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Challenges and Opportunities of Virtual Learning Factories in Comparison to Physical Learning Factories

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Abstract
Learning factories are widely used in engineering education to enable hands-on learning in realistic production environments. Traditionally, these learning environments have been implemented as physical factories, which require substantial financial, spatial, and personnel resources. Advances in digitalization and virtualization have led to increasing interest in virtual learning factories (VLF) as a potential alternative. This paper investigates whether VLF can be considered a viable alternative to physical learning factories (PLF) and identifies their key characteristics, advantages, limitations, opportunities, and risks. A systematic literature review was conducted using the Web of Science, EBSCOHost, and Google Scholar databases, resulting in a qualitative analysis of 44 relevant publications published between 2010 and 2023. The results show that VLF share core didactic principles with PLF, such as project-based learning in multi-stage production environments. Their main advantages include flexibility, scalability, reduced resource consumption, remote accessibility, and enhanced visualization of production processes. However, significant limitations remain, particularly regarding the lack of haptic feedback, high development effort, dependency on specialized personnel, and limited realism of simulated production resources. The study concludes that VLF cannot fully replace PLF but represent a complementary and resource-efficient extension, particularly for planning, analysis, and early-stage training. Future research should focus on standardized architectures, improved sensory immersion, and the integration of human-centered and organizational aspects.

Keywords
Learning Factory; virtual reality; teaching factory; virtual factory; virtualization.

Introduction

In recent years, a discrepancy has emerged between the demand for specific skillsets among employers and the academic offerings that prepare engineering graduates for the workforce. From the perspective of industrial employees, the skillset requirements are characterized by a high level of adaptability to new and emerging technologies in production environments (Mourtzis et al., 2021). It is anticipated that graduates will demonstrate a holistic way of thinking, in regard to interdependence of business units (Massow et al., 2021). Graduates need to demonstrate proficiency in systems behavior, problem solving, methodology, as well as communication and social skills (Jaeger et al., 2013).

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Conversely, academic and educational institutions possess a vast array of methodological competence. Thus, the educational approach is theoretical, with less emphasis on problem-based, project-based, and hands-on learning (Mourtzis et al., 2018). Consequently, there is a shortcoming in the effective transfer of methodological knowledge. This is a crucial element in comprehending and contextualizing the subject matter and integrating it into productive environments (Jaeger et al., 2013).

In order to address the emerging gap between the requirements of industry and the educational offerings, it is essential to implement an optimized learning concept, where students benefit from a substantial comprehension of the operational principles in production environments. In particular, new learning methodologies are required to facilitate training in realistic manufacturing environments. To enhance specific graduate skills with hands-on learning and training a real-world approximation of a factory is therefore emphasized (Jaeger et al., 2013). Through this approach of active knowledge receiving coupled with groupwork sessions, students gain proficiency in social and communication skills while also fostering adaptive problem-solving abilities and an innovative, lateral thinking style (Abele et al., 2017; Stavropoulos et al., 2018).

One potential solution to achieve this objective is the learning factory. As illustrated in Fig. 1 a learning factory is a facility designed for the transfer of knowledge in a real production environment, with the aim of providing training, teaching and research opportunities (Abele et al., 2017; Wagner et al., 2012). The learning factory comprises authentic, multi-stage production processes and incorporates technical and organizational aspects within changeable settings. The creation of products or services allows for the measurement and comparison of learning factory performance (Abele et al., 2017; Kaasinen et al., 2020; Karcher et al., 2023b).

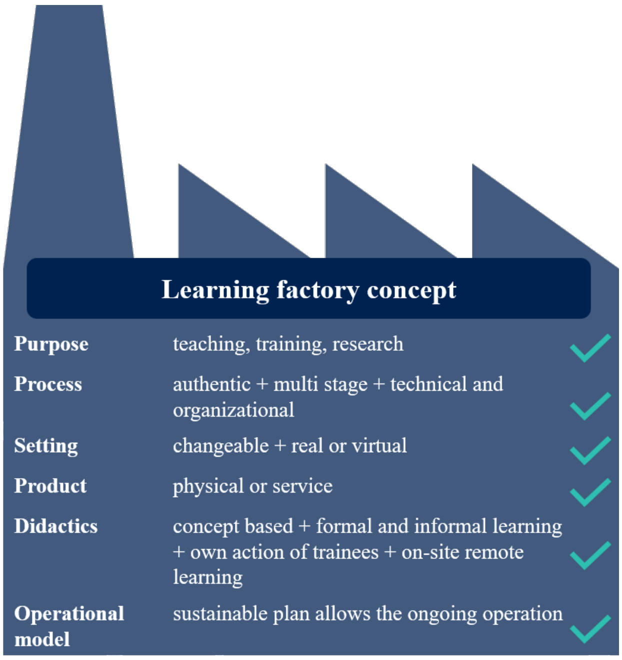

Fig. 1. Learning factory concept according to Abele (Source: Abele et al., 2017, S. 2, without extension)

Since the concept of the learning factory was first introduced, a variety of different types of learning factories have emerged. This study aims to compare two of them: virtual learning factories (VLF) and physical learning factories (PLF). It evaluates their respective benefits, limitations, and applicability, against the backdrop of advancing technologies and the inherent physical constraints in terms of accessibility, scalability, and resources. It investigates whether VLF offer a viable alternative and identifies contexts in which they may enhance learning and research outcomes. For that reason, the following three research questions should be answered:

1. What are the key characteristics of physical learning factories as described in the literature?
2. What are the defining characteristics of virtual learning factories?
3. What are the similarities, differences, strengths, weaknesses, opportunities, and risks of virtual learning factories compared to physical learning factories?

The remainder of this paper is structured as follows. Section 2 outlines the methodology of the conducted systematic literature review, including the selection criteria and analysis procedure. Section 3 introduces the conceptual framework by defining key terminology and clarifying the relationships between core concepts relevant to learning factories in general and virtual learning factories in particular. Section 4 presents the comparative results of the literature review by systematically contrasting physical and virtual learning factories with regard to their realization, strengths, and limitations. Building on these findings, Section 5 discusses the results in relation to the three research questions, critically reflecting on opportunities, risks, and future research directions. Finally, Section 6 summarizes the main findings, answers the research questions, and outlines concluding implications for research and practice.

Methodology of the conducted systematic literature review

In order to respond to the proposed research questions, this study adopts a qualitative, comparative research design based on a systematic literature review and structured content analysis as illustrated in Fig. 2. The literature search was conducted in March 2024. Therefore, only publications available up to the end of 2023 were considered in the analysis. To conduct the research, the following databases were utilized: Google Scholar, the Web of Science and EBSCOHost. The Web of Science was selected due to its focus on high-quality, peer-reviewed journals in engineering and manufacturing research. EBSCOHost was included to cover interdisciplinary publications related to education, management, and economics. Google Scholar was used to identify relevant conference proceedings and otherwise unavailable literature, which play a significant role in learning factory research. The selected studies were coded according to predefined analytical categories derived from the research questions, including technical, didactic, and organizational dimensions as well as reported advantages and limitations. The literature search was conducted using clearly structured Boolean search strings. The following generic search

logic was applied across all databases:
("learning factory" OR "learning factories") AND ("virtual" OR "VR") AND ("training" OR "education")

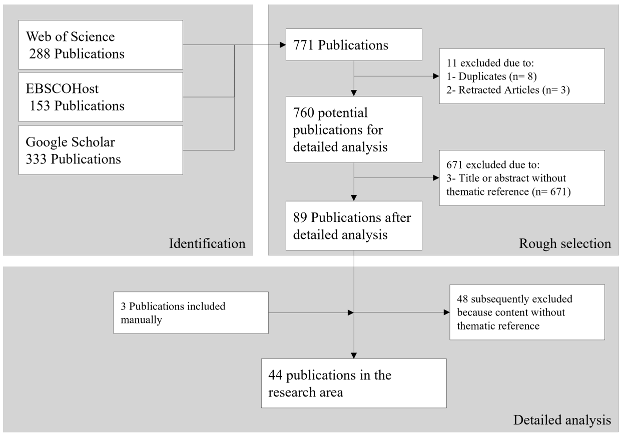

Fig. 2. PRISMA Diagram for the conducted systematic literature review

Database-specific adaptations were applied where required due to differing query syntaxes. In addition to the Boolean search strings, database-specific filters were applied to ensure the scientific quality and relevance of the identified publications. In EBSCOHost, the search was restricted to peer-reviewed journal articles with full-text availability. In Google Scholar, the results were screened with a focus on review articles and conference papers relevant to learning factories and virtual learning environments. The Web of Science search was conducted without additional content-related filters, as this database already provides a curated selection of peer-reviewed scientific publications. These database-specific refinements were necessary due to differences in indexing systems and search functionalities and aimed to increase the precision and relevance of the search results while maintaining consistency with the overall search strategy. In order to ensure the inclusion of the most up-to-date research, publications that have undergone peer review and been published between 2010 and 2023 are considered, with the understanding that the majority of these will be in either German or English.

The preliminary search yielded 771 publications, of which 11 were excluded due to being duplicates or retracted. Of the 760 remaining publications, 671 were excluded due to an absence of thematic reference in the title or abstract. Following an initial title and abstract analysis, 89 publications remain. Following a full-text screening of the remaining publications, 41 papers were selected as relevant for this research. An additional three publications were included through backward reference searching.

The selected publications were analyzed using a qualitative content analysis approach. Relevant information was extracted and coded according to the predefined categories derived from the research questions. These categories included characteristics of learning factories, advantages and disadvantages, didactic aspects, technical requirements, and organizational implications. Based on this coding process, recurring themes and patterns were identified and synthesized. Owing to the heterogeneity of study designs and outcome measures in the reviewed literature, a qualitative narrative comparison was conducted rather than a formal quantitative evaluation framework.

Conceptual Framework and Classification

This section establishes the conceptual framework for the analysis of physical and virtual learning factories by synthesizing key concepts from the literature and clarifying their interrelations. Learning factories are generally understood as educational and research-oriented production environments that integrate realistic manufacturing processes with structured knowledge transfer. With increasing digitalization, different realizations of the learning factory concept have emerged, which vary in their degree of immersion, interaction, and technological implementation.

Building on this development, four conceptual pillars can be identified as central to the realization of a VLF: the production environment, knowledge transfer, digital twin, and extended reality. As illustrated in Fig. 3, these pillars jointly define the conceptual space of virtual learning factories. Only when all four pillars are combined can a learning environment be classified as a VLF in the strict sense. If one or more of these pillars are absent, the resulting concepts may resemble a VLF but represent distinct iterations with different objectives and characteristics. For example, a virtual factory constitutes a digital model of a production system without an explicit educational focus. Digital learning factories emphasize knowledge transfer within digital environments but lack immersive visualization. Teaching factories focus primarily on collaboration between academia and industry, while virtual training environments often address isolated tasks and do not incorporate multi-stage production processes (Chandra Sekaran et al., 2021; Engelhardt-Nowitzki et al., 2020; Shariatzadeh et al., 2014; Wagner et al., 2012).

Within this conceptual framework, physical learning factories represent the traditional and well-established realization of the learning factory concept. They pro-

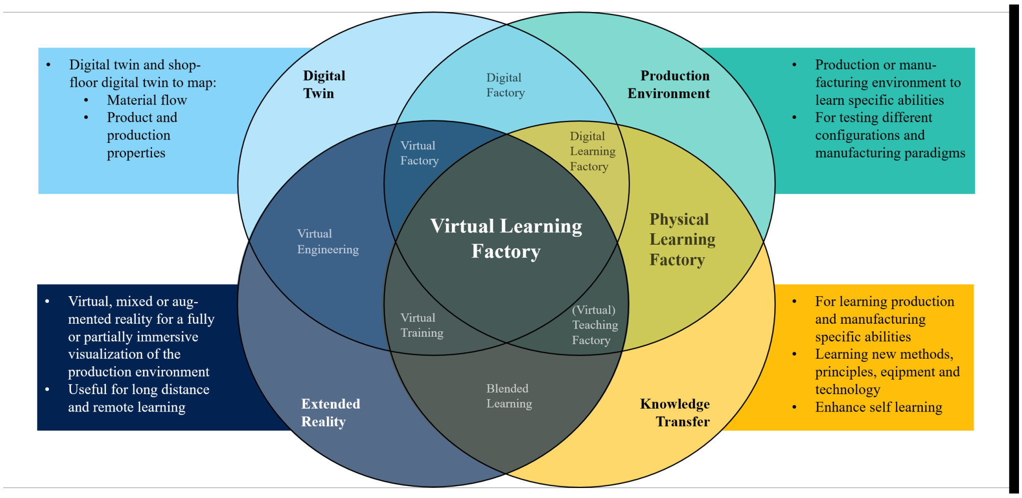

Fig. 3. Main characteristics of the virtual learning factory and bordering concepts

vide the reference point for the subsequent analysis by integrating knowledge transfer and production environments in a physical setting. Virtual learning factories build upon this foundation by extending the concept through digital twins and extended reality technologies, thereby enabling new forms of interaction, analysis, and accessibility.

Production Environment

In the context of learning factories, the production environment represents a central and non-negotiable element of the overall concept. A learning factory is not merely a technical laboratory or a collection of isolated workstations, but a production-oriented setting in which multiple manufacturing and logistics processes are interconnected. The defining characteristic of such an environment is the presence of a realistic production structure that reflects material flows, information flows, and organizational interdependencies across several process stages (Wagner et al., 2012).

To be classified as a learning factory, the production environment must allow the representation and analysis of complete or near-complete production processes rather than isolated tasks. This includes the interaction of machines, human operators, and organizational elements, as well as the occurrence of disturbances, variability, and non-deterministic system behavior. Such dynamics are essential for enabling learners and researchers to observe cause–effect relationships and to evaluate the impact of decisions beyond individual process steps (Büth et al., 2020; Kaasinen et al., 2020).

From an educational perspective, the production environment enables experiential learning in which abstract manufacturing concepts are embedded in a realistic operational context. From a research perspective, it provides a testbed for investigating innovative manufacturing technologies, organizational concepts, and optimization approaches under conditions that approximate industrial practice. Consequently, the existence of a genuine production environment constitutes a key criterion for distinguishing learning factories from learning laboratories, simulation-only environments, or isolated training stations (Rehe & Gebauer, 2022; Zhao et al., 2020; Wagner et al., 2012).

Knowledge Transfer

In the context of learning factories, knowledge transfer extends beyond the transmission of theoretical content and is inherently linked to action-oriented learning within production systems. Learning factories enable participants to acquire knowledge through direct interaction with interconnected manufacturing and logistics processes, thereby fostering experiential and problem-based learning. This situated form of knowledge transfer allows learners to observe the consequences of their decisions within a production environment and to iteratively reflect on process performance, system behavior, and organizational implications (Abele et al., 2017).

By integrating technical, organizational, and social dimensions, learning factories support the development of systems thinking, problem-solving capabilities, and interdisciplinary competencies that are difficult to achieve through conventional classroom-based instruction alone. Consequently, learning factories serve as a key mechanism for transferring research outcomes and innovative manufacturing concepts into educational and industrial practice (Salah et al., 2019; Kim et al., 2020; Wagner et al., 2012; Kaasinen et al., 2020).

Physical Learning Factory

A PLF is a realistic representation of an industrial production environment for educational and research purposes. It comprises a production hall with shop floor areas, physical machinery and tools, raw materials, auxiliary equipment, as well as technical and instructional personnel. The defining characteristic of physical learning factories lies in the direct interaction, enabling learners to experience manufacturing processes under authentic conditions. Due to the exposure of real and dynamic production systems, variations in material flows, and human interaction a degree of unpredictability is introduced that challenges learners to adapt their actions and develop creative problem-solving strategies (Andres et al., 2019).

Within this physical environment, knowledge transfer is realized through experiential and action-oriented learning. The holistic nature of physical learning factories allows learners to perceive production systems through multiple sensory channels, thereby supporting deeper understanding and long-term knowledge retention, thus combining the pillars of "Knowledge Transfer" and "Production Environment" even more (Abele et al., 2017).

Digital Twin

The Digital Twin serves as a pivotal nexus between tangible and digital entities by enabling the structured and dynamic representation of physical production systems within a digital environment. Digital twins can be applied to represent both individual products and comprehensive production processes, thereby allowing complex manufacturing systems to be modeled, analyzed, and modified without direct intervention in the physical environment. One such example is the use of a shopfloor digital twin. In shopfloor digital twins, all entities, relations and attributes are used for the representation of the actual production environmental, material, and information flow. This comprehensive mapping enables the digital twin to mirror not only static system structures but also dynamic behavior, such as process sequences, machine utilization, and human–machine interaction. As a result, the digital twin forms the foundation for system-level analysis and supports a holistic understanding of production environments (Mueller et al., 2017; Yildiz & Mřller, 2021).

In the context of learning factories, the creation of a digital twin typically begins with the systematic digitization and mapping of physical entities such as machines, workstations, products, and human resources into a coherent digital model. This abstraction of the physical production system enables and includes the structured analysis of material and information flows, process interdependencies, and cause–effect relationships within complex manufacturing environments under controlled conditions. Based on this digital representation, visualization and interaction interfaces can be developed that allow learners and researchers to explore production systems from multiple perspectives and to identify process inefficiencies, material flow bottlenecks, or ergonomic issues. By linking the production environment with analytical and interactive capabilities, the digital twin acts as a key enabler for reflective learning and effective knowledge transfer within nonphysical learning factories (David et al., 2018; Karcher et al., 2023a).

Extended Reality

Extended reality constitutes a key enabling technology for VLF, as it provides the interface through which users interact with digital representations of production systems in an immersive and intuitive manner. The term extended reality describes a spectrum of technologies that differ in their degree of immersion and interaction, ranging from augmented reality to fully immersive virtual reality.

Augmented reality enhances the physical world by overlaying digital information onto real environments, allowing users to interact simultaneously with physical objects and virtual data. Virtual reality, in contrast, places the user entirely within a digitally generated environment, enabling a high degree of immersion through visual, auditory, and interactive stimuli. In the context of learning factories, virtual reality is particularly relevant, as it allows users to experience production systems from a first-person perspective and to interact with virtual machines, processes, and workflows as if they were physically present (Juraschek et al., 2018).

The use of extended reality in learning factories supports knowledge transfer by enabling experiential and exploratory learning without the constraints imposed by physical resources. Complex production processes can be visualized, manipulated, and analyzed in real time, while users are able to observe system behavior, test alternative configurations, and reflect on the consequences of their actions. As such, extended reality serves as a crucial link between digital production models, such as digital twins, and human learning and decision-making processes (Büth et al., 2020; Chandra Sekaran et al., 2021).

Virtual learning factory

VLF are fully immersive virtual environments that present process and production data of a digitized learning factory in a visual format, which offers significant potential in regard to advancing virtualization technologies. In VLFs, participants interact with virtual models in place of physical machinery. In an optimal scenario, the virtual environment is constructed in a manner that encompasses all facets of manufacturing and business processes. From a granular perspective, both machinery and the workforce can be regarded as digital entities, encompassing their respective relations and attributes (Abele et al., 2017, 2019; Riemann, Kreß, Roth & Staiger, et al., 2020).

These capabilities have been identified as key factors in the development of a technology testbed designed to accelerate production research. Only when the production environment, knowledge transfer, digital twin, and extended reality are coherently integrated can such a virtual setup be classified as a VLF, rather than as isolated virtual training or simulation. The utilization of this approach facilitates the expeditious acquisition of novel insights and the establishment of a foundational comprehension of production systems (Vijayan & Mork, 2020; Yildiz & Mřller, 2021). Based on the conceptual foundations outlined above, the following section presents the results of the systematic literature review with regard to the advantages, limitations, and comparative characteristics of physical and virtual learning factories.

Table 1
Comparative synthesis of PLF and VLF based on literature-derived evaluation criteria

Criterion	PLF	VLF
Degree of realism	High (real machinery, haptic feedback)	Limited (visual immersion, no full haptics)
Accessibility	Limited by location and time	High (remote and scalable)
Scalability	Low to moderate	High
Safety	Risk due to real machinery	High (no physical hazards)
Investment cost	High	Lower (mainly software and modeling)
Support for manual skills	High	Limited
Support for system analysis	Moderate	High
Flexibility / reconfiguration	Limited	High
Sustainability analysis	Limited	High
Technical complexity	Moderate	High (simulation development)

Comparative results of physical and virtual learning factories

This section presents the comparative results of the systematic literature review with regard to the similarities, differences, strengths, limitations, opportunities, and risks of physical and virtual learning factories, thereby addressing RQ3. Based on the qualitative content analysis, the comparison was structured along a set of evaluation criteria derived from recurring themes in the literature and aligned with the conceptual framework introduced in Section 3. These criteria, summarized in Table 1, comprise technical and interaction-related aspects, accessibility and scalability, didactic effectiveness, organizational and economic factors, and research potential.

A central distinguishing characteristic between physical and virtual learning factories lies in the mode of interaction and the degree of realism. Physical learning factories enable direct interaction with real machinery, materials, and production systems. Thus. They allow learners to gain hands-on experience under authentic industrial conditions. In particular, haptic and sensory feedback support realistic operator behavior and foster situational awareness and manual skills, which are essential for educational scenarios requiring embodied learning and direct physical interaction with production resources. However, these advantages are accompanied by substantial limitations. PLF require considerable financial investment in infrastructure, equipment, maintenance, and qualified personnel. As a consequence, access is often restricted by spatial, temporal, and organizational constraints, which limit scalability and flexibility. In addition, safety and security concerns arise when inexperienced learners operate real machinery, increasing the risk of injuries or unauthorized access (Al-Geddawy, 2020; Andres et al., 2019; Kim et al., 2020; Massow et al., 2021; Shariatzadeh et al., 2014).

Virtual learning factories mitigate several of these constraints and offer distinct advantages in terms of flexibility, scalability, and accessibility. As production environments, equipment, and participants are represented as virtual entities, learning activities are no longer bound to specific locations, time slots, or capacity limitations. Moreover, the simulation of additional or more advanced equipment can be realized at comparatively low cost, while the need for on-site technical personnel is reduced. These characteristics also contribute to enhanced safety, as virtual environments allow experimentation without exposure to physical hazards and enable differentiated access control (Kim et al., 2020; Mueller et al., 2017; Siatras et al., 2021).

Beyond improved accessibility, VLF provide significant opportunities for analysis, experimentation, and research. The absence of physical constraints such as size, weight, or material availability enables scalable "what-if" scenarios, rapid system reconfiguration, and machine substitution. The reuse and optimization of virtual objects further support value stream, ergonomic, and information flow analyses across multiple configurations. In addition, remote access facilitates international and cross-organizational collaboration, enabling the investigation of global value streams and distributed production networks. From a sustainability perspective, VLF reduce the consumption of physical resources and allow the live calculation of energy and material usage, thereby supporting sustainability-oriented decision-making (Büth et al., 2020; Chandra Sekaran et al., 2021; Juraschek et al., 2018; Massow et al., 2021; Riemann, Kreß, Roth, Staiger, et al., 2020; Weeber et al., 2016).

Despite these advantages, virtual learning factories also exhibit notable limitations. The lack of haptic feedback and restricted fields of view in current VR systems limit interaction realism and may hinder the acquisition of certain practical skills. Health-related issues such as motion sickness or nausea have also been reported, while the fidelity of simulated interactions remains below that of real-world production environments. Furthermore, the development and operation of high-quality simulations require extensive expertise in modeling and programming, particularly with regard to machine kinematics and system behavior, resulting in significant time and effort. Therefore, instructors and researchers must possess specialized knowledge and demonstrate a high level of commitment to fully exploit the educational potential of VLF. Moreover, technological constraints may result in reduced data precision, accuracy, and reliability, which negatively affect immersion and, consequently, learning effectiveness. The lack of standardized data exchange mechanisms further complicates integration and interoperability. Finally, several studies indicate that the development of craftsmanship and fine motor skills remains challenging in virtual environments, and empirical evidence regarding the effectiveness of VR-based training remains mixed. While some studies report positive learning outcomes, others find no significant advantages or even contradictory results (Al-Ahmari et al., 2018; Chao et al., 2017; Engelhardt-Nowitzki et al., 2020; Hoedt et al., 2017; Karcher et al., 2023b; Langley et al., 2016; Peron et al., 2021; Pichler et al., 2020; Pratticň & Lamberti, 2021; Riemann, Kreß, Roth & Klipfel, et al., 2020; Roldán et al., 2019; Schumacher & Kohl, 2020; Yildiz et al., 2019).

Discussion

Building on the comparative results presented in Chapter 4, this section discusses the characteristics of physical and virtual learning factories in light of the findings of the systematic literature review. The discussion is structured along the three research questions and aims to contextualize the results, highlight conceptual implications, and identify limitations and directions for future research.

Discussion of RQ1: Characteristics of physical learning factories

The findings related to RQ1 indicate a high degree of consistency in the literature regarding the defining characteristics of PLFs. The synthesis of the results demonstrates that the educational effectiveness of physical learning factories does not stem from isolated elements but from the deliberate integration of realistic production environments and action-oriented knowledge transfer mechanisms. This integration enables learners to engage with technical, organizational, and human aspects of production systems simultaneously. As the literature further suggests, PLFs are primarily understood as learning environments rather than isolated training installations. Their role within engineering education is therefore not limited to skill acquisition but extends to the development of problem-solving abilities and contextual understanding of complex production systems in a real production environment. This conceptual clarity provides a stable reference point for subsequent comparisons with virtual learning factories.

Discussion of RQ2: Characteristics of virtual learning factories

The findings of the systematic literature review indicate that VLF possess a multitude of advantages. However, it is not feasible to retain all the benefits associated with PLF. As both provide a comprehensive production environment for education and research, VLFs are just as effective as their underlying simulation setups. To illustrate, unpredictable equipment behavior, as observed in a real environment, presents a significant challenge for programming. Consequently, the capacity for out-of-the-box thinking and creativity is constrained to the parameters of the simulation, such as the scenario or goal, as well as the simulation programmer's skills. Furthermore, the absence of multisensory input restricts the potential for direct feedback, which is known to enhance learning. Therefore, VLF might be unfeasible in this regard without technical improvement.

The review of the literature revealed that virtual reality is frequently employed for the purpose of factory layout mapping, given that PLF are utilized for the acquisition of the requisite skills for the optimization of production systems. Indeed, no examples of a VLF designed exclusively for this purpose were identified during the course of the research. In contrast, VLF were frequently conceptualized without subsequent implementation. While there are certainly examples of virtual laboratories, no comprehensive multi-stage value creation process was identified in the literature, despite the concept being one with which the research community is familiar. A significant number of VLF described in the literature are, in fact, composed of a physical element that has been digitally mapped. Frequently referenced examples are the Fisher-Price Learning Factory and certain LEGO creations. The system is constituted by fundamental abstractions of machinery and incorporates interfaces for the acquisition and exchange of data. It is therefore important to pursue the development of pure VLF, especially in consideration of technical developments such as the Nvidia Omniverse, which allows for a common interface of different simulation programs, thereby facilitating data exchange for virtual environments.

Discussion of RQ3: Opportunities, risks, and future research directions

Having discussed the characteristics of both approaches, the following section synthesizes their implications in terms of opportunities, risks, and future research directions. Rather than representing mutually exclusive solutions, the literature suggests that virtual learning factories offer significant opportunities to complement and extend physical learning factories, particularly in contexts where flexibility, scalability, and accessibility are critical requirements. One of the most prominent opportunities associated with VLFs lies in their potential to overcome structural limitations inherent to physical learning environments. This characteristic is particularly relevant in higher education and continuing education contexts, where heterogeneous learner groups and limited infrastructure often constrain the use of physical learning factories. At the same time, the literature highlights several risks and challenges that may limit the effectiveness of virtual learning factories if not adequately addressed. A central concern relates to the abstraction of physical processes. While extended reality technologies can enhance immersion, they cannot fully replicate the tactile and embodied experiences associated with real machinery and materials. Consequently, there is a risk that certain practical competencies, particularly those related to manual skills and situational awareness on the shop floor, may be insufficiently developed when learning activities rely exclusively on virtual environments. Another critical aspect discussed in the literature concerns the organizational and human factors associated with the implementation of virtual learning factories. Effective knowledge transfer in virtual environments depends not only on technological capabilities but also on the availability of appropriately designed didactic concepts and adequately trained instructors. Without careful instructional design, there is a risk that VLFs are perceived as complex simulation tools rather than integrated learning environments, thereby reducing their educational impact. This underscores the importance of aligning technological solutions with pedagogical objectives rather than treating virtualization as an end in itself.

Based on these considerations, the literature increasingly points toward hybrid and complementary approaches as a promising direction for future learning factory implementations (Abele et al., 2024). Combining physical and virtual learning factories within a blended learning framework allows educators to leverage the strengths of both approaches: physical learning factories can be used to develop hands-on skills and embodied understanding, while virtual learning factories can support preparation, reflection, system-level analysis, and scenario-based experimentation. Such complementary use mitigates the limitations of each approach while enhancing overall learning effectiveness. Future research should therefore focus on the systematic integration of physical and virtual learning factories rather than on their isolated evaluation. The remote learning capabilities and the collaboration potential are frequently emphasized by various authors. However, the technical implementation is not discussed in further detail. For research purposes, a more detailed account of the implementation of multiple virtual fabrication sites is required, as is an investigation of the role of artificial intelligence in facilitating a deeper comprehension of innovative manufacturing paradigms. One such paradigm is cloud manufacturing, which involves the integration of the production resources of multiple companies with AI-assisted order and manufacturing planning. In particular, empirical studies are needed to investigate how different combinations of physical and virtual elements affect learning outcomes across diverse educational contexts. Moreover, research on standardized architectures, interoperability of digital twins, and scalable extended reality solutions would contribute to reducing development effort and increasing transferability. Finally, greater attention should be paid to human-centered and organizational aspects, including instructor competencies, learner acceptance, and long-term sustainability, to ensure that virtual learning factories evolve as effective and robust components of engineering education.

Conclusions

In Conclusion, VLF exhibit numerous similarities to their physical counterparts, as both can be considered descendants of the same conceptual lineage. Both are based on hands-on, project teaching approaches for the transfer of knowledge and are situated within a multi-staged production environment. Furthermore, VLF provide the opportunity to utilize digital and immersive technology to enhance the learning outcome. But with the current technological development, they lack immersion and require a significant amount of dedication, not only for production-related subjects but also for programming and simulation setup. Their primary strength lies in a secure and controlled setting. Their most significant drawback is the aforementioned deficiency in immersion. In some instances, this can be attributed to the absence of overarching software standards. Nevertheless, it is challenging for students to develop their craft skills in the absence of high-fidelity simulations. As a result, there is a considerable risk that VLF may be rejected by unconvinced lecturers or academic personnel who may lack the requisite technological expertise.

In conjunction with the aforementioned risks, VLF also present a number of opportunities for both educational and research purposes. The high level of flexibility afforded by these facilities allows for the testing of multiple manufacturing concepts without the necessity of constructing an entire facility. This results in significant savings in personnel and natural resources. Furthermore, the inherent capability to implement an effective visualization of an energy and waste management system directly contributes to sustainability. Furthermore, VLF facilitate the participation of disabled individuals, thereby addressing social aspects.

In summary, VLF represent a promising evolution in educational environments, combining traditional didactic principles with advanced digital technologies. Although they possess numerous characteristics in common with their physical counterparts, VLF are distinguished by their flexibility and resource efficiency, as well as their potential to facilitate enhanced learning through extended reality. Nevertheless, obstacles persist, particularly in attaining complete sensory immersion and surmounting the technological impediments that may impede extensive adoption. Notwithstanding the aforementioned challenges, the opportunities they present such as contributing to sustainability and inclusivity in education underscore their potential to significantly impact both teaching and research. As technology continues to advance, it seems likely that the integration of VLF into mainstream education will increase, offering innovative ways to teach complex manufacturing concepts in a more sustainable and inclusive manner.

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