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A Remote Laboratory Experience in Teaching Discrete Event Simulation Modeling for Manufacturing Applications

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Abstract

Under social-distancing directives due to the COVID-19 pandemic, universities faced the problem of how to teach without providing access to the university installations. The physical laboratories and learning factories are essential pieces of equipment that allow for realistic modeling activities. At the Department of Mechanical Engineering in Politecnico di Milano, there is a laboratory that is used to teach students how to perform simulation projects related to manufacturing systems. The lab exploits physical models built with LEGO components. For the semester project in 2020, the developed system is a closed-loop production line with six stations, two of which supervised by operators. During the lockdown, a virtual connection to the laboratory has been exploited to allow students to not lose the opportunity of a fruitful experience. Three cameras have been installed on the model and a real-time dashboard has been developed to further enhance the understandability of the system behavior. Hence, although remotely, data can still be collected from the real system. The experience proved that despite the physical distance, the laboratory remains a valuable asset for an M.Sc. course educational offer.

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Keywords: Remote Laboratory, Manufacturing Systems, Discrete Event Simulation, Learning-by-Play, LEGO.

1. Introduction

The recent global pandemic forced companies and institutions to comply with strict social-distancing directives. In this context, universities faced the problem of how to teach without access to the university installations, such as physical laboratories and learning factories. The addition of an experience in a learning factory has been proved to be benefitial in Industrial Engineering courses, both for the added value of the physical interaction with a system and for the realistic experience of teamwork with a practical goal [1]. The course *Integrated Manufacturing Systems* is offered by Politecnico di Milano to M.Sc. students in Mechanical Engineering. The course focuses on the analysis of complex manufacturing systems using basic theory of discrete event simulation (DES). Students are required to complete a simulation project. The main goal is to challenge students to apply the theoretical contents learned during classes to

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a realistic problem, in which information is not fully available and the problem statement is not perfectly defined. Since this learning outcome is difficult to reach, in previous years the classical project description – traditionally in the form of written text – has been replaced by a lab-scale model of a manufacturing system made with LEGO®[1] components [13]. This allows important additions to the student learning experience such as doing abstraction from a real system, dealing with real data, and facing limited measurement and experimentation capabilities due to cost and time constraints.

In this paper, we describe the experience in the Fall Semester 2020. Although requiring physical resources in the laboratory, the project has been kept in the teaching offer and has been performed remotely. The activities in person have been substituted by remote connections with cameras, and data collection was allowed even if the students were not physically in the lab. The experience has given insights on both the advantages of a remote setting and the incommutable experiences that cannot be covered unless in presence. The rest of the paper is organized as follows: section 2 lists the significant contributions in the literature which dealt with similar laboratory settings in industrial engineering education and remote teaching; section 3 explains the course contents, the project work, and the remote laboratory setting; section 4 summarizes the useful insights and final remarks.

2. State of the art

Industrial and system engineering disciplines often involve the comprehension of complex manufacturing systems. The limited access to real systems is particularly common and may represent an issue for student learning, due to the lack of practical implementation and reduced involvement. Indeed, students are given complex descriptions of industrial cases on course material, but they almost never engage with the practical problem. Recent works sponsor the introduction of interactive activities for teaching purposes (e.g., games, laboratory experiences). Indeed, learning through play can positively contribute to the construction of new awareness based on students pre-existing knowledge [15]. Applications of interactive teaching can be found related to production planning problems [11], supply chain management [14], and production strategy [19].

In general, the exploitation of lab-scale models in engineering projects successfully improves students motivation and involvement, as well as enriching their competences [3]. In fact, students are able to get in contact with practical aspects of main engineering concepts and technical methods by facing with fundamental educational aspects, such as the application of mathematical knowledge, the acquisition of programming skills, as well as the resolution of practical engineering problems. Recently, LEGO has been increasingly used as an educational tool for teaching in several engineering subjects such has robotics [10], computer programming [3], and control theory [4]. In industrial and mechanical engineering courses the adoption of LEGO is less common. Sanchez and Bucio [16] based a course on a manufacturing system realized with LEGO to teach the principles for controlling discrete event systems to postgraduate students. Syberfeldt [18] described a practical exercise to teach simulation-optimization to students using a LEGO-based factory simulating the refinement of raw materials. Jang and Yosephine [8] developed an education platform based on LEGO, in which students can improve their understanding of the processing times and failure rates, their ability to model the system, and their capability to design a good buffer allocation. Auer and Felderer [2] are designing a concept for training of testing experts in Internet-of-Things with LEGO: the goal is to provide training courses close to real-world scenarios. Lugaresi et al. [13] designed a laboratory experience for teaching discrete event simulation, exploiting lab-scale models built with LEGO for covering the system observation and data collection phases of a simulation project.

Meanwhile, several contributions from the literature addressed the need of accessing laboratory equipments from remote. Among others, Ionescu et al. [7] designed a remote laboratory for teaching automatic control concepts to engineering students with two applications: formation control of mobile robots and a ball-plate system. Torres et al. [6] developed a system that allows the student to interact with simulated and real robots through the internet to teach robotics. Jara et al. [9] designed a blended experience for undergraduate students in Automatics and Robotics, in which students experiment with both face-to-face classes in the real plant and remotely in the experimentation environment to finish their practical exercises outside the laboratory. Remote laboratories for teaching manufacturing

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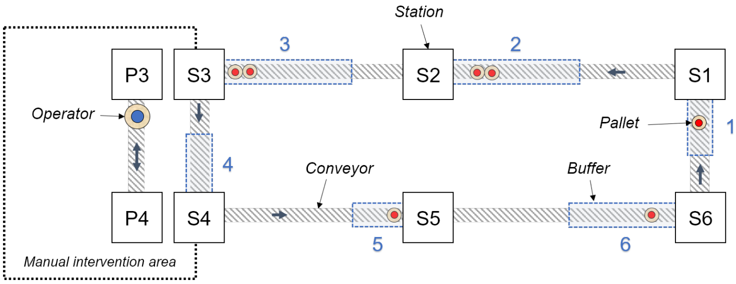

Fig. 1. Logical schema of the production system analyzed in the project.

are less common. Stefanovic [17] analyzed the effectiveness and the issues connected with remote laboratories. As far as our knowledge, no contributions exploited virtual laboratories for teaching production planning and control with DES. Our focus is to substitute the experience of interacting with a physical system exploiting a remote connection to the laboratory space. In this work, we present the preliminary results of the laboratory design, its exploitation for the project work, and the lessons learned.

3. Course Details and Remote Laboratory

The course *Integrated Manufacturing Systems* addresses the uptake of discrete event simulation as decision support system for production planning and control. The course consists of lectures, classworks, and a project work [13]. The project work consists of modeling, analyzing, and improving the performance of a production system. Students are required to work in teams to solve a realistic problem, related to the optimization of the system performance under a defined set of constraints. Every academic year, a different industrial problem is proposed. In the following, we elaborate on the manufacturing system proposed in the Fall Semester 2020 and the project phases.

3.1. Manufacturing System: Lab-scale Model

The physical system is a lab-scale closed-loop production line composed by six stations with intermediate conveyors that operate also as buffers (Fig. 3.1). We denote with B_s the buffer capacity before station s. Blocking after service rule is applied. Pallets are represented by wooden circles tagged with a red plate, and a fixed number of pallets ($n = 20$) circulates into the system. It is assumed that station 1 is the load/unload station and a large number of unprocessed parts are waiting in front of this station. Also, we assume that a finished part can immediately leave the system. Each station can process only one part at the same time. Pallets are held by a station for an amount of time that represents a physical process (e.g., milling, turning). Failures may occur with a certain probability. If a failure occurs, pallets are kept in the station for an additional amount of time. Stations 3 and 4 are supervised by operators, which are modeled by blue discs. Each operator stays in the corresponding position, P3 or P4. If a failure occurs in either station 3 or 4, the station cannot be fixed unless an operator is at the respective position. In addition, the levels of buffers 3, 4, and 5 are constantly monitored and streamed in a time-series database. The parameters of the manufacturing system are available in Table 1. The manufacturing system model is built with LEGO components. Additional details about such lab-scale models are available in related works [12].

3.2. Remote Laboratory Setting

Given the social distancing requirements, in the Fall Semester 2020 the laboratory has been adapted to be accessible via remote connection. Fig. 2 shows the laboratory setting that has been developed for the project. The laboratory is composed by the following items: (1) the physical lab-scale model of the manufacturing system (section 3.1); (2) a dashboard, which allows for the real-time visualization of the current system state; (3) three cameras: in the remote class, cameras 1 and 2 are used to give a birdview and a closer view of the system, respectively. Camera 3 is only used for offline video recordings and high-quality videos upon request; (4) a line PC: the PC allows not only the control of

Table 1. Manufacturing system parameters for the project.

Station s	**Buffer Capacity** B_s	**L/U Time [s]**	**Processing Time [s]**	**Failure Probability**	**Failure Distribution**
1	4	2+2	1	0,15	UNIF(5,60)
2	3	3+3	1.5	0,1	UNIF(5,60)
3	6	2+2	1.1	0.35	EXPO(1)
4	6	2+2	1	0.34	Max(0.5, Norm(4,2))
5	2	3+3	Max(2, Norm(2, 10))	0	0
6	4	2+2	2.5	0	0

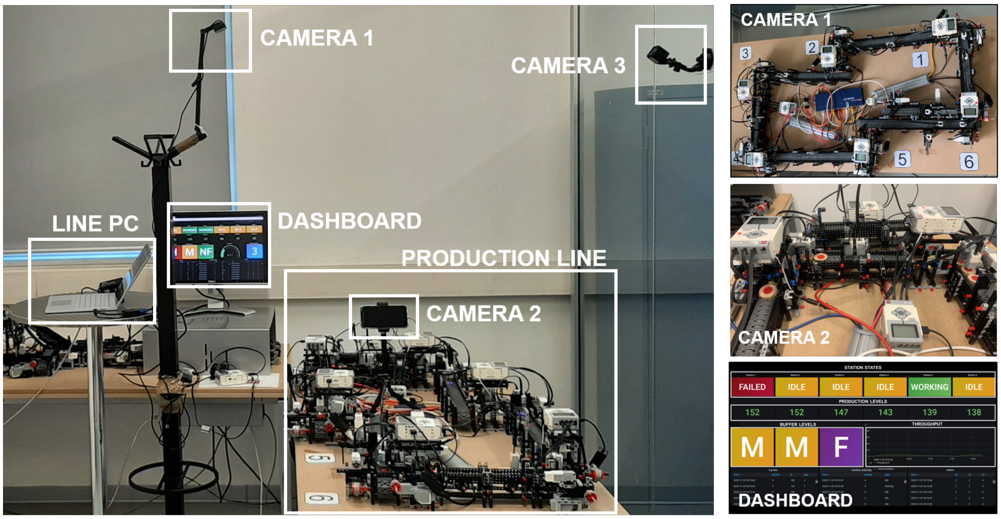

Fig. 2. Remote Laboratory Setting used in this work.

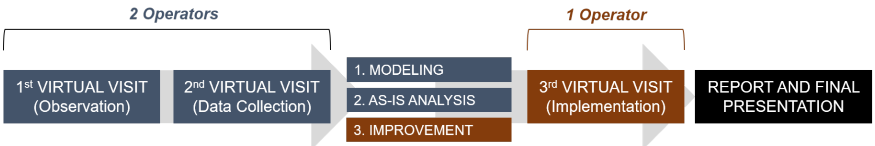

Fig. 3. Logical and temporal evolution of the project work.

the system by a supervisor program, but also the seamless sharing of the cameras and the live dashboard via remote connection. This setting allowed for a smooth organization of the project activities.

3.3. Work Structure and Project Phases

The project is proposed as a 3-month consultancy work. Specifically, it is required to assist an imaginary manufacturing company for the transition in terms of number of operators. Namely, stations 3 and 4 are set to be both supervised by a single operator. As a consequence, the remaining operator has to travel the 30 s path between the two stations, and the company requires a rule to guide the movement. The course project phases are described in Fig. 3. The first virtual visit is dedicated to the observation of the system with two operators. No data acquisition is done during this visit. In a second virtual visit, each team can collect data from the system to retrieve information needed for building a simulation model. The visit time is 2 hours, and around 45 minutes are dedicated to data collection. After the second visit is completed, each team will perform the following activities: (1) **model the behavior of the system**, build a conceptual model and a simulation model; (2) **analyze the performance of the system** according to a set of performance indicators. Namely, it is required: the production volume that the system can reach with probability 80%,

Table 2. Pros and cons of a remote laboratory setting, in comparison with an experience in the physical spaces.

	Laboratory in presence		**Laboratory via remote**	
Simulation Project Aspect	**Pros**	**Cons**	**Pros**	**Cons**
Observation	full visibility on system components; relative importance of different aspects is easily grasped	hard to replicate the same experience; possible long waiting times until some phoenomena occur	possibility to exploit videos to concentrate on critical parts; simultaneous video and data observation	hard to grasp the relative importance of different aspects
Data Collection	real hardware functioning experience	possible long waiting times until some phoenomena occur	possible to dedicate less time on tedious activities	missing the realistic devices issues
Modeling	relative importance of different aspects is easily grasped; abstraction is improved; immediate confrontation with the system (e.g., counterexamples); easily grasp expected behaviour and performance	possible long waiting times until some phoenomena occur; natural tendence to *model everything*; tendence to rely on qualitative analysis	easier to concentrate on quantitative aspects; easier to explore effects on non-contiguous parts on the system	hard to grasp the relative importance of different aspects; missing aspects are harder to find while debugging; harder to select the proper set of performance indicators
Input Analysis	understand the physical meaning of outlier; easier selection of proper datasets to be used	tendence to be less objective	easier to concentrate on quantitative aspects	likely to start with larger datasets; harder to select clean data
Model Validation	easier to spot misalignments in model behaviour	tendence to rely on qualitative analysis	easier to concentrate on quantitative aspects	harder to re-calibrate the model
To-Be Solution Implementation	realistic issues in implemetation with the hardware can be observed	tendence to concentrate on solving technical issues, rather than system-level behaviour	concentrate on the logic, rather than technical issues	less engaging activity; harder to spot further improvement chances

the bottleneck of the system, an assessment on how a different number of circulating pallets in the system might affect its performance; (3) **improve the system performance**: the requirement is a policy that could dictate the position of the operator based on a set of real-time inputs from the system. The teams are asked to exploit the information of the buffer levels 3, 4, and 5. The third and last visit is dedicated to the implementation of the proposed solution. Each group has been given an agenda for virtual visits, and additional assistance has been provided upon request. At project conclusion, teams are asked to present their work during a Q&A session.

4. Useful Insights and Final Remarks

In this paper, we have presented a remote laboratory experience for an M.Sc. course on discrete event simulation for manufacturing. Although challenged by the social-distancing measures, the laboratory enabled students to be challenged by realistic problems. Participants still faced realistic problems, and the experience has been effective without compromising the intended learning outcomes. For instance, input data are still subject to issues such as incorrect or missing values. Since the virtual visit is recorded, students can capture the misalignment between the data and the system behavior. Hence, students are also required to make observations and assumptions about the system behavior autonomously. As in a realistic setting, no information nor data from the system have been given to the participants if not upon specific request. Despite analyzed from remote locations, all the groups were able to gather the important information. This is proved by the fact that all the proposed policies were compliant with the system configuration (i.e., with no deadlocks). The remote laboratory setting proposed in this work can be replicated in learning factories with real industrial equipment. Indeed, the most important activities in the lab are the system observation and data collection. Provided the availability of data storage which can be queried from remote (e.g., a cloud-based database service), such experience can be replicated also in real-equipment learning factories.

The experience also has some limits. For instance, compared to a real setting, students found it hard to calibrate the importance of different elements. For example, some students focused with the same level of detail on load/unload, processing times, and failures. It is reasonable to assume that such misalignments are justifiable by the physical distance, which probably intensifies the fear of *missing something*. Table 2 summarizes the authors thoughts on the different experiences, via remote and in presence.

In the future, the described laboratory setting will be kept regardless on the teaching mode, since it allows for both recording and gathering information in real time. Future efforts will be devoted to create production systems where other decision making problems can be experienced, e.g., machine loading rules, routing of pallets, scheduling. Further, an interesting development could be to provide a direct remote connection to the physical setting (e.g., through an MQTT public broker), and allow students to directly change the system behavior online. Next developments of this work should also formalize the different pedagogical aspects of two different teaching modes (i.e., in lab and remote), highlighting the factors which can be used by trainers to choose the most effective way of teaching.

References

[1] Abele, E., Metternich, J., Tisch, M., 2019. Learning factories, in: Concepts, Guidelines, Best-Practice Examples. Springer.

[2] Auer, T., Felderer, M., 2020. Towards a learning environment for internet of things testing with lego mindstorms, in: 2020 IEEE International Conference on Software Testing, Verification and Validation Workshops (ICSTW), pp. 457–460. doi:10.1109/ICSTW50294.2020.00081.

[3] Behrens, A., Atorf, L., Schwann, R., Ballé, J., Herold, T., Telle, A., 2008. First steps into practical engineering for freshman students using matlab and lego mindstorms robots. Acta Polytechnica Journal of Advanced Engineering 48, 44–49.

[4] Gomez-de Gabriel, J.M., Mandow, A., Fernandez-Lozano, J., Garcia-Cerezo, A.J., 2011. Using lego nxt mobile robots with labview for undergraduate courses on mechatronics. IEEE Transactions on Education 54, 41–47.

[5] Greenwood, A.G., 2017. Striving for ubiquity of simulation in operations through educational enhancements, in: Proceedings of the 2017 Winter Simulation Conference, IEEE. pp. 4252–4263.

[6] Herias, F.A.C., Torres, F., Candelas, F.A., Puente, S.T., Pomares, J., Gil, P., Ortiz, F.G., 2006. Experiences with Virtual Environment and Remote Laboratory for Teaching and Learning Robotics at the University of Alicante. Int. J. of Engineering Education 22, 766–776.

[7] Ionescu, C.M., Fabregas, E., Cristescu, S.M., Dormido, S., De Keyser, R., 2013. A remote laboratory as an innovative educational tool for practicing control engineering concepts. IEEE Transactions on Education 56, 436–442. doi:10.1109/TE.2013.2249516.

[8] Jang, Y.J., Yosephine, V.S., 2016. Lego robotics based project for industrial engineering education. International Journal of Engineering Education 32, 1268–1278.

[9] Jara, C.A., Candelas, F.A., Puente, S.T., Torres, F., 2011. Hands-on experiences of undergraduate students in Automatics and Robotics using a virtual and remote laboratory. Computers and Education 57, 2451–2461. doi:10.1016/j.compedu.2011.07.003.

[10] Kim, S.H., Jeon, J.W., 2006. Educating c language using lego mindstorms robotic invention system 2.0, in: Proceedings of the 2006 IEEE International Conference on Robotics and Automation, Piscataway, New Jersey. pp. 715–720.

[11] Klug, M., Hausberger, P., 2009. Motivaton of students for futher education in simulation by an applied example in a related other course in engineering education: a case study, in: Prooceedings of the 2009 Winter Simulation Conference, IEEE. pp. 248–255.

[12] Lugaresi, G., Alba, V.V., Matta, A., 2021. Lab-scale models of manufacturing systems for testing real-time simulation and production control technologies. Journal of Manufacturing Systems 58, 93–108.

[13] Lugaresi, G., Lin, Z., Frigerio, N., Zhang, M., Matta, A., 2019. Active learning experience in simulation class using a lego®-based manufacturing system, in: 2019 Winter Simulation Conference (WSC), IEEE. pp. 3307–3318.

[14] Martin, N., 2018. Bringing students to practice: Performing a real-life simulation study in an introductory simulation course, in: Proceedings of the 2018 Winter Simulation Conference, IEEE. pp. 4014–4025.

[15] Papert, S., 1980. Mindstorms: Children, computers, and powerful ideas. Basic Books, Inc., New York.

[16] Sanchez, A., Bucio, J., 2012. Improving the teaching of discrete-event control systems using a lego manufacturing prototype. IEEE Transactions on Education 55, 326–331.

[17] Stefanovic, M., 2013. The objectives, architectures and effects of distance learning laboratories for industrial engineering education. Computers and Education 69, 250–262. doi:10.1016/j.compedu.2013.07.011.

[18] Syberfeldt, A., 2010. A lego factory for teaching simulation-based production optimization, in: Proceedings of the 2010 Industrial Simulation Conference, EUROSIS-ETI, Ostend, Belgium. pp. 89–94.

[19] Tobail, A., Crowe, J., Arisha, A., 2011. Learning by gaming: Supply chain application, in: Proceedings of the 2011 Winter Simulation Conference, IEEE. pp. 3940–3951.