There is also a need to develop learning factories for limited budget education, utilizing representative but simpler equipment and software to help widen their use in learning and training. The gaming methodology can be adopted to develop lower cost yet effective leaning factories.

Today, learning factories already cover a wide range of application scenarios. Many of these were created with "the mind of a good engineer". In the future, it will be important, that effective and efficient learning factory configurations can be identified and developed systematically. To do so, it is fundamental to be able to measure learning success in a simple but valid way in order to be able to effectively evaluate learning factory concepts. Further, large-scale and statistically sound research in the learning success assessment field is needed.

Regarding the learning processes, innovations are desirable: learning factories have to enable individual learning paths for participants. Virtual or media supported and remote trainings can enhance the scalability of learning factory approaches.

Learning factories should be linked more closely with innovations (new prototypes, product/production technologies, and production processes). In order to further develop the possibilities of learning factories the numerous partners should continue to share their ideas in networks for good learning factory practices regarding education, training, and research. The first class expertise in research could be engaged effectively in global teaching with a joint international CIRP learning factory curriculum for manufacturing education.

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