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P2O-Lab: A Learning Factory for Digitalization and Modularization

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Abstract

Current market developments lead in several domains to new challenges in terms of production flexibility, a shortening of time-to-market and a more individualized production of "batch size 1". While there are learning factories addressing some of these aspects, most of them are focused primarily on the manufacturing industry and overlook the process industry. In order to fill this gap, this article presents an overview over the concept and implementation of the Process-to-Order Lab. This learning factory focuses on teaching and research in the field of digitalization and modularization applications for the process industry. Therefore, the Process-to-Order Lab acts as a starting point for the development and realization of these concepts, while supporting the process industry through technology research and high-quality hands-on training of students i.e. future employees.

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1. Introduction

The learning factory presented in this article is named Process-to-Order Lab (P2O-Lab), which reflects the long-term goal to enable a future where complex production processes can simply be ordered and set up within days. This would result in a drastically reduced time to market for new products. Consequently lowering the cost for low-volume products and creating new business opportunities in market segments with fast changing customer preferences. To achieve this goal, the P2O-Lab focuses its efforts on the teaching and research of concepts for digitalization and modularization of production processes. In addition, the integration of artificial intelligence applications into the production process is emphasized to create smart systems, which ensure efficient and reliable operation of new plants. One major advantage of the P2O-Lab is that these concepts are not only researched theoretically but also implemented in a continually growing number of technology demonstrators.

At the same time, the close connection between research, teaching and industry partners ensures state-of-the-art research that leads to results that are relevant for both industry and the teaching of upcoming students. At first, the following article discusses the related work and locates the proposed approach within the field of learning factories. This is followed by an overview of the structure of the P2O-Lab including the general

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and didactic concept of the laboratory. Subsequently, various applications of the P2O-Lab concept for academic use and technology transfer will be presented. Finally, the conclusions from the P2O-Lab approach are presented.

2. Related Work

The basic structure of a learning factory is following the concept introduced by [10]. Because a learning factory can be defined in different ways, the authors are leaning the terms definition for this publication on the definitions given by [9]. Therefore a learning factory describes a location and organisational structure, which allows hands-on learning and research through the interaction with production systems authentically resembling technical and organisational systems used in the industry. Additionally, the learning factory has to be guided by a didactic concept which emphasizing experimental and problem-based learning for the teaching and research done in such a learning factory [1]. Currently most learning factories focus on one specific topic, which is at the center of their activities. These learning factories usually try to address cutting edge technologies like flexible or modular production systems [12], artificial intelligence [22] or digital twin applications [15] and their corresponding challenges. In addition, a lot of learning factories like the one described in [15] are solely focused on the knowledge transfer within the academic world through student teaching and workshops. On the other hand a significant group of authors like [21] also present concepts for the use of learning factories to ease the technology transfer between the academic and the industrial sphere. In contrast to these concepts the P2O-Lab tries to merge student education, academic research, and knowledge transfer to the industry for the two mutually supportive focal points: digitalization and modularization. While many other learning factories focus on similar topics within the manufacturing industry, the emphasis for the P2O-Lab lies on the application of these technologies for the sometimes overlooked process industry.

3. The P2O-Lab Structure

3.1. General Concept

In order to classify a learning factory, its properties can be mapped on to the learning factory morphology presented in [18]. This morphology is widely used and therefore allows for a simple comparison and differentiation regarding other learning factories. In table 1 the defining characteristics of the P2O-Lab are highlighted in grey within a slightly modified version of this morphology. Here the goal of the P2O-Lab to support the process industry through research and education of current and future employees i.e. students is clearly stated. Additionally, the focus in teaching and research on industry 4.0 related topics like modular automation, MLOps as well as industrial engineering and resource efficiency is pointed out. In order to efficiently achieve these goals, activities within the P2O-Lab are organised into the major columns ”Digitalization” and ”Modularization”, which will be detailed in the next paragraphs.

Table 1. Modified Learning Factory Morphology for the Operational Model of the P2O-Lab from [18]

Characteristic	Features					
Operator	Academic Institution		Non-Academic Institution		Profit-Oriented Operator	
Trainer	Researcher	Student Assistant	Technical Expert	Manager	Consultant	Educationalist
Target Industry	Process Industry	Manufacturing Industry	Electronics Industry	Automotive Industry	Textile Industry	Construction Industry
Development	Own Development		External Assistant Development		External Development	
Initial Funding	Internal Funds		Public Funds		external Funds	
Ongoing Funding	Internal Funds		Public Funds		external Funds	
Funding Continuity	Short Term Projects (Single Events)		Mid Term Projects (< 3 Years)		Long Term Projects (> 3 Years)	
Main Purpose	Education		Vocational Training		Research	
Secondary Purpose	Test Environment / Pilot Environment		Industrial Production	Innovation Transfer		Public Image
Subject-rel. Learning Contents	Energy and Resource Efficiency	Design	Industry 4.0	IT	MLOps	Industrial Engineering
Role of Learning Factory for Research	Research Object				Research Enabler	
Research Topics	Energy and Resource Efficiency	Design	Industry 4.0	IT	MLOps	Industrial Engineering

3.2. Research Focal Points

3.2.1. Modularization

At its core the P2O-Lab is researching and teaching technologies, which in the future will allow to simply order and set up complex production processes within days. Therefore a major emphasis lies on the development of modular plant automation concepts. In contrast to conventional monolithic plants these concepts subdivide plant architectures into multiple modules, which are not tied to a concrete product, which is produced within the plant. These so called Process Equipment Assemblies (PEA) following the VDI 2776 [20] allow for a fast disassembly of no longer required plants, the reconfiguration of the used modules and the swift assembly of new plants for different products. Accordingly, modular concepts have the potential to drastically reduce the time to market for new products, while also supporting the overall sustainability of a plant through the reuse of their modules. These concepts are reflected in technologies like the Module Type Package (MTP) [19] as well as in articles like [7], which provide further information regarding orchestration in the modular automation concept.

3.2.2. Digitalization

However, a physical modularization alone is not enough to enable a shorter time to market for new products. A successful deployment of a modular automation concept requires a digitized production environment to yield significant time savings. As [17] pointed out a large portion of the added value of such a cyber-physical production system lies in the digital domain. The digitalization offers significant innovation potential regarding the prediction, optimisation, reconfiguration and increased agility of the entire cyber-physical production system. Therefore the P2O-Lab is researching and teaching digitalization aspects like the information modeling of engineering and operation data in order to bring these two information domains closer together [14]. Within this topic special attention is also paid to the automatic transformation of raw data into useful knowledge, which can reduce the workload required for plant operations. One technique to achieve this goal is the use of digital twins for simulation purposes during the process design phase as well as for the virtual commissioning of new plants [16]. When dealing with this kind of challenges the quality of the used data and simulation models is of paramount importance, otherwise wrong conclusions are to be expected. Therefore, improvements in the quality assurance of data and simulation models is another key research area within the digitalization branch of the P2O-Lab [13].

The P2O-Lab researches AI methods in order to further increase speed and user-friendliness of the set-up, production, reconfiguration and quality control procedures for new process plants. A core strategy on this path is the use of AI based soft sensors to infer process information which otherwise would be not accessible to the plant operator [5]. In order to facilitate such AI applications on the one hand emphasis is put on the automation of data handling processes, especially regarding the improvement of MLOps for the process industry [4]. On the other hand the integration of AI-based services into the production environment, e.g. edge computing is being further developed [6], enabling a broad range of applications that further increase the agility and reconfigurability.

3.3. Didactic Concept

The didactic concept of P2O-Lab's teaching efforts can be summarized through the learning factory morphology depicted in table 2, where the didactic properties of the P2O-Lab are highlighted in grey. Here, a clear focus on the improvement of technical and methodological skills through on-site or remote tutorials, workshops and lab courses is illustrated. In order to ensure a structured teaching process the P2O-Lab follows the learning process presented in [8]. The structure of this approach is illustrated in figure 1, which highlights the three main components i.e. teaching through lectures, the self-study of the students and laboratory experience. The goal of this procedure is to firstly give the students all necessary basic knowledge about a specific topic through lectures. Afterwards the students can leverage this knowledge within their self-study to deepen their expertise in certain aspects of the taught field. They then are able to validate their gained knowledge through hands-on experience in the P2O-Lab, where they receive workshops, tutorial or practical lab courses. Within these workshops the participants can test out their previously gained knowledge on real world examples while receiving additional information and feedback from the instructors. Through this concept the P2O-Lab is able to supplement the typical theory driven education approach, which is predominantly used in the teaching of

many engineering chairs, with hands-on learning opportunities. This seeks to increase the students overall understanding of the topic, while also bridging the gap between teaching, academic research and real world application of the developed technologies. In addition, the P2O-Lab is used for collaborations and workshops with psychologists and other students or researchers from non-technical fields, giving them rare direct access to a real production environment and thus enabling a wide range of interdisciplinary research. To enable such a practical learning experiences the P2O-Lab provides an extensive infrastructure of approximately 108 m^2 of laboratory space. The P2O-Lab holds ready modules for a lot of different functions needed within the process industry. This includes PEAs for the mixing, fermenting and tempering of products as well as signaling and measuring equipment. A few examples of these PEAs can be seen in figure 2.

Table 2. Modified Learning Factory Morphology for the Didactics of the P2O-Lab from [18]

Characteristic	Features				
Competence Classes	Technical and Methodological Competencies		Social and Communication Competencies	Personal Competencies	Activity and Implementation Oriented Competencies
Learning Scenario Strategy	Instruction	Demonstration		Closed Scenario	Open Scenario
Communication Channel	On-site Learning (in the Factory Environment)			Remote Connection (to the Factory Environment)	
Functionality of Product	Functional Product	Didactically Adapted, with Limited Functionality		Without Function, for Demonstration only	
Type of the Training	Tutorial	Practical Lab Course	Seminar	Workshop	Project Work
Learning Success Evaluation	Knowledge Test (written)	Knowledge Test (oral)	Written Report	Oral Presentation	Practical Exam

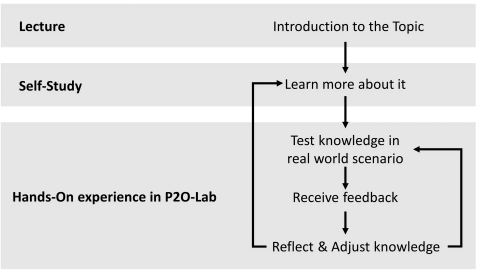

Fig. 1. Learning Process based on [8]

Fig. 2. Examples of P2O-Lab's Modular PEAs (left to right): Mixing PEA, Parallel-Dosing PEA, Bioreactor PEA, Signal-Light PEA, Media-Supply PEA, Control PEA

4. Enabling Research, Teaching and Technology Transfer in the P2O-Lab

4.1. P2O-Lab for Academic Use

In practise the illustrated infrastructure is used to realize a multitude of different learning experiences within the academic setting. Students for example can visit the P2O-Lab during their lectures about process control systems to get a hands-on understanding of the current concepts for modular plant automation. For these tutorials and workshops the didactic concept presented in section 3.3 is applied in order to ensure a maximal learning outcome for the students. Additionally, diploma theses and other student research projects are conducted in all three thematic focus areas of the P2O-Lab, which gives students the valuable opportunity to immerse themselves deeply into specific aspects of modular automation, digitalization or AI applications while having immediate access to physical equipment to test their theories. Nevertheless, in a significant amount of time the laboratory is also reserved for doctoral research or project based research in cooperation with industry or public partners. This research does not only extend the knowledge within the addressed field of interest, but also indirectly ensures that the students are introduced to an working environment, which is suitable for state of the art research within their field of study. A few examples of these research projects will be given in the next section.

4.2. P2O-Lab for Technology & Knowledge Transfer

In addition to student teaching and academic research, the transfer of technology from the academic to the industrial sphere is an important goal for the P2O-Lab. On the one hand, this is done through workshops in

which current research findings of the P2O-Lab and the resulting technologies or concepts are introduced to industry representatives. On the other hand, it is often times even more effective to directly collaborate during the research phase. This ensures that the research efforts are targeting problems, which are of high relevance for industrial applications, while also providing the learning factory with funding opportunities and insights into the current best practices within the industry. These insights are then used to continue the development of the P2O-Lab, ensuring its suitability for state of the art research. To further illustrate this point, a short overview over two current research projects is given in the following paragraph. The P2O-Lab is transferring its knowledge about modularisation and digitalization to the sub-project ”eModule” of the german ”H2Giga” initiative, which investigates ways to make elektrolysis technology for gigawatt-scale hydrogen production ready for series production [2, 11]. Therefore, a lot of ongoing research within the learning factory is dedicated to the development of integration profiles and optimisation algorithms for modular water-electrolysers as well as their integration into a wide range of engineering workflows. Additionally, two modular small-scale demonstrators for PEM-electrolysis and AEM-electrolysis will be set up in order to demonstrate the technology scale-up and to validate the generated research results. Once this modular hydrogen production is set up in the learning factory, it will also offer students a quite rare opportunity to get direct hands-on experience with one of the core technologies for power-to-X applications on a production level. At the same time current research regarding artificial intelligence is focused on the project ”KEEN” [3]. This project, involving a total of 20 public and private partners, seeks to incorporate AI-based technologies into all steps of process modelling, plant engineering and operation optimisation for the process industry. Here the P2O-Lab acts as a testing ground for implementations of AI-based solutions in order to validate their performance in real world conditions and to improve them further to be ready for usage in pilot applications. Additionally, the P2O-Lab serves as an incubator lab, which seeks to define AI-based business models that can extend the research efforts beyond the publicly funded period.

5. Conclusion

This article introduced the P2O-Lab as a learning factory, which allows students, PhD researchers and industrial partners to deepen their knowledge about digitalization, modular automation and AI applications for the process industry in a hands-on fashion. Furthermore, the key concepts of these topics were presented together with the general and didactic concept of the learning factory. To illustrate the actual implementation of these concepts, examples from the academic usage of the P2O-Lab as well as examples of the knowledge transfer to the industry were given. The future work of the learning factory will focus on integrating the research results regarding digitalization, modular automation and artificial intelligence for specific use-cases in the process industry, such as hydrogen or biopharma production. In addition, the operating model of the P2O-Lab will be further developed so that it can be fully economically self-sustaining.

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