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The State-of-the-Art and Prospects of Learning Factories

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Abstract

Changeability of manufacturing systems is an important enabler for offering large variety of competitive products to satisfy customers' requirements. Learning factories, as teaching and research environments, can play a key role in developing new solutions for changeability, transferring them to the industry and using them in educating engineers. The results of a survey of existing learning factories and their characteristics are presented. Their use in research, teaching and industrial projects is analyzed. A novel scheme to classify those systems with regard to their design, products and their changeability characteristics is outlined. Conclusions about the future of learning factories are drawn.

Keywords: Learning Factories; Experimental Factories; Changeable Manufacturing Systems; Change Enablers; Classification

1. Introduction

The growing demand for customer-specific product solutions, the ever increasing dynamic requirements of products, and the shorter product life cycles require innovative concepts and solutions for manufacturing systems. These days, a great number of enterprises have to cope with high variety and the fast change of products and product variants [1-2]. Hence, flexible processes, agile technologies and changeable and reconfigurable manufacturing systems are becoming increasingly significant for industry. The response to these challenges and development of physical and logical change enablers should be considered and realized [3]. Such developments have to be geared towards their transfer and application in industrial enterprises. One approach to deal with these challenges is the emergence of experimental and research environments, such as learning factories, which can be used to develop and demonstrate these concepts and educate engineering students and industry practitioners about their potential [4-7].

There are a number of research institutions worldwide that have already established learning and experimental manufacturing facilities in their labs. However, only a few are geared towards developing change enablers.

The aim of this paper is to investigate the existing learning factories as prototypes for changeable and reconfigurable manufacturing systems. Several of these systems were analyzed to identify the state-of-the-art and prospects for their future development. A novel scheme for the classification of learning factories was also established. Moreover a special case study of learning factories, the iFactory in the Intelligent Manufacturing Systems Centre at the University of Windsor, Canada [5], is introduced to illustrate the potential of learning factories in fulfilling the requirements of changeability. The iFactory is a "Factory-in-a-Lab" that is a truly changeable industrial grade manufacturing system. It is the only one of its kind in North America and the second in the world (the first similar system was established at the University of Stuttgart [8]). It is a transformable assembly system that offers unique opportunities for developing state-of-the-art research concepts for changeable manufacturing

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systems and for the transfer of these concepts to industry [5].

The Intelligent Manufacturing Systems (IMS) Centre [8-10] and the Department of Factory Planning and Factory Management [2] [11] are investigating changeability and reconfigurability of manufacturing systems with the help of innovative research environments (changeable learning factories). Therefore, both are cooperating together and with other centers in Europe and North America to generate synergistic effects for developing novel and industrially relevant concepts and solutions for changeable manufacturing. As a first step within this cooperation the two institutions have investigated the state-of-the-art of learning and experimental factories. In the following sections the results of that investigation will be outlined.

2. Classification Scheme for Learning Factories

A novel classification scheme was developed to systematically explore the state-of-the-art of learning factories. This was realized on the basis of the morphological-typological theory [12]. Within this section an overview of the procedure to develop that scheme is given.

STEP 1: Terminology Definition

For describing the research subject of this contribution the term "learning factory" was defined first since many interpretations of it have been used.

The term has 2 words: "learning" and "factory" and therefore should be used for systems that have elements of both. It should comprise a real learning environment including realistic production processes. It can be used and adjusted for teaching purposes of different target groups. By using a learning factory for teaching, theoretical knowledge can be more effectively communicated and tested for practical applications, and learning results can be transferred to industry. This paper focuses particularly on learning factories for changeable and reconfigurable manufacturing systems [4-5].

The learning environment is ideal for transferring research outcomes to industry. New changeable and reconfigurable manufacturing systems can be investigated; novel systems concepts and changeability enablers can be developed, realized, tested and evaluated. Basic research emphasis is related to manufacturing systems, products and the organization/enterprise and their relationships [5].

The considered learning factories comprise physical and digital environments. The physical environment includes real system components like machining, assembly, logistics, and information flow and energy flow modules. Integrated planning, modeling, visualization and simulation tools are parts of the digital environment. Both physical and the digital environments should also be integrated. This offers new possibilities to transfer digitally created solutions to a real system for testing, evaluation and demonstration. Furthermore, there should be an automatic feedback from the real system components to the digital environment to plan adaptation and change [5] [11].

In addition, a learning factory for a changeable manufacturing system requires specific characteristics that can be achieved through the change enablers such as universality, mobility, modularity scalability and compatibility [1] [6].

This terminology definition forms the basis for developing a classification scheme to identify existing learning factories, that are dealing with changeability and that are geared towards their characteristics.

STEP 2: Compilation of a Structural Model

Based on step 1, a structural model was established, the components of which are shown in figure 1. The aim of step 2 is to establish a basis to identify parameters and parameter values for characterizing learning factories that are geared towards changeability. Using the change enablers in figure 1, parameters for the physical and the digital environment relevant for learning factories and corresponding manufacturing systems in industry were defined. Considering system, product and organization parameters required to outline the research subject were determined for factory objects, such as machinery, plants, logistics means, and production and information technology as described in step 3.

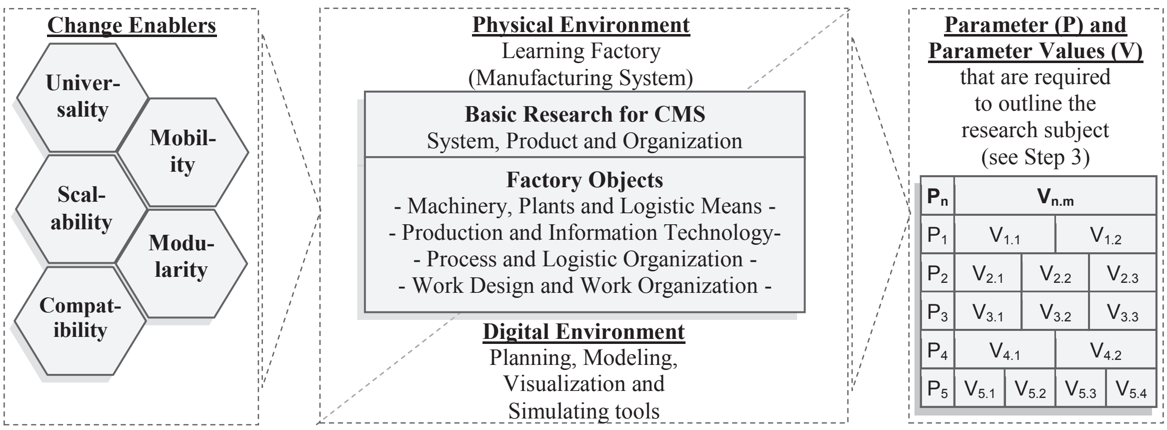

Fig. 1. Model for Describing the Research Subject

STEP 3: Identification of Parameters and Their Values

There are several possibilities for representing the parameters and their values. A decision table was used as shown partly in figure 2.

The values of the parameters consist of “true” or “not true”, and further value characteristic. A first-order parameter is for example “the availability of mobile equipment or system modules” and corresponding values are “mobile equipment is available” (“true”) or “is not available” (“not true”). The first order was detailed through a number of second-order parameters. Figure 2 shows three examples. Thus, the parameter “availability of mobile equipment” and its value “true” possesses the second-order parameter “Type of equipment” and the values “wheels”, “print feet” and “screw joints”. In addition there are initial approaches to extend the classification by establishing third-order parameters.

STEP 4: Definition of the Dependent Variable

The definition of the dependent variable is necessary to identify learning factories that are geared towards the characteristics of changeability and to investigate future prospects for corresponding systems.

The dependent variable of the classification scheme is due to the objectives suitability of a learning factory for teaching, for research and for transferring research results to industry. Accordingly the dependent variable is a combination of the suitability for these application fields and the initial point for the specification of the ideal type in step 5.

STEP 5: Attributes of Ideal Learning Factory

Based on the aimed suitability of a learning factory for a changeable manufacturing system, parameter values were determined that are describing an ideal learning environment corresponding to the terminology definition in step 1.

Regarding the first-order parameters of the classification scheme in figure 2, the attributes of an ideal learning factory are described by the parameter values “true”. In figure 2 this ideal type for the first-order parameters is illustrated by means of the grey shaded areas.

For the second-order several levels of the suitability concerning the parameter values were defined. Here the ideal parameter values are grey shaded as well. Further levels are illustrated by different shades of gray whereas the brighter the color the lower the level of suitability.

STEP 6: Testing the Classification Scheme

The final step is to test the proposed classification scheme. Existing learning factories have been classified using the decision table (figure 2). By comparing the results of that classification with the ideal type, learning factories were evaluated regarding their degree of fulfilling the ideal value of the dependent variable. Section 3 contains some results of applying the developed classification method.

3. State-of-the-Art of Learning Factories

For exploring the state-of-the-art of learning factories a comprehensive literature survey was conducted. In addition, a questionnaire was sent to all members of CIRP. Altogether more than 25 research and development organizations that have established learning factories were investigated.

Within the survey the manufacturing systems were explored. In this context, questions about equipment, manufacturer and year of installation, as well as manufacturing and logistics processes were asked.

Further questions were related to the product that is manufactured using the system. The main points were

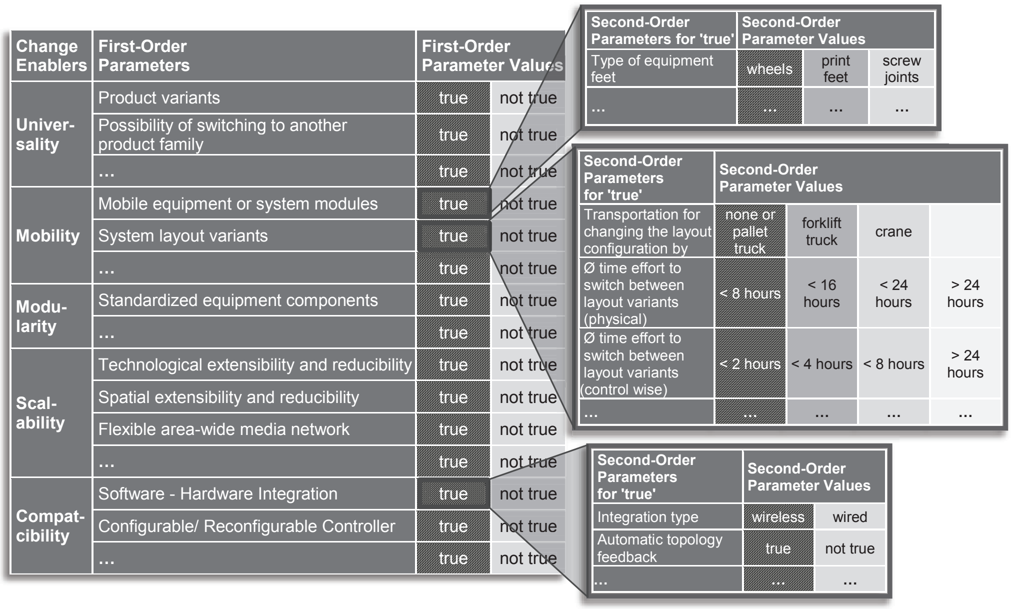

Fig. 2. Excerpt of the Decision Table for Classifying Learning Factories

product description, structure (machined features, parts and sub-assemblies), possible product variants and variant criteria as well as a potential simplification, particularly for the learning factory.

Regarding the use of the systems, questions were asked about teaching (course topics, level, courses to industry, experience), research (fields, experience) and projects with industry (fields of application, contents).

The last emphasis of the questionnaire was concerning characteristics of changeability of the learning factories. In this regard chance enablers like universality, mobility, modularity, scalability and compatibility were investigated as well as the possibility of different system component combinations or layout variants to change the system (physically and control wise).

Since there is a heterogeneous understanding about the term learning factory, how far the systems correspond to the terminology and specifications outlined in this paper (see section 2, “Step 1: Description of the Research Subject”) was examined. Therefore a matrix including a basic classification for necessary features was used. If the basic classification results indicate that the necessary features are fulfilled, the learning factory was analyzed in detail regarding its changeability attributes (see figure 2).

Within the application of this classification scheme, learning factories were compared with the ideal type that had been theoretically specified for changeable and reconfigurable learning environments (see section 2, “Step 5: Specification of the Ideal Type”). Despite the number of existing learning factories, it became obvious that there are only a few systems that are relevant for identifying prospects for the future development of changeable and reconfigurable learning factories. Plenty of facilities called “learning factories” are in fact not sufficiently fulfilling the requirements of the change enablers and corresponding parameters and parameter values for the ideal type (see section 2, “Step 3: Identification of Parameters and Parameter Values”). Systems that are partly geared towards some characteristics of changeability (about 7 out of more than 20), are briefly described in the following section.

3.1. Examples of Learning Factories

The Process Learning Factory CiP was installed at the Institute of Production Management, Technology and Machine Tools (TU Darmstadt). It consists of machining, assembly, cleaning and quality assurance equipment. The products of the learning environment are a pneumatic cylinder (machining of 8 variants), a gear motor (assembly of 4000+ variants) and a keychain (machining of 2 variants). The factory is used for teaching industry topics about lean production and students about advanced design. Research issues are didactical concepts for education in manufacturing and lean production. The changeability of the learning factory is related to possible changes in production setups that can be realized by several equipment modules.

At the Institute of Production Systems and Logistics (Leibniz University Hanover), a learning environment is installed for two different purposes. The IFA Production Training is used for teaching lean production methods such as Heijunka, Kanban, CIP, Synchron production and 6S. The Competence Factory is a prototype that is supposed to prepare staff for change situations and to enable the human for change. The equipment of the learning environment consists of modules for manual assembly and storage. Its product, a charging unit for cordless electrical screwdrivers, is available in 4 variants. The variants can be increased by expanding the product through a switch. Characteristics of changeability are realized by the modularity and scalability of the Plug n play elements of the mounting system, whereby the system can be changed quickly and easily.

The Department of Factory Planning and Factory Management (Chemnitz University of Technology) possesses the Experimental and Digital Factory (EDF). The EDF is part of a networked laboratory environment which is a unique characteristic of this learning factory. Further parts of the environment are an innovation, a CAD, a vehicle, an ergonomics, a usability and a biometric laboratory, as well as a project house. It consists of assembly and processing cells, an AGV, a monorail system, a gantry robot and a high rack storage. Its product, a simplified model of a cylinder block, is fitted for the simulation of mass customization due to variants that are realized by changing the components color and thickness. It is used as a teaching and research environment for changeability with regard to product, process and resource. The EDF also provides a testing environment for equipment manufacturers. Mobile cells, layout variants, a flexible area-wide media network, and software-hardware integration between the real cells and the digital environment are some examples for fulfilling the requirements of the change enablers.

The Institute for Machine Tool and Industrial Management of the Technical University of Munich owns two different learning factories. The Learning Factory for Energy Productivity and the Learning Factory for Lean Production. The Learning Factory for Energy Productivity is equipped with a turning machine, a conveyor furnace, a SCARA Robot, an assembly station, a compressed air system and a steam generator. It has a changeable design, to implement identified optimization measures. But nevertheless the focus of the factory is the energy productivity. The product manufactured is a gearbox that is used to demonstrate and investigate the effects of measures, tools and methodologies to reduce energy consumption in an existing production environment. The teaching in this factory is also solely focused on energy productivity, here the energy value stream, production planning and control, manufacturing processes, human behavior and organization are taught. Industry is most likely interested in improvement of industrial manufacturing sites, areas or machines regarding energy consumption.

The second learning factory of the Technical University of Munich, the Learning Factory for Lean Production is geared towards changeability. That is achieved with universal assembling tables and equipment as well as the high mobility of the equipment. Besides the universal assembling tables the factory is featured with a pick-to-light system, kanban material feeding system, a quality control station, digital planning tables (visTABLE) and machine-tools for SMED and TPM. For demonstration purposes, two kinds of gearboxes (planetary gear and spur gear, with 24 variants each) were designed. The equipped motor is a dummy with normal threads and screws, instead of self-cutting ones. The learning factory is only used for teaching principles and methodologies of lean production.

Further learning factories that are partly geared towards changeability characteristics are installed at BIBA (Institute for Production Systems and Logistics / University of Bremen), the Chair of Industrial Engineering (TU Dortmund), the Chair of Production Systems (Ruhr-University Bochum) and the Technologie-Initiative SmartfactoryKL (Kaiserslautern).

Using the developed classification scheme, a system that fulfills the requirements of an ideal type for changeable learning environment to a high degree was identified. In cooperation with FESTO the Learning Factory for advanced Industrial Engineering was established at the Institute for Industrial Manufacturing and Management (University of Stuttgart). The system consists of equipment for manual and automatic assembly, transportation, storage and inspection, as well as an AGV and a mobile compact coating center. It is used for knowledge transfer (methods, tools) concerning changeability and industrial engineering and for research about changeable and reconfigurable manufacturing systems (innovative sustainable and changeable production, optimization of dynamic work flows, integration of manufacturing steps into assembly). Projects with industry are related to the topic sustainable powder coating integrated in changeable production. Moreover, it is used to offer workshops for managers, designers and planners from industry. The learning factory is geared towards characteristics of changeability and its product, an office desk set, is available in more than 10,000 variants. In addition the system comprises standardized and mobile modules with Plug n play elements, which fosters the configuration of different layout variants. Hardware-Software Integration is related to the linking of the modules of the physical environment with the tools of the digital factory.

3.2. iFactory at University of Windsor, Canada

The Intelligent Manufacturing Systems (IMS) Centre (University of Windsor) has also established a state-of-the-art facility at the IMS Centre. It is a multi-layer infrastructure that consists of the complementary facilities: Innovation Design Studio, iDesign, a suite of logical change enablers, iPlan, and the physical iFactory [5].

The Innovation Design Studio (iDesign) fosters innovative design and group interactions. It consists of interactive designers' displays supported by the latest software and powerful computing environment for synthesis, configuration, modeling and analysis of products, processes and manufacturing systems and Siemens PLM suite of software. Developed products can be physically realized using a rapid prototyping machine.

The transformable manufacturing Platform (iFactory) for product assembly was also supplied by FESTO. It includes Plug n play modules that can be easily reconfigured to change the system layout and functionality. It has advanced robotic and manual assembly cells, inspection cells, automated material handling equipment, branch cells, storage retrieval systems, and line-up and line-down termination cells. The system allows not only for making different product variants, but also for reconfiguring its modules and changing its layout in less than an hour. Its unique drive technology, control, interfaces and modularity concept are essential for developing, testing and demonstrating the innovative physical and logical enablers of changeability.

The linking of the digital and physical environment by defining the positions of the several Plug n play modules is examined by simulation models in iPlan. The modules of the iFactory are equipped with topology feedback. Therefore, the control system of iPlan recognizes automatically the physical configuration of the physical learning environment (iFactory).

4. Conclusion

This study and associated survey revealed that the terminology surrounding learning factories is still developing. The minimum set of capabilities that should be present to call a facility a learning factory should be specified as well as the attributes of an ideal learning factory. Learning factories are not present in developing countries due to the high cost associated with establishing and operating them. However, many simpler or limited variants exist in many other countries and serve very useful in terms of education, research and industrial development purposes.

There is a need for joining efforts among those who have established learning factories to develop teaching and hands-on learning modules and applications that can be shared among users to save development time and share development experiences and lessons.

Learning factories are not simply duplicates of industrial factories. Some industrial practitioners, when they are exposed to them, may think “this is not a system my company can use”. It should be made clear that the concepts, strategies and soft and hard change enablers developed and verified using learning factories can be used by any company facing the challenge of remaining competitive and efficient in the face of continuous change and expanding product variety.

A survey of leading research and development organization was conducted in addition to an extensive literature survey. The purpose of this evaluation is to identify those learning factories that possess sufficient attributes of changeability. In this context their suitability for teaching, research and transferring research results to industry was examined.

A novel classification scheme has been introduced and applied to investigate and evaluate the state-of-the-art of learning factories and learning environments established in education and research institutes worldwide. Using the classification scheme, an ideal type of learning factory was theoretically defined. It forms the basis of the future prospects for changeable and reconfigurable learning environments. Hence, the future development of those systems should be geared towards approaching the parameter values of the ideal learning factory developed based on change enablers. The ideal system type specifies characteristics for products and product variants, equipment and their components, layout variants, properties for extensibility and reducibility, as well as requirements for integration with the digital environment of learning factories.

During this investigation research fields for the future development of changeable manufacturing systems have emerged. Some of these research fields are related to the following topics “Innovation and design of manufacturing system”, “Models and enablers of product variety”, “Novel organization concepts for changeable manufacturing systems”, “Models and enablers for changeable production planning and control for changes in market demands”, “Concepts and solutions for process planning for product and system variants”.

The developed novel classification scheme, and especially the specifications of the ideal type for a changeable learning factory, may be extended and enhanced in the future.

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