DIGITAL LEARNING FACTORIES: CONCEPTUALIZATION, REVIEW AND DISCUSSION

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Abstract: Learning factory is a modern approach toward educating future production engineers with emphasis on product realization. To date, many publications have presented methodologies and implementations of virtual environments for training production engineering students. However, the advantages/applications of the virtual environments have not been clearly highlighted specifically for learning factories and their study scenarios. This work discusses and further develops the concept of digital learning factory where virtual environments are applied as complementary tools beside the physical teaching approach to boost the learning experience and discusses the benefits. Furthermore, a case study has been considered to further elaborate the concept.

Keywords: learning factory, virtual learning environments, digital learning factory.

1. INTRODUCTION

The concept of learning factory first originated from the coalition of three universities of Penn State, Washington and Puerto Rico-Mayagüez with collaboration of a government laboratory (Sandia National Laboratories). On July 15, 1994, this Manufacturing Engineering Education Partnership (MEEP) was granted a governmental fund to create the first "learning factory" with the goal of providing a practice-based engineering curriculum where students could put theories into practice and tackle real projects and scenarios with close collaboration with industry (Lamancusa, *et al*., 1997). The defined objective of learning factories was to emphasize on product realization (i.e. understanding the life-cycle of a product) and to provide engineers with the ability to optimize different stages of a product life cycle. (Lamancusa, *et al*., 1997). The required capabilities and attributes of a learning factory have been discussed and highlighted by (Wagner, *et al*., 2012) where learning factories are considered to be capable of developing new solutions for changeability and transferring them to the industries. Learning factories nowadays, perform studies mainly on the three concepts of lean, energy consumption and low-cost automation and use different teaching scenarios to achieve their goals. The authors in (Cachay, *et al*., 2012) have recently verified the hypothesis that students attending learning factories gain greater application-performance and a higher degree of action-oriented learning compared to those receiving conventional education. The expected outcomes of learning factories can be categorized as below:

1. Gaining an experience of different concepts and principles of production systems.
2. Gaining an experience regarding working with machines, tools, or physical equipment in the factory.
3. Obtaining social experiences such as group work and the ability to confront upcoming challenges.
4. Gaining an experience of working in realistic production environments and the meaning of situated cognition which is bodily involvement

Based on the required outcomes, the learning style of learning factories is required to be sensory, active and visual. Since the best learning output is only achieved when both teaching and learning styles match (Felder and Silverman, 1988), to fulfil this learning style and as a perquisite of the learning factory concept, the physical activity plays an important role.

To date, virtual environments not only have proved a considerable impact on improving the agility of production systems due to early evaluation, but have also provided possibilities in enhancing the quality of future engineers' education, and motivating their studies (Manesh and Schaefer, 2010a). As a consequence, virtual environments are non-separable parts of today's enterprises. Moreover, for the purpose of training and education, they are considered as important and strategic means to facilitate manufacturing education (Manesh and Schaefer, 2010b). Many publications have discussed or presented methodology and implementations of virtual environments for visualizing or training the production systems; see [(Manesh and Schaefer, 2010b; Dessouky, *et al*, 1998; Dessouky, *et al*, 2001; Cassandras, *et al*, 2004; Chi and Spedding, 2006; Goeser, *et al*, 2011; Ong and Mannan, 2004; Zhong and Shirinzadeh; 2008)] and the references therein. Regarding learning factories, there exist several applications in which the virtual environments are studied beside the physical practice such as (Hummel and Westkämper, 2006) and (Riffelmacher, et al, 2007). Since all the four categories of experiences are necessary to achieve, the selection of use conditions and types of virtual environments has to be made wisely. The effect of a virtual learning factory is also based on the perceived affordance, i.e. users should easily understand and use the system since the graphic interface is designed with regard to the purpose of the virtual learning factory (Gibson, 1979). Even though virtual environments can be of high interest for learning factories and their objectives, there are a number of open questions to be answered such as: What are the benefits and shortcomings of the virtual environments for the goals of learning factories?, Can learning factories nowadays move to a fully virtual learning system and still satisfy their goals? If not, what should be the right balance between physical and virtual learning to increase the learning rate? Furthermore, what factors affect this balance?, and how should the decision be made regarding choosing virtual versus physical learning environments or a combination of these two?

This work discusses and further develops the concept of digital learning factory and the different aspects of virtual environments' applications and benefits for learning factories. Furthurmore, a methodology is developed to aid the process of decision making for creating digital learning factories. The scope of this research is limited to the lean principle category (including line balancing, production leveling, bottleneck analysis, cell design, human resource allocation and space management) which is studied in majority of learning factories nowadays. It includes material flow analysis, process planning, layout design and their inter-relationship in which the process plan is considered as an input. The learning factory CiP (Center of industrial Productivity) at TU Darmstadt with a focus on lean studies has been selected for conducting a case study for this purpose. The rest of this work is organized as follows: chapter 2 gives a review on virtual reality and virtual learning environments. A comparison of digital/physical learning factories is given in chapter 3 and the different aspects of each, are discussed. Chapter 4 provides a guidline on how to perform the decision making process for creating a digital learning factory. Chapter 5 presents the case study at CiP and chapter 6 concludes the paper.

2. VIRTUAL REALITY AND VIRTUAL LEARNING ENVIRONMENTS

“Virtual reality” abbreviated as VR refers to a 3D computer-simulated environment where people can have realistic experiences through their sensory capabilities (Mujber, *et al*., 2004). Ideas of enabling artificial objects to be realized as perceptions of user's real world were later born and called “augmented reality” or AR (Lu,*et al.*, 1999). In the field of production and material engineering, virtual reality technologies have enabled the development of virtual workshops where different production systems, manufacturing processes, machines and prototypes can be modelled, simulated, verified and visualized. This process leads to an early evaluation of product manufacturability and optimization of the production processes and layout before they actually take place in real life (prior to the start of production) (Mujber, *et al*., 2004). Both digital manufacturing and digital factory concepts have been the outcomes of this rich research with numerous benefits for enterprises such as reducing time to market, cost and supporting their competitiveness (Gregor and Medvecky, 2010).

Due to the abilities to visualize processes and layouts, presenting a holistic view of production systems as well as providing numerous data and analyses in a short amount of time (which cannot be easily obtained by the means of physical experience in real factory environments), virtual environments are considered to be useful for the purpose of learning production concepts (Manesh and Schaefer, 2010b; Dalgarno and Lee, 2010). Moreover, they allow users to interact with the system and get feedback which adds to their benefits. (Pan, *et al*, 2006) has given an overview of virtual environment applications. Virtual learning environments (VLE's) are computer-based teaching and learning systems. Applications of VLE's for training students in the field of production and manufacturing are discussed in (Manesh and Schaefer, 2010b) where it is concluded that use of VLE is an important and strategic mean to facilitate manufacturing education. According to (Pan, *et al*, 2006) and (Xu and Wang, 2006) VLE's are advantageous tools for the purpose of learning/teaching production concepts and systems especially when the learning process of the real system is not possible, expensive or time-consuming. As this is sometimes also the case for learning factories, VLE's can be very useful. Note that the concept of digital

learning factory in this research is referred to a learning factory that makes use of digital tools and environments for the purpose of learning production related concepts and subjects. The usage percentage of the digital environments can vary based on existing limitations and objectives of each learning factory.

3. COMPARISON OF PHYSICAL LEARNING FACTORIES WITH DIGITAL LEARNING FACTORIES

In this chapter, the benefits of digital learning factories (which apply digital environments) as complement to learning factories that mainly focus on the physical training (referred to as physical learning factories) are discussed. Moreover, the virtual environment's shortcomings according to the major objectives of learning factories are highlighted. The two physical and digital learning factory concepts are compared in five different categories of investment, study scenario, study process, study results and Learner's experience in table 1. The advantages/disadvantages are indicated by the signs of "+" and "-". The question mark, "?", specifies the fact that more analysis is required as other factors can affect the result.

Prior to every learning process, an investment is required in order to provide the teaching environment and tools. Digital learning factories mainly require investment for the IT infrastructure, networking, software requirements, IT-personnel, etc. and also partly for the physical environment. On the other hand, physical learning factories require investment in the production plant, machines, technicians and their related cost. As different learning factories study different scenarios and have different objectives and moreover the digital learning factory can avoid some unnecessary facility investments, a cost analysis is required for comparing the investment factor. Therefore no conclusion can be made at this point. After providing the required equipment and environment for teaching, the study scenarios; probably a simplified version of an industry scenario, have to be described. These scenarios explain the structure and steps for teaching/learning a specific topic and have to be chosen wisely among an unlimited number of possible scenarios. The study process is referred to the time period in which the learner studies and performs the defined scenarios. The study process is followed by the final process of gathering, analyzing and concluding the study results. The learner obtains a number of experiences during and after the study has occurred. Having the main goals of providing a product realization perspective, a realistic working experience in production environments and abilities to optimize the system, this category can be considered the most important category among all. Although virtual environments can benefit learning factories regarding the previous four categories, they are not considered a good option when it comes to achieving realistic experiences. This is mainly because science and technology still has not been able to cover all the human senses and experiences through virtual environments or is still in the initial steps of this research process at least for production systems. Therefore a fully digital learning factory cannot exist nor replace the traditional learning factories at least with the current technology. On the other hand, research has been conducted on visualization methods in order to provide the human sight with an identical experience as the real visual senses e.g. the augmented reality technology is one of these examples that has brought virtual environments within the human sight.

Table 1. Comparison of digital and physical learning factories in five categories.

Digital learning factory	**Physical learning factory**
Investment	
? Investment on the IT infrastructure is required in addition to a partly investment on the production facility. This can vary depending on different factors such as the study scenario.	? Investment on the production facility exists but almost no major IT infrastructure is required. However this does not necessarily lead to a smaller investment compared to the other category.
Study scenario definition	
+ Faster simulation speed of different scenarios. Therefore a scenario which takes for example a month to be simulated in physical environment might only require a few minutes to be simulated virtually.	- Time limitation as it takes longer time to build and simulate each scenario. Moreover, the available times of participants are limited therefore the scenario period should not excess this time.
+ Almost no budget and space limitation due to a virtual environment.	- Cost and space limitation due to the physical environment limitations
+ Facilitating the process of simulating uncertainties and failures.	- Difficult, expensive and time consuming to model uncertainties such as machine failures.
+ More convenient holistic analysis especially regarding supply chain studies.	- Study scope limitation (*i.e.* studying the whole supply chain can be very complicated and in most cases not possible).

+ Providing more study scenarios due to the convenient changeability of study cases in virtual environments.	- Pre-defined and limited study scenarios (altering the existing scenarios requires both budget and time) .
Study process	
+ Physical presence of both learner and instructor is not required which allows the option of distant learning and as a result can increase the number of participants.	- Physical presence of learner and instructor is required.
+ Provides the possibility for learners to test their imaginary scenarios as well as the study scenarios with almost no concern regarding limitation factors such as budget and space.	- Offers limited freedom to learners for manipulating scenarios based on their curiosity and preferences due to the existing budget, space and time limitations.
+ Can shorten the study period due to higher simulation speed. Also can repeat these simulations for several times in order to get a closer to reality view.	- Usually longer study periods (differs regarding the study scope and subject) as different scenarios have to be run individually. Further, the effects of a change in production line characteristics may not be immediately observed -- indeed, a considerable time might be needed for the output to show the difference.
+ Decreases risks and safety issues specifically for beginners with no experience of work in production facilities. Moreover, can provide virtual working instructions of machines, virtual manoeuvre for emergencies such as fire, *etc.*	- Safety risks may exist specially for beginners with no working background. + The risks are more realistic and will probably better affect the learning outcome as a realistic experience of the danger is achieved.
+ Allows simultaneous multiple studies and on-time comparison of different scenarios.	- Not possible to run different scenarios simultaneously. Basically one specific scenario can be studied at a time due to the existing limitations.
- Requires simulation background and experience of working with simulation software as learners should be capable of manipulating the scenarios and obtain the outputs which might not be the case for all the participants. As a result some time has to be put into obtaining these requirements.	+ No simulation knowledge background is required for both learners and instructors.
+ Allows more participants as the capacity is mainly related to the number of computers.	- Limited number of participants because of the limited capacity of the working forces required for the physical production scenario.
Study results	
+ Faster analyzing speed and shorter analyzing time	- Usually longer analyzing time is required since information first has to be gathered manually and then analyzed.
+ Fewer human errors are involved during the analyzing process as the process is performed automatically. - Human errors can sometimes be considered useful if leading to learning experiences.	- Usually more human errors exist especially during collecting/inputting data from/into different software.
+ Allows more statistical analysis on the outputs due to the existence of different statistical software.	- Usually a limited number of statistical analyses are performed.
+ Provides more visualization tools and possibilities (view from different angles and sides, slow motion, graphs, diagrams, *etc*.)	- Limited visualizing tools to visualize the results and compare them.
Learner's experience	
- Physical experiences such as teamwork, working with machines, *etc*. is not obtained through digital environments.	+ Physical experience is obtained due to the physical presence of learners
+ Simulation software experience is obtained as a useful tool for future engineers	- No software experience is obtained
- The obtained experience can be forgotten soon if not put into practice.	+ Lasts longer in the memory of learners as has been practiced physically
- Might decrease the learning rate in case of long-term study periods as sitting behind a computer can get boring.	+ Might affect the learning results as the process of learning is more fun and practical

4. AN APPROACH TO IDENTIFY SUITABLE DIGITAL ENVIRONMENTS FOR LEARNING FACTORIES

The study of previous work regarding the application of digital environments for learning factories and learning shows that no general guideline or framework is utilized for aiding the decision-making process. As a result, the developers of the digital models usually have only utilized the available resources and tools for implementing the model. This approach could impose unnecessary cost without consideration and evaluation of other possible solutions and results in a non-optimized outcome independent from the affecting parameters. Therefore it is necessary to provide a methodology which can guide learning factory designers (who define scenarios and develop digital models) to develop the appropriate digital environment for learning. We propose the following steps to be carried out to ensure an efficient utilization of resources for the purpose of learning in learning factories based on the input parameters.

1. Identify the learning factory category: this indicates the focus of study which can vary between lean, energy consumption, low cost automation or any other main topic.
2. Identify the learning module: breaking the main category of study into sub-categories will provide the learning modules. In other words, learning modules can be defined as all the topics related to the main category that can be further studied.
3. Identify limitations of physical learning process: These limitations can be indicated for each learning module and based on the available resources and existing requirements. Table 1 can be used for this step as a guide.
4. Identify the possible contributions of VR that can aid the limitations in step 3.
5. Design a study scenario based on the learning module, available resources and affecting parameters. Note that identifying all the other parameters that can affect the decision making process (e.g. learner's backgrounds, study periods, subject of study, etc.) is beyond the scope of this work.
6. Assign appropriate tools for modelling the defined scenario in a virtual environment. Note that again all the affecting parameters (mentioned above) have to be considered in this stage for decision making.
7. Model the defined scenario with the aid of selected tools.
8. Deliver the model and get feedback. Improve the model based on the received feedbacks. Also note that it is important to define an easy to understand interface where the model can be changed easily by non-expert people and students.

One simple example can be discussed here to show the necessity of identifying these parameters and their effects on the decision making process. One of these parameters is the learner’s backgrounds and the categories they belong to which can definitely affect the appropriate learning methods and tools. In this work, the learning methods can vary between physical, digital and a combination of these two. As discussed earlier, learning factories nowadays can increase the learning efficiency by moving from a solely physical approach to a combinational approach. However, how to focus on each of the physical/digital learning approaches can depend on different parameters including learner’s backgrounds. Moreover, in a digital learning approach, the decision of a suitable digital tool also depends on these parameters. For example, according to the case study data, the majority of learners in learning factories are students, however, employees and managers also participate in some of their courses. As each category has different backgrounds and skills and also requires different needs for future, the type of their studies should be wisely selected (digital versus physical). According to each of these learner’s categories backgrounds which is a mixture of theoretical, physical and managerial skills (with different weights), one can decide the suitable learning method. As a future work, in order to determine the background distribution of each category, a questionnaire may be used. Students are typically better in theoretical knowledge compared to the physical skills and therefore learning factories in this case can more benefit them if a study with more focus on the physical aspect is applied. However, recent research indicates the possibility to overcome the need for experience from physical learning tools by using different media (Säljö, 2010). Note that employees usually have more physical skills than managers. However, this does not necessarily mean that managers need to improve their physical skills as this is not what they aim for. Therefore a study with more focus on the digital aspect can seem to be a more suitable choice for both groups. To conclude, it is recommended to further study each and every of these parameters after identifying them in order to find the appropriate proportion of digital versus physical learning methods in learning factories.

5. TU DARMSTADT'S LEARNING FACTORY (CIP) – CASE STUDY

TU Darmstadt with a focus on lean studies is selected for the case study. The goal is to demonstrate the benefits that virtual environments can add to the CiP physical learning process regarding the lean concept. As the study process of lean is mainly related to analyzing the flow of material, buffers and structure of stations, two digital models were developed—one with a focus on the system level (to analyze the flow) and one with a focus on cell

level (to analyze and visualize stations)—and their capabilities for a better learning experience are discussed. The developed models are then first verified theoretically and then through a visit to the production site.

5.1. A 2-dimensional (2D) simulation using ExtendSim.

To study CiP material flow, a 2D discrete event simulation is developed in ExtendSim. 2D simulator softwares are good sources for teaching production scenarios. However, they are not capable of providing a 3-dimensional (3D) vision and therefore should not be considered as the only option for aiding learning factories. Figure 3 represents the whole production line of CiP along with its suppliers which is modelled and simulated in ExtendSim. This model allows simulation of scenarios which are impossible to be simulated in real life due to different limitations. One simple example of such scenario in CiP is the bottleneck analysis and line balancing. To remove the bottleneck, one simple solution is to increase the number of those stations. However, due to the limitation of space at CiP, this is not possible.

5.2. A 3-dimensional (3D) simulation using Tecnomatix Process Simulate.

3D simulator softwares can supplement 2D simulations by providing an improved visualization. Even though 3D environments nowadays are capable to provide almost good visions of the production system (however, many studies are working on improving this vision for a better immersion), they are not totally capable of transferring other human senses. Existence of all of these senses is required to provide a true sensation and immersion into a production system. The assembly stations of CiP were selected to be simulated in a 3D view in Tecnomatix process simulate software and a 3D model of the five assembly stations along with their assembly processes, required components, jigs, fixtures and tools was created.

The work methodology and the developed models are presented in figure 1.

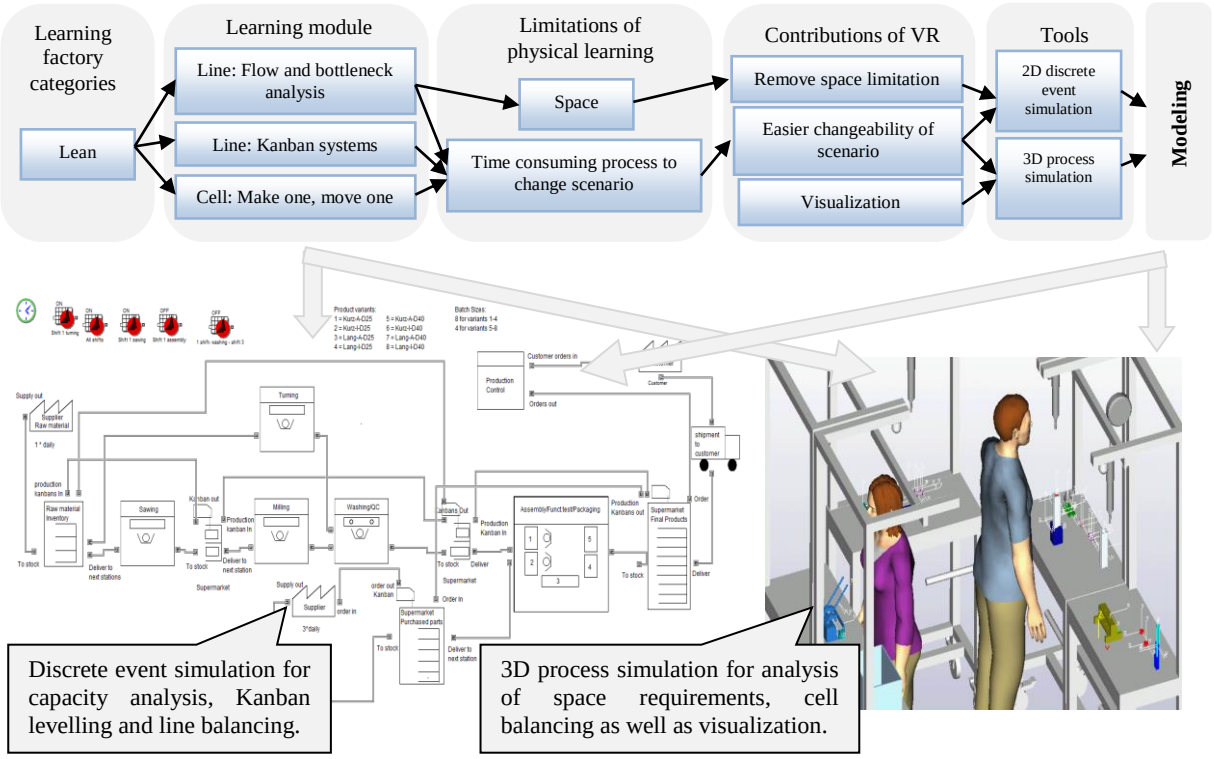

Fig. 1. Case study methodology and developed models.

The developed models can provide the following advantages. Note that expanding the 3D model to the whole production line of TU Darmstadt's learning factory can obviously increase the number of benefits and enhance the visualization.

- Visualizing CiP's assembly stations which can be used for learning and teaching purposes. As an example, it allows the user to monitor the assembly process and the correct orientation of parts during the assembly process. Therefore, the above model can be further used for developing a visual working instruction

(replacing the current paper instructions at CiP) to increase the learning rate. This also provides the infrastructure to use augmented reality tools (such as glasses) to aid the assembly process.
- Allowing the study of different production scenarios and analyzing their results in shorter duration of time. For example machine failures, adding new product variants or new machines, different working shifts, analyzing different Kanban sizes, etc. might be impossible, time consuming and expensive at CiP and therefore not studied.
- Allowing further optimization of work stations, tables and assembly movements regarding ergonomics.
- Flexibility to change data and scenarios and obtaining various analyses is considered the main benefit of this model for the purpose of learning.

6. CONCLUDING REMARKS

In this work, virtual environments and their applications for the purpose of learning in learning factories were discussed and studied. The required steps for identifying the suitable learning factory (digital vs. physical) are proposed and discussed. A case study was also conducted at TU Darmstadt's learning factory (CiP) in Germany using the above guideline to verify the use of virtual environments. The concluding remarks of this work are as follows:

- Learning factories (as modern approaches for educating production concepts) require other complementary teaching methods (i.e. digital learning factory as discussed in this paper) to guarantee the highest learning rate along with their traditional physical practice-based teaching system.
- Both 2D and 3D virtual environments are useful tools for simulating the production systems and aiding the learning process in learning factories and can increase the learning rate of learners if applied wisely and in correct conditions.
- The above fact has been illustrated by the conducted case study. Some of the limitations of the TU Darmstadt's current study scenario were shown to be easily solved through the developed models. Moreover, the models provide solutions for improvement of the learning process.
- A fully digital learning factory concept cannot exist nowadays at least with the current virtual technologies as experiencing some senses (such as touch or smell) and concepts (such as team work) are not completely achievable within virtual environments. Therefore the application of virtual environments should be considered as a supplementary tool for the learning/teaching purposes along with the traditional physical teaching system. In other words, depending on the quality of available virtual environment technology and objectives of studies, digital learning factories contain a physical component which can vary from being the major part of teaching to nothing at all.
- The focus on either digital or physical aspects of the teaching in learning factories should vary based on different factors such as learner's backgrounds, study periods and subject of study. The first factor was discussed through an intuitive analysis in this work.

As a result, this work explains why learning factories should make use of virtual environments by highlighting their benefits and the reason behind why physical practice should still remain in learning factories. However, the subjects regarding how, to what extent and where to use such virtual environments are not discussed. Therefore, the main future work related to this research can be described as follows:

- Further investigation regarding the proposed methodology is required in case other scopes and areas of studies are selected. Note that the proposed methodology was tested solely (via a case study) within the mentioned scope of this work.
- Identifying and discussing all the factors that can affect the decision making of the required methods for learning the production concepts in learning factories i.e. scenarios of learning factories, scope of study, learner’s perspective and background.
- Proposing a framework to indicate when to choose the digital vs. physical teaching environments or vice versa regarding the above identified factors.
- Providing a guideline to specifically indicate what digital environments and models (including the software, its required specification and the appropriate scenarios) to use for each of the learning factories' teaching scopes (in case a digital teaching approach is required). For example to discuss what virtual environments provide the most benefit for learning factories with a focus on lean concept, energy consumption or low-cost automation.

Even though imagining a completely digitalized learning factory with no needs of physical practice environments is impossible at the time, in a near future this vision can become a reality. However, it is good to keep in mind the famous quote: “I hear and I forget, I see and I remember, I do and I understand”. To guaranty

an efficient and reliable outcome, further research regarding the meaning of situated cognition and multimodality in a virtual learning context can be of interest.

ACKNOWLEDGEMENTS

The authors wish to thank VINNOVA and XPRES (Initiative for excellence in production research) for financing and supporting this research and development.

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