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FactoryBricks: a New Learning Platform for Smart Manufacturing Systems

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Abstract

Manufacturing industries are facing radical changes under the technological acceleration of Industry 4.0. The manufacturing workforce is not ready for such disruptions due to the lack of vertical skills on digital technologies. Production planning and control of manufacturing systems is often an experience-based art. Further, the companies need of offering training paths for long-life learning of their employees finds several obstacles in the availability of skilled trainers and the trainee's low engagement with traditional learning models. This paper presents how the *FactoryBricks* project aims at overcoming the aforementioned issues. The project delivers effective training courses to enable the uptake of industrial technologies and smart manufacturing systems for professionals, either executives or technicians. Beside digital learning contents, the learners are offered an interaction with lab-scale models of production systems built with modular components such as LEGO®. The courses are designed in a modular way, and aim to teach manufacturing concepts in three main topics: (1) the physical system and its dynamics, (2) the physical-digital data connections for smart online analytics, and (3) the exploitation of digital models for production. The paper also presents the results of the prototypical implementation of the project.

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Keywords: Industry 4.0; Learning Platform; Smart Manufacturing Systems; Training.

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1. Introduction

The current production landscape is undergoing a change from monolithic structures to modular and service-oriented value creation networks. Indeed, Industry 4.0 brought a set of technologies to be exploited in the industrial context. Smart devices such as sensors and connected products make it possible to design digital counterparts of physical

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systems, to take smarter decisions in industrial processes. However, they also introduced a higher complexity in production systems. The users of these technologies need to obtain the right skill set to rapidly integrate within a smart manufacturing environment. Hence, proper training of the workforce becomes essential for European manufacturing firms to maintain their leadership.

The 2021 project *FactoryBricks* aims to deliver effective training courses enabling the uptake of industrial IoT technologies, and digital and smart manufacturing. The project creates an active learning environment for professionals who need training on the digitization of manufacturing equipment. Modular learning contents are designed to teach waste-free manufacturing concepts by creation, interconnection, digitization, and operation of miniaturized manufacturing systems and the related IoT technologies. Course contents are provided on the EU-funded platform *Skills.Move*. A *FactoryBricks* package can be used by the trainees to build a lab-scale manufacturing system with modular components (e.g., LEGO Mindstorms®, Fischertechnik®) and additional industrial IoT-compatible devices (e.g., Arduino Nano and RaspberryPi). Trainees can perform activities both autonomously or in a team.

2. Related Works

A key impediment to Industry 4.0's rapid implementation is its perceived complexity and abstractness. Erol et al. [2] propose a scenario-based Industry 4.0 Learning Factory model to solve these challenges. The authors created a "problem-competency cube" based on competency categories and typical problem areas of digital production systems, as suggested by the RAMI4.0 architecture model, to serve as a reference for targeted development of problem-specific competencies. Ferreira et al. [9] identified and characterized test beds and proof-of-concept experiments developed in learning factories to support Industry 4.0 adoption, with a focus on simulation modeling.

There are different concepts for innovative educational approaches [3]. In general, two main methods can be identified: (1) on-the-job training (OJT), in which employees are trained at the workplace, and (2) off-the-job training (OFF-JT), where activities are performed apart from the workplace. In addition to continuing education courses, it is also possible to conceive individual training or special forms of training, such as competitions or business games, self-study with and without IT support. McHauser et al. developed the *Model-Factory-In-A-Box* concept [7]. It is a mobile training factory that has proved to be effective to develop new skills in a realistic manufacturing setting, spanning from lean manufacturing to digital technologies. This setting improves participant recollection, learning results, and it motivates organizations to take action by demonstrating to participants that progress is possible when individuals work together as a team and use a common language of techniques. In this context, LEGO® is increasingly being used for educational purposes in engineering. LEGO® can be exploited to enhance students' motivation and competences to teach important technical concepts and methods in a practical way [5]. Three closely related works are mentioned here for example. Syberfeldt [11] described a practical exercise with students to teach simulation-based optimisation using the example of a chewing gum production using a LEGO® factory. Sanchez and Bucio [10] discussed on the usefulness of LEGO® as a teaching and learning tool in a postgraduate course on the control of discrete-event systems. Here, students are challenged to design and implement modular hierarchical discrete-event control for an automated manufacturing system built from LEGO® bricks. Lugaresi et al. [5] described a teaching project in which mechanical engineering students develop competences in discrete event simulation with a lab-scale model built with LEGO®.

Despite the aforementioned approaches, literature is poor of solutions to create awareness on production planning and control for smart manufacturing systems. Further, most approaches rely on the physical presence of trainees in laboratories, which recently proved to be a limitation [6]. Also, most training courses do not offer modular contents. The *FactoryBricks* project overcomes these barriers by: (1) providing an easy-to-use kit through a LEGO®-based lab-scale manufacturing system, which enables both OJT and OFF-JT; (2) allowing a hybrid training approach through online-based courses, and (3) offering modular courses, which easily adapt to already-developed skill sets.

3. Project Details

The goal is the development of different learning paths focused on three topics which can be related to different levels of the ISA-95 framework IEC 62264 [8]: field communication (levels 0 and 1), waste-free manufacturing (levels 2 and 3), and industry 4.0 (levels 0 to 4). For each topic, two learning paths are created: one with basic and one with advanced complexity, for a total of six learning paths. Finally, the created digital learning contents are offered

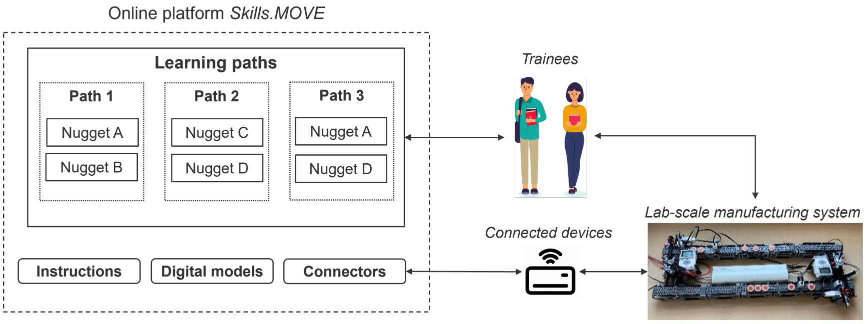

Fig. 1. The project framework.

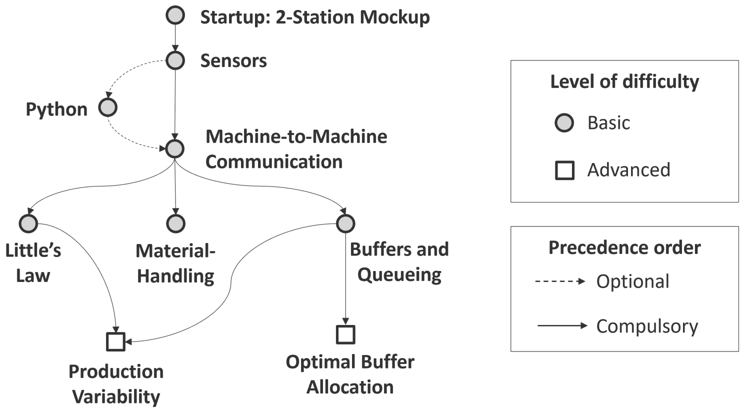

Fig. 2. The structure of the learning path "waste-free manufacturing".

through the *Skills.Move* platform. The project creates an active learning environment for professionals using three elements: (i) digital learning contents to be carried out with the use of (ii) lab-scale models and (iii) digital models of production systems (an overview of this framework is proposed in Fig. 1). The learning contents are designed as modular and scalable components to compose the learning paths. Indeed, each nugget might be included in one or more paths. An example of how the nuggets contribute to create a learning path is described in Fig. 2. Most of these concepts can be explained and understood by building and operating miniaturized manufacturing systems, the related IoT technologies, and their digital counterparts. Hence, the first nuggets in each path are related to the building of a lab-scale manufacturing system and to the development of digital models for an easy reproduction of the system dynamics. After this building phase, trainees can actively experiment with the lab-scale system guided by the learning contents and using the digital models for prediction and/or experimentation of new scenarios to be eventually tested in the physical system. Sections 3.1 and 3.2 further elaborate on these phases. The mixed modalities introduced in didactic sequences contribute to support skills' acquisitions for the learners compared to other training formats such as online courses or blended solutions [12], that usually do not include the physical experimentation with a lab-scale model especially designed for training purposes.

3.1. Lab-scale Physical System Kit

A *FactoryBricks* kit (Fig. 3a) includes all the needed material to build a lab-scale manufacturing system with LEGO® components, which are easily accessible on the market. The building phase takes approximately three hours for a trainee with null previous experience with LEGO® components (Fig. 3b). The final result is a miniaturized manufacturing system with two workstations, where circulating pallets are carried by a conveyor connecting the workstations (Fig. 3c). The system dimensions are less than 60 centimeters of width by 120 centimeters of length. The small dimensions, along with the low time for the building phase, the inexpensive components and the ease of

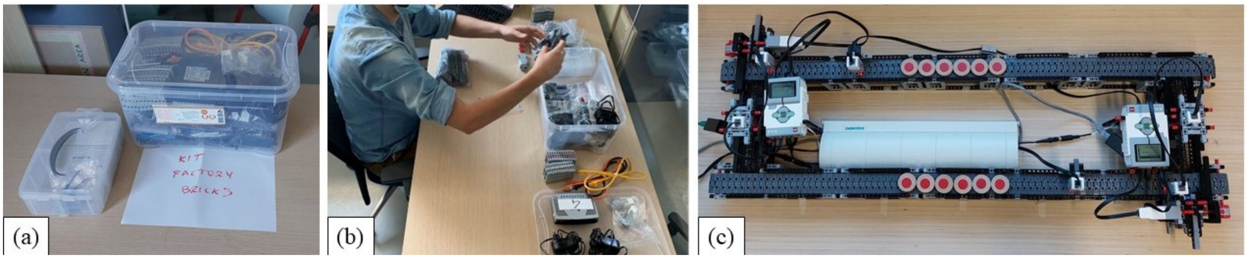

Fig. 3. Building phase of the lab-scale production system: from the base kit (a), to the building phase (b), to the final built-up system (c).

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Table 1. Applications of the production system digital model in *FactoryBricks*.

		Scope of digital model			
Nuggets	*Scope of nugget*	*Parameter setting*	*Buffer capacity*	*Data generation*	*Performance estimation*
Production Variability	Impact of variability in part-flow and production performance	•			•
Material Handling	Part-flow management			•	•
Optimal Buffer	Optimize buffer size		•		•
Data Mining	Find improvement opportunities from unstructured data			•	•

their accessibility on the market, make this lab-scale system a suitable and affordable tool for any company that wants to enhance the skills-set of its employees. Further details on LEGO®-based models are available in related works [4].

3.2. Digital Models

The digital model (Fig. 5a) represents the digital counterpart of the physical lab-scale model (Fig. 3c). The model has been built using ARENA software and it is provided to the users. This tool has been chosen for its ease of use and the possibility to be used within a free license. The role of the digital model is to retrieve updated data from the real system and simulate the impact of a certain action on the system performance over a long-term period. The digital model is used to evaluate and export data such as the system throughput, the utilization of each station, the current and average number of items in a buffer. The trainees are invited to use the digital models to test how different scenarios lead to a different system behavior: for instance, the buffer capacities can be changed to assess the impact of internal or external phenomena leading to higher or lower system variability.

Table 1 shows the available applications of the digital model within the *FactoryBricks* project. Once both digital and physical models are conFig.d with the same parameters, the presence sensors from the physical model can capture information on the time and the number of pallets that are produced by the physical system. Hence, the physical-digital connection is enabled by the use of text files with the recordings of presence sensors installed in the physical model. The choice of such format is due to its simplicity and ease-of-access from a wide spectrum of users. Fig. 4 shows the typical list of steps which is proposed to the course participants. The trainees are invited to perform simulation experiments on the digital model and assess the physical model performance over a long-term period. Indeed, the output data can be analyzed to find the root-causes of a phenomena or to propose continuous-improvement actions. Those improvements can be made in both the digital model and the physical system. Also, this process can be repeated, allowing for continuous improvement iterations.

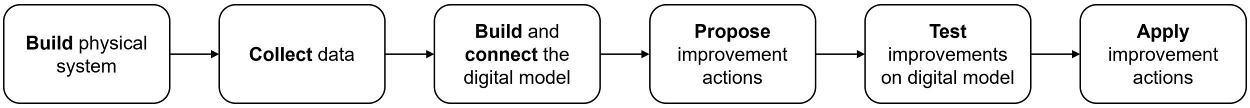

Fig. 4. List of steps for the integration of physical and digital model within the project courses.

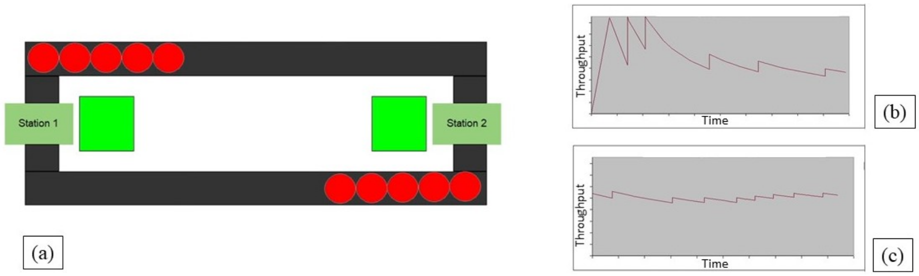

Fig. 5. The digital model of the lab-scale production system model (a) along with two practical application of its use to measure system throughput with different sources of variability, (b) and (c).

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3.3. Significant Example

In the following, we summarize the nugget titled ”Production Variability” as significant example. After the completion of this nugget, the learner should be able to: (1) describe the causes of variability in a production system, (2) analyze the impacts of this variability, and (3) use appropriate strategies to prevent variability effects.

The nugget has been designed in accordance to the problem-solving approach proposed by Abele [1]. The nugget starts with a series of tasks to be performed by the learner on the lab-scale LEGO® system (Fig. 3c). The goal is to use practical experiments to assess how the system throughput changes when different sources of variability are inserted in the system (e.g., machine failures) and how to mitigate the variability effects by increasing the buffer capacities. During this phase, the learner obtains a practical evidence that failures can cause variability in a production system and impact on its throughput, and can study how to mitigate these effects (e.g., by increasing buffer capacities). At this point, the nugget introduces a series of theoretical concepts related to the experiments that the learner just carried out (e.g., the difference between a deterministic and a stochastic system characterized by variability). In order to facilitate the understanding of these concepts with the help of the digital model (Fig. 5a), the nugget shows how the system throughput changes over time when the system is subject to high (Fig. 5b) or low (Fig. 5c) variability. In this way, the learner acquires theoretical knowledge on what variability means, why it arises and what it can cause. Finally, the nugget delivers some techniques to mitigate the variability impacts on production systems, providing to the learner the theoretical explanation on why increasing the buffer capacity can significantly reduce the variability effects.

4. Preliminary Results

The project team organised a course roll-out test once a sufficient number of learning nuggets reached a ready-to-use level. The roll-out test was carried out with participants from academia and industry, i.e. twenty-five master students from the industrial engineering course, and one industrial engineer with more than twenty-five years of experience in production systems. Each student completed the same nuggets; namely: (1) Little’s law, (2) Buffers and Queuing, and (3) Production variability. Each participant in the roll-out phase had to fill a feedback form to provide useful comments to assess and improve the learning contents offered by the *FactoryBricks* project. This feedback collection process was performed because the main idea of the project is to propose learner-centric approach, in order to give to the learner an active role. A first positive and recurring feedback regarded the significant active learning induced by the nuggets, indicating a major cognitive and practical engagement by the testers. In addition, for each tested nugget a remarkable percentage of the testers (65% to 75%) declared to have reached the expected learning outcomes the nugget should provide, highlighting the learning effectiveness of the contents. Finally, all the testers underlined that the nuggets are easily understandable for beginners in the study of common issues for the design and management of production systems and that the experience with videos and/or the physical model is greatly effective to understand the concepts explained in the nuggets. On the other hand, the feedback-collection suggested some improvements, such as adding more examples from practical cases and providing more time to study the contents. Also, one tester identified the limits of a two-stations lab-scale model, especially to represent the variability of a complex manufacturing system.

5. Conclusions

Industry 4.0 has brought a range of technologies that can be used in the industrial context, but also increased the complexity of production systems. The constant changes require appropriate methods and approaches to train employees in the deployment of future technologies through lifelong learning programs. This paper presented an approach which combines digital learning formats with a lab-scale manufacturing system. The *FactoryBricks* project focuses on three main topics: field communication, waste-free manufacturing, Industry 4.0. The modular design of the lab-scale manufacturing system makes it easy to integrate other topics by adding new components, such as sensors or actuators, or using existing components and by developing suitable training formats which can be added to the learning platform. The preliminary roll-out phase highlighted how the problem-solving approach enables the trainees to go beyond the basic process of “learn and apply”. The scenarios collectively imagined for *FactoryBricks* supports the learner in the exploration, reflection, and critical thinking. Even though the learning platform allows employees to acquire competences in future technologies, the adaptation of what has been learned to the actual workplace remains challenging. This is also due to the relative simplicity of the lab-scale models proposed in this project, which remain significantly different from real environments. Next developments of this work shall focus on developing more complex models. In the future, the nuggets consumption should lead to get feedback from a larger sample of users so to obtain a more accurate evaluation of the effectiveness of the project approach.

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