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Using Digitalization As An Enabler For Changeability In Production Systems In A Learning Factory Environment

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Abstract

Existing as well as new production systems need to adapt to meet increasing requirements of global, volatile markets. Companies aim to keep their production systems physically changeable while at the same time raise their level of digitalization. The human is a key aspect in the design process of production systems. Humans can only systematically develop suitable solutions if they have the necessary competencies to make reliable decisions. A promising approach to teach the required competencies is the use of gamification in form of learning factories. Approaches for learning factories addressing either digitalization or changeability are already described in literature. Although it lacks an examination on how to teach competencies in a learning factory environment, it enables participants to use digitalization methodically to promote changeability in production systems. This paper describes the required competencies regarding the implementation of changeability in production systems as well as competencies to support changeability making use of digitalization. In addition, it presents a concept for a learning factory workshop. Each round describes a new external impact on the production system that needs to be actively addressed by implementing interactive solutions containing digitalization as well as changeability methods.

Keywords

Learning factory; Gamification; Changeability; Digitalization; Competencies

1. Introduction

In the course of the digital transformation and increasingly volatile markets, companies have to digitalize their production systems while at the same time remain capable of change. A central point in the design of such systems are the professionals creating the production system, who can only systematically work out the creative process of the conception if they have the necessary competencies. One promising approach is the use of learning factories to teach the required competencies. These small-scale factories provide learners with the opportunity to actively take part in implementing and improving production processes in a realistic environment and to experience the results of their decisions without delay. The content learned in this way does not represent a mere extension of technical expertise but aims on developing competencies in dealing with methods and situations. These competencies can then also be applied on an industrial scale with little transfer effort [1]. Depending on the purpose and orientation, learning factories teach a very specific subarea of engineering, whereby the tasks to be solved are always derived from real problem situations and therefore equip learners with the tools to react immediately to such problems in real life situations [2].

The global digital transformation and the associated megatrends are creating a continuously changing market situation that is forcing companies to constantly adapt their production systems and, ideally, design them to be capable of change [2]. Varying customer requirements, changes in legislation and short-term strategical adjustments are examples of internal and external influences that force companies to transform their production systems constantly [3]. At the same time, digitalization is putting pressure on manufacturing companies. To operate efficiently, quickly and thus competitively, companies require digital support processes.

As mentioned above, professionals face the task of designing future production systems to be both changeable and digitally supported. To be able to do this, they need access to training that enables them to acquire the necessary skills and competencies. Literature shows that the focus of most learning factories, operated at corporate or university level, is on lean management workshops and demonstrating how digitalization technologies can be implemented to support lean manufacturing [5,4]. Although changeability has already been implemented in the form of modularized assembly workstations [6], literature on existing learning factories does not contain any examples that explicitly address the proactive design of changeability supported by digital transformation technologies. A description of a learning factory on changeability supported by digitalization technologies can help to improve the training of professionals who design future production systems.

The subsequent section describes the basic function of learning factories and the way of teaching competencies. Furthermore, it gives a brief overview on changeability in factories and digitalization indexing. It provides the framework for the analysis of the needed competencies to improve changeability in a factory, supported by digitalization technology in section three. Section four presents the learning factory workshop concept that has been developed. Lastly, the conclusions of the paper are summarized and future research possibilities are outlined.

2. Theoretical foundation on learning factories, changeability and digitalization

2.1 Learning Factories

Learning factories give participants the opportunity to actively engage in the implementation and improvement of production processes in a realistic environment while experiencing the results of their decisions without time delay [7]. Learning factories originate from the derivation of the principle of university clinics in the medical field [5] whereby both the high practical relevance of the students and the direct proximity of research to daily practice were taken into account. Although the term "learning factory" was first used in a research proposal by a consortium led by Penn State University [5] the literature agrees that the movement for the widespread use of learning factories originated in Central Europe, and from there expanded around the world [5,8]. A distinction is made between learning factories for research purposes and those for the education and training of professionals [5,4]. This paper considers only the teaching component. Depending on the purpose and orientation, learning factories teach a very specific part of engineering, whereby the tasks to be solved always derive from real world problems and therefore equip the learners with tools for immediate reaction [2]. As a result, learners develop professional competencies while remaining in a non-risky environment [9]. The approach of physically experiencing a learning process promises a significantly deeper anchoring of the imparted information as well as more joy in the learning process [11,10]. Another major advantage of learning factories is the fact that experimental learning is demonstrably more suitable for generating knowledge [12]. The lack of consequences of errors for ongoing business processes in the real environment clearly promotes curiosity and the willingness to experiment in learning factories. In their paper "Digital Learning Factories: Conceptualization, Review and Discussion" Haghighi et al. [10] break down four central areas of a learning factory in industrial engineering, on which this paper is based.

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.*

The last two areas listed are sufficiently documented in literature in the general context of learning factories [6]. Therefore, this paper is limited to the principle of changeability in production systems and the use of digitalization technologies as tools needed to improve changeability.

The majority of existing learning factories currently address topics of lean management as well as how to deal with digital transformation technologies [5,7,13]. In a recently published study Martinez et al. show the rapid increase in publications dealing with learning factories since 2015 [6]. In the field of changeability these papers address for example the general handling of volatile market conditions [14], reconfigurable assembly processes [15] or building capabilities for agility in learning factory settings [16]. In the field of digitalization, the number of populations is larger. Lozano et al. examined 70 papers on digitalization and point out that 65 of them contain the term cyber-physical-system [17]. Common concepts and technologies such as RFID, digital milkrun, pick-by-light and how to teach the appropriate skills in using these technologies are already well documented [18]. In their paper "Digitalization as a catalyst for lean production: A learning factory approach for digital store floor management", Meissner et al. analyze the influence of digitalization on lean management topics, whereby adaptability is only mentioned briefly [19]. A more holistic approach is presented by Graz University of Technology in their LEAD (Lean, Energy efficient, Agile and Digital) learning factory. They describe the following requirements as prerequisites for building a learning factory for transformability: (1) Holistic case framework including a comprehensive image of the value chain, different types of external uncertainties and customer needs; (2) Access to ecosystem data; (3) IT systems (hardware/software) to process data; (4) Modular and flexible production setup and (5) Multiple case scenarios [14]. The combination of changeability and digitalization in a learning factory environment has not yet been deeply investigated. The authors used the value chain of the lean management learning factory already existent, allowing access to the ecosystem data and IT systems. Therefore, the concept in this paper focuses on changeable production setups and developing game round scenarios. As described below, some basics on changeability and digitalization are required to enable the creation of a tailored concept for a learning factory workshop.

2.2 Changeability

Changeability is defined as the ability to make short-term, but at the same time economic, technological, logistical, organizational and personnel changes that exceed the flexibility held in reserve, when the need arises [3]. The majority of changes themselves in a production system take place in the dimensions of the number of units, quality, time, product and cost structure [19]. Turbulences in the environment of a production system act as so-called change drivers, which are defined as internal or external influences that force a production system to change through their direct influence [3]. Examples of change drivers are: changing customer requirements, changes in legislation or internal strategy changes. The literature distinguishes between three classes of change drivers: target drivers, element drivers, and number-of-units and variant drivers, which have different effects on the production system [3]. These drivers are contrasted by the change enablers. The primary change enablers are universality, mobility, scalability, modularity and compatibility [20].

Universality describes the ability of man and machine to manufacture a wide variety of products and variants and their usage in changing tasks. Mobility describes the dynamic movability of objects within a factory.

The design of the objects allows them to be rearranged in a short time by means of rollers or by using an overhead crane. Scalability can be considered as the property of a production system to be able to expand and reduce its own capacities in spatial, technical and personnel terms. Modularity is understood as the ability of a production system to provide standardized units that can be exchanged for other, equally standardized parts as required. Finally, the change enabler compatibility creates the basis for networking individual units and devices within the production system by providing interfaces [20]. Meyer-Schwickerath et al. proposed a framework for the development and evaluation of response strategies to counter change drivers with the targeted use of change enablers [21]. It will be used later to identify certain competencies regarding changeability. Changeability per se, as well as the cited characteristics of change enablers, have so far been described only in terms of their physical characteristics. However, to adequately address constantly changing markets and the associated need for changeability, the digital aspects of change capability should also be considered [2].

2.3 Digitalization

The field of digitalization in learning factories is broad. For finding competencies to support the implementation of changeability in production systems, this paper takes into account two major publications. On the one hand, the concept is based on the industry 4.0 maturity index [22], on the other hand it considers a study that aims for identifying and categorizing the 25 most relevant competencies for digitalization [23]. In the latter paper competencies were categorized regarding information technology, multidisciplinary, electrical, business administration and mechanical engineering. An explanation of the identified competencies is provided in the next section.

Schuh et al. differentiate digitalization further and developed a model for classifying digitalization and industry 4.0 into so-called "benefit-oriented development stages" [22]. Stage 1 of the path describes the "computerization" of a company. Already widespread in most companies, computerization addresses the cost-effective, precise and low-error handling of routine processes, for example in the form of a computer-controlled milling machine. The second stage of the development path is "connectivity," which involves networking the machines that work in isolation as part of computerization. The Internet is also part of connectivity and enables centralized control of production facilities spread across the globe. "Visibility" forms the third stage of the model and enables the operator of a production facility to collect real-time data using numerous sensors and a collection network. The aggregation of the captured data allows the production facility to be mapped as a "digital shadow" in a virtual environment where the current operating status of each machine can be viewed. The fourth stage of the development path is the application of the digital shadow to better understand the complex interrelationships within the company and thus gain "transparency" about the processes taking place. Derived from the transparency of the data, forecasts can be calculated in the fifth stage of the model, which simulate different future scenarios by specifying a probability. The sixth and final stage of the development path addresses the "adaptability" of a production system. This refers to the autonomous reaction of the system to internal and external influences and the independent application of automated and self-optimizing counteractions [22].

3. Methodology to identify game rounds for the learning factory concept

Based on the existing structures, the learning factory concept in this paper is grounded on a well-timed production system that uses kanban for both material supply and order processing. However, to familiarize the participants with the full potential of digitalization technologies the production system works completely analog. The desired form of the learning factory is a production system, which, in accordance with the benefit-oriented development path, records all relevant production data, gains transparency of the processes from the data obtained and finally generates or independently initiates recommendations for action. In this way, the system can respond early to drivers of change and is designed in a way that drivers can be countered within a very short time by changing the production system itself.

To structure the conceptual design of the learning factory, the teaching objectives were defined based on the first two areas of interest referring to Haghighi et al. as mentioned earlier. In the area of changeability, the didactic objectives are the secure handling of the concepts of flexibility and changeability as well as the control loop of changeability according to Nyhuis [24]. They should have an understanding of different change drivers and their consequences for the system within the turbulent environment and the interactions between change drivers and change enablers.

In the field of digitalization, the aim of the learning factory is to provide participants with a comprehensive overview of the technologies underlying the concept. Building on this theoretical foundation, the aim of the learning factory is to emphasize sufficiently the importance of connecting the available technologies with reference to each individual case. In addition, participants should have an understanding of the respective areas of application of the technologies and the actions required to use them effectively and efficiently. Lastly, a key point is to sensitize the participants to the possibility of a technical failure in digitally supported systems. Ideally, at the end of the learning factory workshop, participants will have a brief knowledge of the interaction between existing changeability and the use of digitalization technologies, both negatively and positively. Ultimately, the learning factory needs to enable the participants to independently design adaptable, digitally supported production systems or to improve existing systems through targeted actions.

In the course of game rounds carried out in the learning factory, the participants will encounter different drivers of change that either make it necessary to use the implemented changeability or force the players to spontaneously transform the existing system. Optimally, they will then resort to the available digitalization technologies and use them as supporting change enablers to master the drivers.

Therefore, in the conceptual design of the learning factory it is advisable to interpret the process backwards. Identifying the change enablers and their digital supporters serves as a starting point to derive the necessary competencies to handle them. This is followed by filtering from a catalog of change drivers that require the broadest possible spectrum of changeability competencies in order to be mastered. The first step is to record competencies relating to the general implementation and integration of changeability in production systems. The aim of the analysis is to create a competency catalog based on the matrix structure for evaluating technical-methodical competencies according to Abel et al. [9]. The second step is to identify competencies regarding the five primary change enablers as well as the three change driver classes enhancing the competency catalog. Step three is to include the competencies for exploiting the potential of digitalization in the context of the benefit-oriented development stages by Schuh et al. Next, a fictitious scenario is assigned to each potential change driver in a real-world environment, which could have an effect on the production system within the learning factory environment. Subsequently, the change driver scenarios are examined, evaluated and classified as applicable or non-applicable with regard to their feasibility in a highly simplified model environment as used in the learning factory. This is followed by the identification of four different entry scenarios of change drivers on the production system, which are examined as game round scenarios along the digitalization development path, which is needed to be able to recognize the change at an early stage in the game round. In preparation for the dynamics of participants, possible options for action for each changeability scenario are being identified.

In accordance with the procedure described above, the following section develops a catalog of competencies for changeability supported by digitalization in a learning factory environment.

4. Competencies on changeability and digitalization

For the documentation and description of competencies relevant to the professional field, the matrix structure developed by Abel et al. for the assessment of professional-methodical competencies is being used [9]. It subdivides a main competence (e.g. ability to perform a method) into several sub-competencies. Each sub-competence is assigned the respective action, e.g. analysis of the actual process. Furthermore, required professional knowledge and underlying conceptual knowledge is assigned to each sub-competence. As an example: for the application of the Single Minute Exchange of Die (SMED) method, the knowledge of the concept and the knowledge of the purpose and area of application of the SMED method would be required accordingly as professional knowledge. In addition, process knowledge is required on how the resulting shorter setup times affect material stocks and throughput times. Finally, as conceptual knowledge, there needs to be the understanding that setup optimization primarily makes sense if the associated equipment represents the bottleneck in the production system [9].

For the determination of the necessary sub-competencies in the field of changeability, the four design fields technology, logistics, organization and human resources were used [19]. Furthermore, the identified sub-competencies are based on the procedure for developing and evaluating response strategies [21]. Table 1 shows an example tuple from the competence catalog. The full catalog consists of 51 sub-competencies, categorized underneath Table 1.

Table 1: Listing example from the competence catalog

No.	Partial competence	Action	Professional knowledge	Process knowledge	Conceptual knowledge
1	Participants have the ability to identify the need for change	Evaluate production system in terms of existing adaptability.	Knowledge of the concept and general relationship between the production system and the environment.	Knowledge of the implications of sufficient or insufficient transformability.	Understanding that transformability only needs to be improved if it is not sufficient for potential drivers.

A total of 35 sub-competencies in the field of changeability were identified and described in accordance with the matrix structure for assessing technical and methodological competencies. The sub-competencies were subdivided into the three competencies "Assessing changeability" (10 items), "Recognizing change drivers" (5 items) and "Using change enablers" (20 items). The sub-competencies for dealing with change enablers were further subdivided into the five enablers universality (4 items), mobility (4 items), scalability (3 items), modularity (5 items) and compatibility (4 items).

The digitalization competency catalog consists of competencies relating to the classification and application of technologies in the context of the digitalization maturity index [22] as well as the 25 competencies most relevant for digitalization [23]. Latter were reduced to the five most relevant sub-competencies in the field of digitalization by means of a pairwise comparison. These include the fields of identification systems, data analytics, cloud computing, databases and network technology, from each of which a sub-competence was derived (5 items). Based on the Industry 4.0 maturity index, the six levels of the model Computerization (1 item), Connectivity (2 items), Visibility (2 items), Transparency (2 items), Predictability (2 items) and Adaptability (2 items) result in a total of 11 sub-competencies.

The catalog of competencies to be taught contains a total of 51 sub-competencies, broken down into the main competencies of handling changeability, change drivers and change enablers, supported by digitalization.

5. Learning factory on digitally supported changeability in production systems

For the implementation in a learning factory concept, it is necessary to bring the taught competencies into a logical sequence so that game events are understandable to the participants. Therefore, in the present case, it is necessary to integrate the concept of changeability into the game rounds, considering possible driver categories. These drivers then need to be countered with a specific change enabler and, in parallel, it must be communicated how the different levels of the digitalization maturity index can help to recognize and initiate the necessary change.

For the pre-selection of possible change driver scenarios, the exemplary change driver catalog according to Klemke et al. [25] is used for the preliminary selection of possible change driver scenarios. It distinguishes 16 changeability drivers in eight categories being legislator and associations, customer and market, suppliers, employees, technology, competitors and miscellaneous. Each category gets assigned two exemplary change drivers, which are subdivided into ten element drivers, five number-of-units and variant drivers and one target driver. To address the reference to possible instabilities within the production systems, the failure of a digitalization technology is also included in the catalog as an element driver of the "Technology" category, resulting in a total of 17 change drivers.

To examine the listed change drivers for their possible use in the context of the learning factory, each scenario is assigned an estimated time frame in which the driver will presumably influence the production system. Additionally, a scenario will be given that would be suitable for integration in the learning factory. The gradation of the assigned change timeframes is subdivided into less than two months, two to twelve months, twelve to 60 months, and timeframes of more than 60 months.

Grouping the individual stages of the digitalization maturity index enables the entire development path to be demonstrated, starting from a completely analog production system in the first game round. In each of the remaining three rounds of the game, two stages of the development path are combined and implemented. The first game round only serves to convey the mechanism of changeability and socialization with the existing analog production system. Table 2 shows the structure of the identified game rounds and the respective driver scenarios within the rounds.

Table 2: Structure of the identified game rounds

Round	**Benefit-oriented development path**	**Change driver**	**Change driver scenario**	**Change Enabler**	**Digitalization actions**	**Improvement actions**
1	Not digitized	Changed part quality	Only philips screwdriver is available, participants face slotted screws because no others are available.	Modularity	-	Universal screwdriver
2	Computerization & Connectivity	New products from competitors Change in make-or-buy strategy	Competition has individual license plates, initially sales slump, but then goes up again when individual license plates can also be attached.	Scalability Universality	Participants write small program to enable 3D printer to print rims on a conveyer for mass production. The implement their program into the MES software.	Use production machine rims (3D printer) for license plates Reduce employees first, then increase again
3	Visibility & Transparency	New/changed requirements for product properties	SUV is requested by customers, requires different undercarriage chassis. Customer requests more transparency on traceability.	Universality Mobility	Participants develop a KPI system by writing SQL-Queries that are directly displayed on their andon board while producing.	Layout rearrangement Design vehicle base universally Move customer order decoupling point
4	Predictability & Adaptability	Sales figures slump Shorten delivery time	New competitor on the market Company has to shrink healthily or switch to pure chassis production in a very short time, in order to survive.	Compatibility Scalability	Participants create a simple timeseries-based machine learning software that predicts customer demand on certain car variants.	Layout rearrangement Use forecast on customer orders are more interested in other vehicles, but the chassis for the SUV is very popular, but must be manufactured with shorter delivery times

Depending on the round in the workshop, participants have to apply different change enablers to continue to operate the production system economically. Additionally, they have to implement a digitalization approach, in order to fulfill costumer demands. The driver of the wrong screws in round 1 can be countered by means of modularity, in which different bits can be added to the modular screwdriver. As this round only serves the purpose of teaching the basic principle of changeability, there will be no digitalization implementations. Round two involves converting the existing production system and using the existing 3D printer to produce license plates. To do so, they have to write a basic javascript software snippet, that connects the printer to the MES system in order to automate rim printing. As the sale related key performance indicators (KPIs) suddenly drop, participants must first reduce and then increase the staff employed by means of scaling. In round three, participants need to change the entire product design to create a modular base that is fitted with the respective chassis for normal vehicle and off-road vehicle at the end of the assembly process. The resulting change in layout is initially not possible due to bolted down workstations. It must be possible to solve this problem by mobilizing the tables, for example by means of rollers [8]. In order to meet customer requirements regarding the transparency of the production and shipping progress, the group has to extract some KPIs from the MES. They do this by completing a short course on structured language queries (SQL) that enables them to build their own KPI-System from the MES data. KPIs are now displayed on an andon board throughout the whole game round, enabling the group to anticipate the shift in customer variant demands. Round four starts with the participants following up on how they determined the point of change in round three, based on their KPI system. Instructors provide the group with examples of supervised learning approaches based on free software to predict certain outcomes. Participants customize the given models according to their experiences from the game and the developed KPI system. The goal is to develop a system that predicts changes in customer demands based on data from the latter round. The driver of collapsing sales related KPIs, detected early by the new prediction system, leaves the participants with two options. They can either scale down the production system to produce the remaining vehicles in a more economical way or convert the entire production system to a chassis-only production.

The aim of the game rounds is for the participants to perceive not only the basic mechanisms of changeability but also how the use of digitalization buys them time to be able to recognize and initiate a necessary change in reasonable time. To point out the weak points of these technologies, one of the technologies should be eliminated in one of the last two rounds to make the participants aware of their dependence on the overall function of the implemented IT systems.

6. Conclusions and Outlook

Designing changeable, digitally supported production systems requires certain competencies of the planning staff. Learning factories can help to acquire these competencies without influencing live production operations. For this purpose, the respective learning factories must be precisely tailored to the topics to be taught to enable the participants to gain the necessary competencies while playing. Existing learning factories address either changeability or digitalization. Systematic analysis of the field of changeability in combination with the stage model of the digitalization and industry 4.0 maturity index helps to understand the interactions. In order to be able to convey the leverage effect of digitalization technologies on the early detection and initiation of a change in a production system, a multi-round learning factory workshop is required. The process described in this paper represents an approach to communicating the topics of changeability, change drivers and change enablers in the context of digitalization. Follow-up tasks are to continue implementing the concept in practice, measuring the learning successes, and iteratively improve the learning factory concept. Additionally, the concept could be enhanced by integrating new technology like machine learning.

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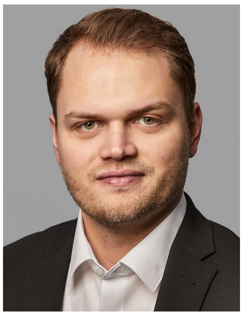
Biography



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