Brief review of methods and techniques used in Learning Factories in the context of Industry 4.0

G C Neacsu*, I G Pascu, E L Nitu and A C Gavriluta
University of Pitesti, Faculty of Mechanics and Technology, Manufacturing and Industrial Management Department, Targul din Vale Street No.1, Romania

*georgiana.neacsu@upit.ro

Abstract. The rapid evolution of science and technology has forced the processes and systems of production, training and learning to adapt to innovation and the digital era of industrial technology. In the case of production processes and systems, innovation and digitalization refer to the transformation of production units into smart factories. In the case of training and learning processes and systems, innovation and digitalization lead to the creation of learning factories. Thus, this process involves the use of modern methods and techniques to develop innovative training, learning and production processes and systems. This paper is an analysis of recent studies and seeks to briefly present the evolution of industrial production processes and systems and Industry 4.0 but also the concept of learning factory. The paper also presents a review of the main methods and techniques used in innovative industrial training, learning and production processes and systems. Finally, some conclusions related to the use of these methods and techniques are summarized.

1. Introduction

1.1. The evolution of industrial production processes and systems
The evolution of production processes began in the 600s with the spread of water mills. Over the years, the most known production processes have remained: craft production, which began in 1850, followed by American production in 1900, which is no longer used, then in 1913 mass production, 1955 Lean production, then mass customization in 1980, global manufacturing in 2000 and sustainable production in 2010 [1], presented in figure 1 [1,2].

The evolution of production systems, represented in figure 2 [3], began around the 1900s with the appearance of the assembly line, followed by the Toyota production system (TPS) in 1960, then flexible manufacturing systems (FMS) in 1980, reconfigurable manufacturing systems (RMS) in 1990 and Cloud-based manufacturing systems (CBMS).

1.2. The evolution of Learning Factory
The history of learning factories (LF) began in the late 1980s or early 1990s in Germany, with the CIM learning factory, largely unknown today [4]. The first form of learning factories appeared since the middle ages, in the form of crafts in workshops, taught by craftsmen to disciples [5]. After the end of Second World War, Japan established and developed systematic quality systems and quality circles in 1962. In the beginning of the 1970s Germany established learning in small groups with the concept of the so-called Lernstatt (a composition of the German words “lernen” = to learn and “Werkstatt” =
factory/workshop). In 1980, there was another change in the way work processes were improved in which application-oriented learning methods related to specific complex situations were addressed. This development of workplace learning has been facilitated by the emergence and spread of new information and communication technologies, but also by new organizational concepts. At the beginning of the 1990s, new theoretical approaches to application-oriented learning were developed [6]. Figure 3 [6] shows the historical development of learning approaches, from the first form to the present.

**Figure 1.** The evolution of production processes, adapted after [1] and [2]

**Figure 2.** The evolution of production systems [3]
The term Industry 4.0 officially appeared in 2011 at industrial trade fair "Hannover Messe" [7]. The prefix 4.0 shows us that Industry 4.0 is a direct successor to the other three industrial revolutions developed in previous years.

Thus, the first industrial revolution appeared at the end of the 18th century and refers to the introduction of mechanical production equipment driven by the force of water or steam. The second industrial revolution refers to the use of electric drive of production equipment and the realization of a mass production based on the division of labor and developed in the late nineteenth century. Later in the twentieth century came the third industrial revolution that focused on the use of electronic systems and information technology in production automation [8]. In figure 4 [9] the evolution of the technologies of the four industrial revolutions is presented.

This paper aims to present the concept and a classification of learning factory and a short review of the main methods and techniques used in innovative industrial training, learning and production processes and systems.

2. Learning Factory

2.1. The concept of Learning Factory

The learning factory can be seen as an idealized replica of an industry section/workshop in which informal, non-formal and formal learning can take place. Thus, learning factories contribute greatly to a healthy connection between industry, research and education [6].

The literature describes various positive effects of the learning factory concept such as: enhancement of the quality of education and training in general [10], creation of possibilities for research, innovation,
and technology transfer [11], catalyst for business creation [12], development of soft skills and interdisciplinary competences [13], strengthening of attitude and work philosophy [14], motivation to learn and motivation and confidence to apply [15], overcoming problems of traditional teaching methods, strengthening of the link between industry and academia [16], strengthening the link between education and research [17], improving the prestige of industry and manufacturing and design education [18].

2.2. Learning Factory classification

Analyzing the existing learning factories, it can be stated that they are most frequently found in the following areas: learning factories in education, in training and learning factories in research. In learning factories in the field of education, in general, several ways of learning are approached: open, steered, and closed student projects; active learning in learning factories; action-oriented learning in learning factories; experiential learning and learning factories; game-based learning in learning factories and gamification; problem-based learning in learning factories; project-based learning in learning factories; research-based learning in learning factories [6]. The learning factory, for educational scope, can be used for stand-alone student projects and industry partnered student projects [19], see figure 5 [6].

Figure 5. The use of learning factories in education in connection with stand-alone and industry - partnered projects [6]

In learning factories used for learning, in most cases, the main goal is to competency development [16], can be used as a part of change management approaches [20], and in recent years, in context with digitalization and Industry 4.0, in the field of demonstration of new technologies and innovations [21]. In the field of research, the link with learning factories is made by learning factories as research objects and learning factories as research enablers [6]. The concept is presented in figure 6 [22].

Figure 6. Learning factories as research enablers [22]

This concept describes how research problems are identified and solutions are tested and verified with the help of the physical model learning factory, at low cost and complexity compared to research in real production factories.
Table 1 gives an overview of established learning factories existence and presented in various scientific articles.

**Table 1. Overview on existing learning factories**

| Name of Learning Factory                  | Location                                                                 | Activity type | Article |
|-------------------------------------------|--------------------------------------------------------------------------|---------------|---------|
| Alberta Learning Factory                  | University of Alberta, Edmonton, Canada                                   | X             | [23]    |
| AM model factory                          | FAPS/ KTmfK, Nürnberg, Germany                                            | X             | [24]    |
| Anglo American Training Center            | Johannesburg, South Africa                                               | X             | [25]    |
| BERTHA                                    | Bremen Institute for Mechanical Engineering, University Bremen, Germany  | X             | [26]    |
| CubeFactory                               | TU Berlin, Germany                                                       | X             | [27]    |
| FMS Training Center                       | Laboratory of Mechanical Engineering and Industrial Systems, Tampere University of Technology, Finland | X             | [28]    |
| Industrial Engineering Laboratory         | IPS, TU Dortmund, Germany                                                | X             | [29]    |
| Learning Factory at the Campus Velbert/Heiligenhaus | University of Applied Sciences Bochum Heiligenhaus, Germany             | X             | [30]    |
| Learning Factory Split                    | FESB, University Split, Croatia                                          | X             | [31]    |
| Live Training Center                      | Live Training Center, Bruchsal, Germany                                   | X             | [32]    |
| Model Factories                           | McKinsey, U.S.A                                                          | X             | [33]    |
| Product Development Process Learning Factory | Laboratory for Computer Integrated Design and Manufacturing, Methodist University of Piracicaba, Brazil | X             | [34]    |
| Railway Operation Research Center         | Chair of Railway Engineering, TU Darmstadt Germany                       | X             | [35]    |
| SEPT Learning Factory                     | Booth School of Engineering Practice and Technology, McMaster University, Canada | X             | [36]    |
| Textile Learning Factory 4.0              | ITA Aachen, Germany                                                     | X             | [37]    |
Once with development of the concepts of Learning Factory and Industry 4.0, methods, techniques and tools in the area of training, learning and production processes and systems have also been developed. The most common, in the studied literature, are summarized in Table 2.

### Table 2. Methods, techniques and tools

| Methods                        | Techniques and tools                                                                 | Application domain     | Article |
|--------------------------------|--------------------------------------------------------------------------------------|------------------------|---------|
| Virtual / augmented / mixed reality | Unity game engine, questionnaires  
Holographic devices, real-time production tracking  
HTC-Vive, Jack 8.4., Process Simulate, module: SCARE and Jack | education              | [42]    |
| Digital assistant              | Unity 3D, Microsoft HoloLens, Software CAD  
RTLX  
C++ and Qt | product design  
industrial | [45]    |
| Experiment-based learning      | Kanban, Industry 4.0 technologies: IoT and internet of things (IIoT), cyber-physical systems  
Systems CAD/CAM/CAE, software  
Teamcenter, NX, Microsoft Office  
Fused deposition modeling (FDM), selective laser melting (SLM) for metals, and selective laser sintering (SLS) | research  
industrial | [36]    |
| Project-based learning         | Flow analysis, MATLAB, RFID, cyber-physical systems  
ERP, cyber-physical systems, printer Lego-3D | education  
[23]    |
| Problem-based learning         | Simulation  
Just-in-Time, Push-Pull production, Tact time, Kanban, Kaizen, VSM | education  
[29]    |
| Intuitive learning             | Print 3D, recycle | industrial | [27]    |
A brief description of the specific methods and techniques used in Learning Factories in the context of Industry 4.0 and their application situations are given below.

3.1. Virtual/ augmented/ mixed reality
The concepts of virtual reality, augmented reality and mixed reality are among the most common innovative methods used in the development of training, learning and production processes and systems.

Virtual reality (VR) is considered a paradigm that through computers and human-computer interfaces creates the effect of a three-dimensional world [49] in which the user can obtain sensory experiences in a similar way to the real world [50]. Phrase virtual reality has been proposed, in 1989, by Jaron Lanier [51].

In the paper [42], Darque Pinto studying the impact of using virtual reality in learning a foreign language compared to the conventional audio method. Thus, the experiment involved 12 students, aged between 12 and 15 years old, from a private school in Portugal. The materials used in the study were delivered in audio and VR format, a knowledge retention objective test (in English), and a sense of presence and a satisfaction questionnaire (in Portuguese). The simulation contains two scenarios created by using the Unity game engine. The first scenario is a formal dialogue, which takes place in an office, while the second scenario refers to an informal dialogue, which takes place in a pub. Specific props and characters were introduced in both scenarios. The tools used in the research were various questionnaires related to presence, satisfaction and verification of knowledge. The questionnaire used for measure the sense of presence was Igroup Presence Questionnaire (IPQ) [52], the one for the satisfaction of the participant was After-Scenario Questionnaire (ASQ) [53], and for to evaluate students’ knowledge retention an eight questions multiple-choice test was created by the English teachers of the school. Each study participant tested each scenario, alternatively. Following the analysis of the results for the presence and satisfaction, it was found that the VR learning mode is preferred by the participants (figure 7, [42]).

In the case of knowledge retention in none of the conditions it was reached the minimum value of 50%, but it could be observed in the informal scene, virtual reality had more than 40% of correct answers. The results are represented in figure 8 [42].

In the paper [44], Martin Dahl presents another approach to the use of virtual reality, namely by expanding the virtual commissioning (VC) with VR concepts. In the experiment was used an existing robot cell within the Production System Laboratory (PSL) at Chalmers University of...
Technology, Sweden. The robot cell is made up of four ABB-robots, one KUKA-robot and a pallets conveyor. Virtual model of the cell has been created in Process Simulate, a software provided by Siemens and includes a human operator who must test the sensors, buttons and safety equipment. In order to achieve this and to add to the virtual function VR concepts, different tools were used: HTC-Vive, Jack 8.4., Process Simulate and two modules: SCARE and Jack. The HTC Vive device consists of one HMD, which allows the display of two different images are shown for the user, one for the left eye and one for the right eye, and two hand held controllers can be used for 360° motion capture. At the beginning of the simulation the user is outside the robot cell from where he can operate the virtual door opening button. After opening the doors, the safety stop will be activated and the operator will be able to check if the system is working properly. Figure 9 [44] is an image of the robot cell in the virtual model (figure 9b) and the real cell (figure 9a). The expansion of VC with VR elements has helped to move from observation to interaction with the virtual production system.

![a) the real cell  b) the virtual model of the cell](image)

Figure 9. Comparison between the real- and virtual production cell [44]

Augmented Reality (AR) can be defined as a system that includes a combination of the real world and the virtual world, interactive in real time, registered in 3D and their overlap in the real world [54]. The term augmented reality first appeared in 1992 in the work of Tom Caudell [55].

An approach to augmented reality is presented by Dimitris Mourtzis in paper [45], in which he developed an application that uses augmented reality to evaluate and improve the product design process (figure 10, [45]).

![Figure 10. Product Design Evaluation in Teaching Factories using Augmented Reality](image)

The augmented reality tool used in this case is the Microsoft HoloLens headset, which offers the capability to see the designed geometry in a realistic scale, in the field of view of the designer, while also interacting with the virtual object like it is real, using grab and rotate moves. Thus, the designer gains a realistic experience from experience. The development of applications on this headset was possible thanks to the use of the Unity 3D platform. The geometry of the object is extracted directly from the CAD. The user can grab, move and rotate the virtual object to be able to check the design of the product from different perspectives and in this way the defects that could not be seen in the CAD software will be easily detected. Thus, the integration of the application that uses augmented reality has
brought visible improvements in the results of the participants in the delivery factory, the errors being reduced by 12% and the assembly process of the products being 10% faster.

Mixed reality (MR) is a technology that, from a historical and conceptual point of view, has evolved from virtual reality [56] and that offers the user an experience that incorporates both the real and the virtual world [57]. Max Juraschek presents in paper [43] the benefits of using mixed reality in a learning factory. Thus, he states that the existence of mixed reality in learning factories allows the creation of an experience that combines the real world with the virtual one using both real and virtual objects. Juraschek argues that combining the real world with the virtual one in learning factories improves the learning process. The paper presents two potential applications of mixed reality that can be used in learning factories and are represented in figure 11, [43].

![Figure 11. The potential fields of applications of mixed reality in learning factories [43]](image)

Thus, Juraschek considers that one of the applications can be about learning the notions of mixed reality in the learning factory by intertwining didactics with technology. The second application refers to the use of mixed reality in the learning process, he believes that combining digital content with the real world can help make it easier to understand processes and methods.

3.2. Digital assistant

A digital consent system supports the interaction of the operator with the work equipment for the proper performance of work tasks [58]. The concept of digital assistance system is addressed by Hendrik Oestreich in the paper [46] in which a study of the effectiveness of learning with digital assistance is performed compared to traditional learning by explanation in a real assembly scenario, represented in figure 12, [46].

![Figure 12. Workbench with the assistance system [46]](image)

This assembly station equipped with a digital assistance system consists of three work areas. Proximity sensors are integrated in the support on which the assembly is placed and thus on the screen specific to each work area are displayed the instructions and tasks, specific to each stage, which must be performed in order to move to the next work area. Switching to the next work area is done by pressing
a confirmation button on the screen. The study was conducted on a number of 13 people for learning with digital assistance and on a number of 3 people for traditional learning with a teacher. The study lasted 5 days and each participant had to complete a questionnaire at the first and last experience. The study found that learning with the help of the digital system is as effective as in the case of traditional learning.

Another approach about digital assistant is presented by Volkan Aksu in [47]. This shows how a digital assistant can support the quality of work of people with disabilities and independence in carrying out tasks. Based on some thinking tests of the needs, requirements and problems of users with disabilities created a hardware-based prototype which supports users in stages of the cutting, gluing and folding, necessary for the production of a jewelry box. Thus, to guide the user in the cutting process, a 3D mould was made, equipped with remote controlled LEDs controlled by Arduino and Bluetooth technology and video instructions played on mobile devices (figure 13a [47]). For playing the instructions were used software with a user-friendly graphical interface using C++ and Qt. The passing the next step is done by pressing, by the user, a button on the mould. For the gluing task, an automatic glue dispenser with timer control and foot pedal it was used (figure 13b). To perform the last step, two identical mould were used (figure 13c [47]). In this study took part five male participants, with ages from 20 to 21 and different levels of cognitive disability.

Finally, the results on task efficiency and subjective evaluation were analyzed. Regarding the efficiency of the tasks, the efficiency of the participants in performing the cutting task regarding the time, accuracy and completeness, the results being presented in figure 14 [47].
The subjective evaluation of the participants' interaction was measured according to the mental effort and the use of the system (figure 15).

**Figure 15.** Comparison of Subjective Perceived Effort (SEA) and of System Usability Scale (SUS) in “with-support” and “without-support”-condition [47]

This paper shows that a care system can improve the quality of work and increase employment opportunities for people with disabilities.

4. Conclusions

The rapid evolution of processes and systems of production, training and learning, determined the development of methods, techniques and tools to keep up with new technology. This review presents the implementation of methods and techniques in different scenarios of production simulation, learning and training, applied in industry or educational institutions. The most common methods in the in the studied literature are: virtual reality, augmented reality, mixed reality, experiment-based learning, project-based learning, problem-based learning, intuitive learning and digital assistance.

In the case of using virtual reality, augmented and mixed, it was found that both in the learning scenario and in the production simulation scenario, these methods are much more agreed by users, compared to conventional methods, due to the experiences they offer. In most cases of using learning methods, users had the opportunity to experience real scenarios in production, in order to improve different skills and abilities. The use and implementation of these methods, techniques and tools could be a major support in the development of innovative production, training and learning processes and systems.

The study will continue by developing and/or integrating of some methods and techniques used in innovative industrial training, learning and production processes and systems in the existing Lean Learning Factory [41] from the University of Pitesti.

References

[1] Mourtzis D and Doukas M 2014 The evolution of manufacturing systems: From craftsmanship to the era of customisation *IGI Global*

[2] Koren Y 2010 *The global manufacturing revolution: Product-Process-Business Integration an Reconfigurable Systems*

[3] Wu D, Rosen D W, Wang L and Schaefer D 2014 Cloud-Based Manufacturing: Old Wine in New Bottles? *Procedia CIRP* **17** 94 – 99

[4] Reith S 1988 Außerbetriebliche CIM-Schulung in der „Lernfabrik“ *Springer-Verlag Berlin Heidelberg*

[5] Schaper N 2000 *Gestaltung und Evaluation arbeitsbezogener Lernumgebungen*

[6] Abele E Joachim M and Michael T 2019 *Learning Factories - Concepts, Guidelines, Best-Practice Examples*
[7] Sabine P 2017 The Vision of Industrie 4.0 in the Making – a Case of Future Told, Tamed, and Traded Nanoethics 11 107–121
[8] Dorel B 2016 A patra revoluţie industrială a început. Este pregătită România pentru a face faţă sfidărilor acestei noi revoluţii? Revista de politica ştiinţei şi scientometrie 5 194 – 201
[9] Munirathinam S 2020 Industry 4.0: Industrial Internet of Things (IoT) Advances in Computers
[10] Abele E Eichhorn N and Kuhn S 2007 Increase of productivity based on capability building in a learning factory 11th International Conference on Production Engineering Zagreb
[11] Entingh D J Andrews C J Kenkeremath D C Mock J E and Janis F T 1987 Guide book for technology transfer managers: Moving public R & D to the marketplace Washington.
[12] Ecodesign circle: Learning factory ecodesign, available at https://www.ecodesigncircle.eu/resources-for-you/learning-factory-ecodesign, accessed: 2020-03-24
[13] Kreimeier D Morlock F Prinz C Krückhans B Bakir D C and Meier H 2014 Holistic learning factories - A concept to train lean management, resource efficiency as well as management and organization improvement skills 47th CIRP Conference on Manufacturing Systems
[14] Badurdeen F Marksberry P Hall A and Gregory B 2010 Teaching lean manufacturing with simulations and games: A survey and future directions Simulation & Gaming 41 (4) 465–486
[15] Tisch M Hertle C Abele E Metternich J and Tenberg R 2015 Learning factory design: A competency-oriented approach integrating three design levels International Journal of Computer Integrated Manufacturing 1355–1375
[16] Tisch M Hertle C Cachay J Abele E Metternich J and Tenberg R 2013 A systematic approach on developing action-oriented, competency-based learning factories 46th CIRP Conference on Manufacturing Systems 580–585
[17] Blume S Madanchi N Böhme S Posselt G Thiede S and Herrmann C 2015 Dien Lernfabrik - Research-based learning for sustainable production engineering 5th CIRP Sponsored Conference on Learning Factories 126–131
[18] Abele E Metternich J Tisch M Chryssolouris G Sihn W ElMaraghy H A Hummel V and Ranz F Learning factories for research, education, and training 5th CIRP-Sponsored Conference on Learning Factories 1–6
[19] Jørgensen JE Lamancusa JZ Zayas-Castro JL Ratner J 1955 The Learning Factory Proc. of the Fourth World Conference on Engineering Education
[20] Wagner C Heinen T Regber H and Nyhuis P 2010 Fit for change—Der Mensch als Wandlungsbefähiger. Zeitschrift für wirtschaftlichen Fabrikbetrieb 722–727
[21] Erol S Jäger A Hold P Ott K and Sihn 2016 W Tangible industry 4.0: A scenario-based approach to learning for the future of production 6th CIRP-Sponsored Conference on Learning Factories 13–18
[22] Siefermann S Böllhoff J Metternich J and Bellaghnach A 2014 Evaluation of workmeasurement concepts for a cellular manufacturing reference line to enable low cost automation for lean machining 47th CIRP Conference on Manufacturing Systems 588–593
[23] Ahmad R 2018 Alberta Learning Factory for training reconfigurable assembly process value stream mapping 8th Conference on Learning Factories 2018 – Advanced Engineering Education & Training for Manufacturing Innovation 237-242
[24] Yoo I S 2016 Model Factory for Additive Manufacturing of Mechatronic Products: Interconnecting World-Class Technology Partnerships with Leading AM Players 6th CIRP Conference on Learning Factories Procedia CIRP 54 210 – 214
[25] Makumbe S 2018 Effectiveness of using Learning Factories to import Lean principles in mining employees 8th Conference on Learning Factories 2018 – Advanced Engineering Education & Training for Manufacturing Innovation Procedia Manufacturing 23 69-74
[26] Schreiber S 2016 BERTHA - A flexible learning factory for manual assembly 6th CIRP Conference on Learning Factories Procedia CIRP 54 119 – 123
[27] Muschard B 2015 Realization of a learning environment to promote sustainable value creation in areas with insufficient infrastructure 5th Conference on Learning Factories 2015 Procedia CIRP 32 70 – 75

[28] Toivonen V 2018 The FMS Training Center – a versatile learning environment for engineering education, 8th Conference on Learning Factories 2018 – Advanced Engineering Education & Training for Manufacturing Innovation Procedia Manufacturing 23 135 - 140

[29] Steffen M 2012 Problem Based Learning in Industrial Engineering Education at TU Dortmund University

[30] Faller C and Feldmüller D 2015 Industry 4.0 learning factory for regional SMEs 5th CIRP Sponsored Conference on Learning Factories Procedia CIRP 32 88–91

[31] Veza I Gjeldum N and Mladineo M 2015 Lean learning factory at FESB - University of Split 5th CIRP-Sponsored Conference on Learning Factories Procedia CIRP 32 132–137

[32] Reichert and Markus 2011 Qualification of employees in the development department with SEW live training center in E. A bele, J. Cachay, A. Heb, & S. Scheibner (Eds.) 1st Conference on Learning factories 100-117 Darmstadt

[33] Hammer M 2014 Making operational transformations successful with experiential learning CIRP General Assembly Nantes

[34] Schützer K Rodrigues L F Bertazzi J A Durão L F C S and Zancul E 2017 Learning environment to support the product development process Procedia Manufacturing 9 347–353

[35] Streitzig C and Oetting A 2016 Railway operation research centre — A learning factory for the railway sector Procedia CIRP 54 25–30

[36] Elbestawi M 2018 SEPT Learning Factory for Industry 4.0 Education and Applied Research Procedia Manufacturing 23 249-254

[37] Küsters D Praß N and Gloy Y S 2017 Textile learning factory 4.0—Preparing Germany’s textile industry for the digital future Procedia Manufacturing 9 214–221

[38] Blöchl S J and Schneider M 2016 Simulation game for intelligent production logistics—The PuLL® learning factory Procedia CIRP 54 130–135

[39] Sivard G and Lundholm T 2013 XPRES—A digital learning factory for adaptive and sustainable manufacturing of future products 3rd Conference on Learning Factories 32–154 Augsburg

[40] Baena F 2017 Learning Factory: The Path to Industry 4.0 7th Conference on Learning Factories Procedia Manufacturing 9 73 – 80

[41] Nitu E L and Gavriluta A C 2019 Lean Learning Factory at the University of Pitesti IOP Conf. Series: Materials Science and Engineering 1018 2021) 012022 doi:10.1088/1757-899X/1018/1/012022

[42] Pinto D 2019 Virtual Reality in Education: Learning a Foreign Language, WorldCIST’19 589-597

[43] Juraschek M 2018 Mixed Reality in Learning Factories Procedia Manufacturing 23 153-158

[44] Dahl M 2017 Virtual Reality Commissioning in Production Systems Preparation 22th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)

[45] Mourtzis D 2018 Augmented Reality supported Product Design towards Industry 4.0: a Teaching Factory paradigm Procedia Manufacturing 23 207-212

[46] Oestreich H Töniges T Wojtynek M and Wrede S 2019 Interactive Learning of Assembly Processes using Digital Assistance 9th Conference on Learning Factories 2019 Procedia Manufacturing 31 14–19

[47] Volkan A Sascha J Björn K and Carsten R A 2019 Digital Assistance System Providing Step-by-Step Support for People with Disabilities in Production Tasks 2019 Springer International Publishing AG 775–785

[48] Stephan S 2017 Learning in the AutFab – the fully automated Industrie 4.0 learning factory of the University of Applied Sciences Darmstadt 7th Conference on Learning Factories Procedia Manufacturing 9 81–88

[49] Bryson S 1996 Virtual Reality in Scientific Visualization

[50] Yoh M 2001 The Reality of Virtual Reality Proceedings of the Seventh International Conference on Virtual Systems and Multimedia
[51] Ebersole S 1997 *A brief history of virtual reality and its social applications* University of Southern Colorado

[52] Schubert T Friedmann F and Regenbrecht H 2001 The experience of presence: factor analytic insights *Presence Teleoperators Virtual Environ* **10** (3) 266–281

[53] Lewis J R 1995 IBM computer usability satisfaction questionnaires: psychometric evaluation and instructions for use *International Journal of Human-Computer* **7** (1) 57–78

[54] Azuma R T 1997 A survey of augmented reality *Presence-Teleoperators and Virtual Environments* 355–385

[55] Caudell T P and Mizell D W 1992 Augmented reality: An application of heads-up display technology to manual manufacturing processes, System Sciences, *Proceedings of the Twenty-Fifth Hawaii International Conference* 2 659–669

[56] Kunz A and Fjeld M 1994 Mixed Reality: A Survey *Computer Science*

[57] Milgram P and Kishino F 1994 A taxonomy of mixed reality visual displays, *IEICE Trans, Information and Systems* **77** 1321-1329

[58] Keller T Bayer C Bausch P and Metternich J 2019 Benefit evaluation of digital assistance systems for assembly workstations *52nd CIRP Conference on Manufacturing Systems Procedia CIRP* **81** 441–446