Proceedings of the 2019 Winter Simulation Conference
N. Mustafee, K.-H.G. Bae, S. Lazarova-Molnar, M. Rabe, C. Szabo, P. Haas, and Y.-J. Son, eds.

ACTIVE LEARNING EXPERIENCE IN SIMULATION CLASS USING A LEGO®-BASED MANUFACTURING SYSTEM

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ABSTRACT

Simulation classes have the main advantage of deeply involving and stimulating students through intensive work in computer laboratories and projects. The counterpart is often the lack of the real system that is subject to simulation modeling. Creating, building and validating a simulation model of a system that cannot be observed represent a real obstacle for student learning. In this paper, we describe the experience from an educational project launched in a course of manufacturing systems for mechanical engineering students in which discrete event simulation plays a fundamental role in performance evaluation. The project has been designed to exploit student interaction with a LEGO®–based physical system. Students have the possibility to learn from the physical system and making experiments together with the simulation model built during project activities. The project details are also described with the hope that the project becomes a simulation case study and be replicated in other courses.

1 INTRODUCTION

Teaching in Higher Education is often challenging for the lack of practical implementation and difficulties in student involvement. Industrial and systems engineering discipline often involves the comprehension of complex manufacturing systems and the resolution of problems based on a proper model of the real system. The limited access to real systems is particularly common and may represent an issue for student learning. Indeed, students are used to understand complex descriptions of industrial cases on course material (e.g., lectures notes, technical notes, books and papers), but they almost never face with the problem practically. At the same time, several recent works sponsor the introduction of interactive activities (e.g., games, laboratory experiences) for teaching purposes. For instance, Padilla et al. (2016) consider games as an effective tool to learn complex topics, such as creating simulations, because *"students use the game as an experimental setting just like one would a simulation"*. Further, quoting Resnick and Robinson (2017): *"Creativity doesn't come from laughter and fun: it comes from experimenting, taking risks, and testing the boundaries."* Very recently in fact, the role of experience has gained particular attention in Higher Education (Buckley, Nerantzi, and Spiers 2017). In a world where creativity has gained much importance, project activities could help to provide students with a better competence of practical application and problem solving abilities. In addition, the more the projects are aligned with their passions, the better the result achieved.

978-1-7281-3283-9/19/$31.00 ©2019 IEEE

As in the literature, the exploitation of LEGO® in engineering projects successfully improves students' motivation, involvement and enriches their competences (Behrens et al. 2010). 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.

In this work, we focus on the course of Integrated Manufacturing Systems offered by Politecnico di Milano. The course is focused on the analysis of complex manufacturing systems and it consists of lectures and classwork modules on presence. Course content includes description of manufacturing systems and basic theory of discrete event simulation (DES). The course requires the execution of a project, in which students have the goal of improving the performance of a given manufacturing system. As far as simulation content, students are required to build a model of the manufacturing system to improve, validate the model with statistical techniques and execute experiments in order to choose a proper solution. From an educational perspective, the simulation project has the main goal of challenging students to apply the theoretical contents learned during classes to an industrial and system engineering problem, in which information is not fully available and problem statement is not perfectly defined. This expected learning outcome is difficult to reach, because the system to improve is usually described with a textual representation supported by the use of diagrams and numerical tables. Hence, students miss important milestones in their learning such as doing abstraction from real system, dealing with real data and their related practical issues, limited measurement capabilities and experimentation with real system due to cost and time, etc.

In this paper, we describe the experience from an educational project that uses a LEGO®-based physical system (LEGO® Manufacturing System or LMS in this paper) as the real system students must improve. The LMS can be operated by students who can observe and learn from its behaviour, design experiments and collect data to support their decisions. In such a way, we tried to fill the lack of a real manufacturing system by designing and constructing a miniaturized system to be studied and improved by students in their project activities.

The content is organized as follows. A state of the art on similar educational projects is reported in the next section. Section 3 describes the learning goals and contents of the course. Section 4 describes the simulation project in detail. Project development with its phases are summarized in section 5. A final discussion closes this work in section 6.

2 STATE OF THE ART

Recent literature about simulation education highlighted the possibility of teaching simulation through interactive means (Eijkman 2012; Greenwood 2017). According to the so-called *constructionism* idea, learning through play can positively contribute to the construction of new awareness based on the students pre-existing knowledge (Papert 1980).

2.1 Interactive Teaching of Simulation

Klug and Hausberger (2009) set up an interactive lab in which each student had a production planning problem to solve. Mustafee and Katsaliaki (2010) presented a business game to simulate the supply chain of blood units from donors to patients. The goal was to make students understanding the complex principles behind a supply chain and to give them tools to make decisions in complex situations. Indeed, the teams could easily test the implication of their decisions and the outcomes of their supply policies. Tobail, Crowe, and Arisha (2011) developed an interactive business game in which participants mimic real life decision making processes by playing a managerial role in the automotive supply chain. The game enabled students to learn the impact of strategic decisions on other portions and players of the supply chain. A similar game was developed by Lee (2011), with the goal to make practitioners exercise the *"science and art of making tradeoffs between schedule, scope, cost, and quality while solving project management problems"*. Padilla et al. (2016) used two games that focused on learning the effects of changing input parameters of the model by immediately seeing the impacts on the outcomes of the simulation. Hübl and Fischer (2017) designed a business game embedded in a web interface in which the gamers could act as purchasing, production, sales and finance managers, with the target to identify sales and production volumes for the next planning periods. Martin (2018) introduced a real-life simulation project regarding the unloading process of a cross-dock. Students had to test the effect of a possible reorganization of the docks layout and balance the workers workload. The goals of the experience were to perform a simulation project within a realistic business context and to learn how to use raw data files from an industrial information system.

2.2 LEGO®-Based Education

The design philosophy of the LEGO® instructional material is based on the concepts that students should not only construct the knowledge by themselves and that effective learning is established through play (Hussain, Lindh, and Shukur 2006). Recently, LEGO® MINDSTORMS® has being increasingly used as an educational tool for teaching in several engineering subjects such has robotics, computer programming, and control. Several applications of LEGO® -based systems for teaching purposes can be found in the literature. Kim and Jeon (2006) taught embedded systems by letting students design their own robots with LEGO® and code in C language. Behrens et al. (2008) encouraged students to use known mathematical basics to program real-world applications performed by LEGO® robots. The target is to motivate students to learn MATLAB® code in building their robots. Kim (2011) and, similarly, Gomez-de Gabriel et al. (2011), used LEGO® MINDSTORMS® for teaching classical and modern control theories in undergraduate courses. Grandi, Falconi, and Melchiorri (2014) used LEGO® to teach how to develop structured and modular-code-based software in Java by throwing a robotic challenge. Papadimitriou and Papadopoulos (2007) investigated the possibility of teaching mechatronics and robotic controls through reverse engineering of key LEGO® components. Klassner and Anderson (2003) praised the advantages of letting students apply computing principles in constructing robots and designing problem-solving code, and exploits lab exercises using the LEGO® MINDSTORMS® robots to illustrate and explore computer science concepts. Several other applications can be found, for example in PID control design (Wadoo and Jain 2012), model checking (Iversen et al. 2000), and data acquisition (Cruz-Martín et al. 2012).

In general, the adoption of LEGO® in Industrial and Mechanical Engineering courses that focus on manufacturing systems is less common, however some contributions can be found. Sanchez and Bucio (2012) based a course on a manufacturing system realized with LEGO® to teach the principles for controlling discrete event systems to postgraduate students and to allow them to gather hands-on experience with an automated system. Project goal was the design and realization of a hierarchical supervisor for the physical model. The physical system was a closed-loop line composed by two workstations, two feeding systems, two dispatchers and a conveyor belt system. Production planning was done in compliance with the ISA-S88 standard for industrial batch control. Students were required to design a modular-hierarchical coordination architecture capable of supervising the execution of the production schedule of the LEGO® system, and to design controllers to supervise the resource allocation tasks during production. The development of a model for performance evaluation was not required.

Syberfeldt (2010) described a practical exercise to teach simulation-optimization to students using a physical LEGO® factory simulating the refinement of raw materials. The system was composed by three stations in line with dedicated controllers. The goal was to provide students an additional tool for learning and understanding simulation-optimization. The main purpose of the course was to make students understanding the benefits of performance evaluation. Indeed during the Project Work, they were asked to find the best system configuration with the aim of maximizing the profit by changing either the product mix or the buffer capacity allocation along the line. Artificial Neural Network (ANN) was used for performance evaluation as surrogate model of the physical system.

Jang and Yosephine (2017) developed a LEGO® MINDSTORMS® flow line consisting in one feeder and two machines with an intermediate buffer. The machines were programmed to simulate failures of different duration. Hence, the system was affected by blocking of the first machine and starvation of

Table 1: Brief comparison of literature contributions where different types of LMSs are used for teaching in IE.

	Sanchez and Bucio (2012)	**Syberfeldt (2010)**	**Jang and Yosephine (2017)**	**This Work**
Analyzed System	Closed-loop Line	Flow Line	Flow Line	Closed-loop Line
Processing Times	Deterministic	Stochastic	Stochastic	Stochastic
Failures	NO	NO	YES	YES
Data collection	NO	YES	YES	YES
Method used	*Not required*	ANN	Markov Chains	DES
Reconfiguration	NO	YES	YES	YES

the second. The course had three main goals: understanding the processing times and failure rates by collecting data, modeling the system with the objective to optimize the throughput, the cycle time, and WIP, and designing the system in terms of buffer allocation. The LEGO® -based project proved to be effective in motivating students. Thanks to the developed system, students have been able to learn and understand the basic concepts of stochastic modeling, production planning, and scheduling. The authors also showed that the students' understanding of the issues of dynamic behavior of manufacturing systems was improved more effectively than with traditional lecture-based learning. Markov-chains are used as system performance evaluation method.

Our focus is similar to the last three aforementioned papers. Indeed, we target to teach students how to model a real manufacturing system and to use DES as performance evaluation method. Table 1 summarizes the similarities and differences among the aforementioned papers and our contribution. In particular, differently from all the mentioned contributions, our work exploits LEGO® to teach the modeling phase of Discrete Event Simulation and the use of simulation for industrial systems performance evaluation.

3 COURSE: LEARNING GOALS AND CONTENTS

The course allows students to analyze the performance of complex manufacturing systems using simulation models. The course consists of lectures and classwork modules on presence. Classwork module is delivered in computer laboratory to allow students to use state-of-the-art software for simulation of manufacturing systems. In the LMS laboratory students are required to make experiments oriented to accomplish problem solving activities in the Project Work. Students are required to work in teams to accomplish the Project Work.

Lecture sessions allow students to have the **basic knowledge and understanding** of:

- The main elements of integrated manufacturing systems and their relationships;
- The basic principles of discrete event simulation;
- The basic analysis methodologies in the context of simulation.

Classwork modules in computer laboratory sessions allow students to **apply knowledge and understanding**. In particular through the following activities:

- Modeling several integrated manufacturing systems using DES software, e.g., manufacturing lines, assembly lines, flexible manufacturing systems;
- Building DES models with data input analysis techniques;
- Understanding system behavior with data output analysis techniques;
- Ranking and comparing alternative manufacturing systems using simulation outputs.

In the Project Work activities, students develop the ability to **handle complexity** of manufacturing systems, to **integrate knowledge** acquired in other courses on productions systems and industrial plants, to **formulate judgement** with incomplete and uncertain data, to study in a manner that may be largely

self-directed and/or **autonomous**. Students also develop the ability to **communicate** their choices and conclusions to specialist audiences. Project Work activities allow students to:

- Autonomously analyze and design an integrated manufacturing system in a context of partial information. Students are required to retrieve the rest of information from observation of the LMS.
- Obtain data and acquiring knowledge from experiments in a physical laboratory. Data collection in reality is often related to dirty, uncompleted, and inconsistent data. The use of data physically generated from the LMS helps to touch the real problems simulationist encounters. Further, validation of simulation model is more effective with the LMS used by students to generate real data from physical experiments.
- Choose modeling detail level from physical system to conceptual model. The step from system observation to development of the conceptual model requires abstraction capabilities. This is usually difficult to reach in educational project due to the lack of real system availability. In practice, this lack is often compensated by a text describing the real system using words and layouts. However, dealing with a real system is much more effective for students who have to understand the system dynamics, which elements to include in the conceptual model, which assumptions to introduce, etc.

In addition, students choose computer coding strategies for building simulation models in a software platform, and summarize and present the results with technical documents and oral presentations. These two latter abilities are not affected by the use or not of the LMS.

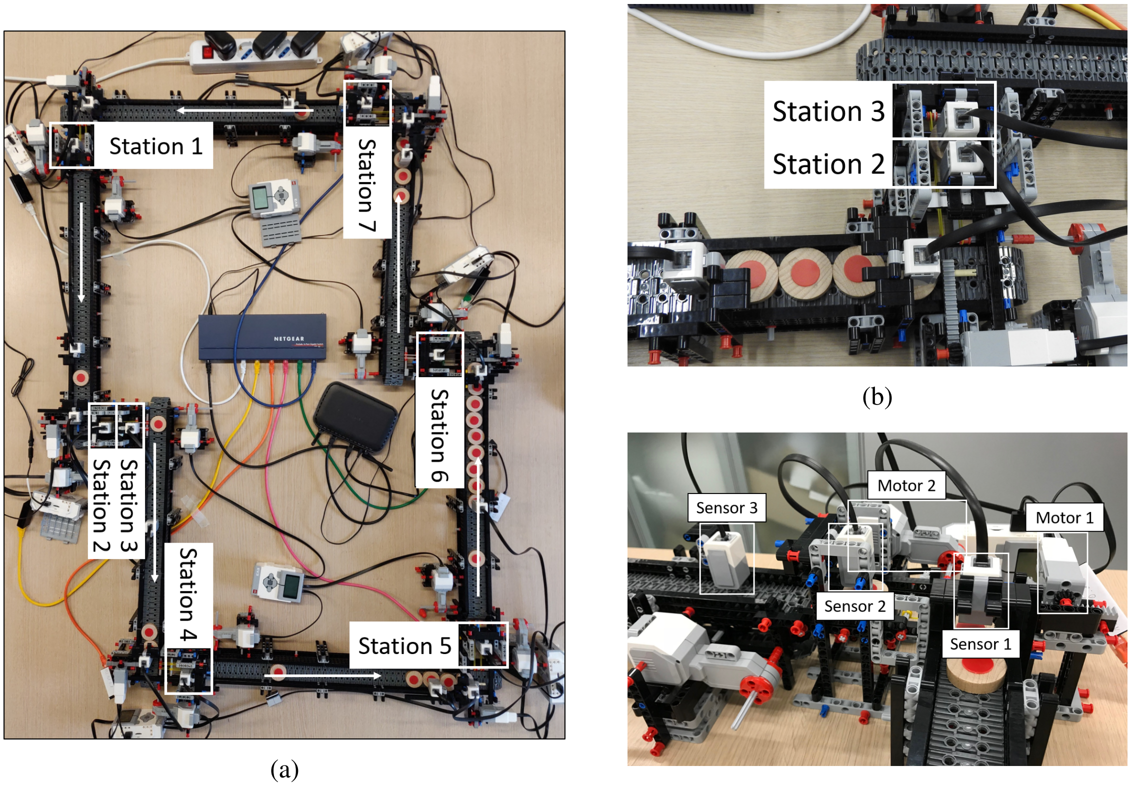
4 PROJECT WORK DESCRIPTION AND PHYSICAL MODEL

The Project Work consists of modeling, analyzing, and improving the performance of a production system. The project has three main outcomes. The first is a valid DES model of the current system behavior. The second outcome is the evaluation, with the use of simulation, of system performance and the identification of system bottleneck. Also, it is required to analyze how the number of circulating pallets might affect the performance. The third outcome is a new system configuration in terms of buffer allocation along the system such that system productivity increases compared to AS-IS situation.

4.1 The LEGO®-Based Physical Model

The physical system is a closed-loop production line composed by $S = 7$ stations with intermediate conveyors that operate also as buffers (Figure 1a). Denote with x_s the buffer capacity after station s such that $\mathbf{x} = \{x_s\}|s = 1,\ldots,S$ is the vector representing system layout. Blocking after service rule is applied. Each part is loaded onto a pallet (i.e., wooden circles tagged with red mark in Figure 1a) and a fixed number of pallets ($n = 25$) circulates into the system. It is assumed that station $s = 1$ is the load/unload station and a large number of unprocessed parts are waiting in front of the first station. Also, we assume that a finished part can immediately leave the system. One station can process only one part at the same time. Station 2 and Station 3 (Figure 1b) work in sequence with no intermediate buffer. Only one part is allowed between Station 2 and Station 3 therefore these could be modeled as one single station in the simulation model.

Conveyors are controlled through proprietary LEGO®-EV3 software and they move at a constant speed. The stations are controlled by LEGO®-EV3 units which are programmed using customized Python scripts (EV3DEV OS). Each station has its own script that is run locally such that different distributions of the processing times can be assigned to different stations. Machine condition of working (i.e., a pallet is loaded onto the machine), starvation (i.e., upstream buffer is empty), and blocking (i.e., downstream buffer is full) are supervised through sensors. Additional details about how to build the LMS have been described in Lugaresi, Travaglini, and Matta ().



(a)

(b)

(c)

Figure 1: Overview of the LMS used for the didactic project.

4.2 System Design Parameters

Stations $s = 1,4,5$ represent manual operations such that the processing times are modeled as stochastic. Stations $s = 2,3,6,7$ represent automatic stations such that processing times are modeled as deterministic. All stations are perfectly reliable except for stations $s = 6,7$ which may fail. For these stations, the production is affected by a failure in 35% of cases. High failure probabilities are set to increase the amount of failure data that students can observe during experiments. Two sets of processing time distributions, which lead to different bottlenecks, are assigned to different groups of students randomly. Table 2 reports one set of the processing times of the stations, the distributions of the repairing times for Station 6 and Station 7. Buffer capacities x_s are common for all systems. In addition, each group has its own seeds and these seeds are the same in all the visits.

In order to load/unload pallets between conveyors and stations, a LEGO® loading system has been implemented such as the loading/unloading times are deterministic although affected by natural noise. These times are not negligible compared to the processing times and each varies between 1.5 and 2.5 seconds. Moreover, all the conveyors have a speed of 3 pallets per second. The system is unbalanced and it has been designed to allow a potential increment of system performance by adjusting the buffer capacities along the line.

A time of one hour and half is dedicated to students' visit and 45 minutes among that are dedicated to running the LMS. Design parameters of the system are not shown to students. They need to observe the system and collect data during the visit. In order to ensure that enough data can be acquired to fit distribution during the visit, short processing times are assigned to each stations. Therefore, at least 200 records can be obtained to estimate the processing time for each station and 70 records for each repairing times. System throughput, estimated by DES, is about 5.6 parts per minute.

Table 2: System parameters: Triangular (TR), Weibull (WB), and Uniform (UN) distributions are used.

Station s	1	2	3	4	5	6	7
Processing Times [s]	TR(2,4,6)	2	2	WB(5,2)	WB(6,1.5)	2	2
Repairing Times [s]	-	-	-	-	-	TR(8,9.5,11)	UN(10,13)
Failure Probability	0	0	0	0	0	0.35	0.35
Buffer Capacity x_s	5	0	9	3	9	3	13

Although the system parameters are designed to allow students to acquire enough data, the system variability is high. Given the limited amount of acquired data, the distributions fitted by students may be biased due to the sampling noise. Also, students interactions with the system might affect the number of records they can get. For instance, some teams might move pallets while the model is running or might interrupt the service at a certain station to study starvation and blocking conditions.

5 PROJECT DEVELOPMENT

A description of project phases and information available at student-side is provided.

5.1 Project Phases

The project is divided into four phases, scheduled as in Table 3.

During *Phase 1*, each team observed the system in the laboratory, studied its layout and the behavior, developed and validated a DES model. Teams visited the system twice in this phase. In the first visit, all Team Leaders gathered and observed the system while it was working as preliminary analysis . The second visit was planned for each team individually. During the second visit, each team could acquire input data for building the simulation model while the system was working. Extra sensors were provided to the students, they could place them anywhere in the system to collect data. Besides, they were also allowed to perform manually the acquisition, for instance, by chronometers or video shooting. Students had 45 minutes for data acquisition activity.

Phase 2 includes using the simulator developed in *Phase 1* for the AS-IS system analysis, specifically, the bottleneck detection and pallet number analysis. Students were expected to properly apply the knowledge and techniques taught in the lectures and extract relevant insights from the DES output in their analysis. There are various works for bottleneck detection in literature, and the students were not restricted to any specific techniques.

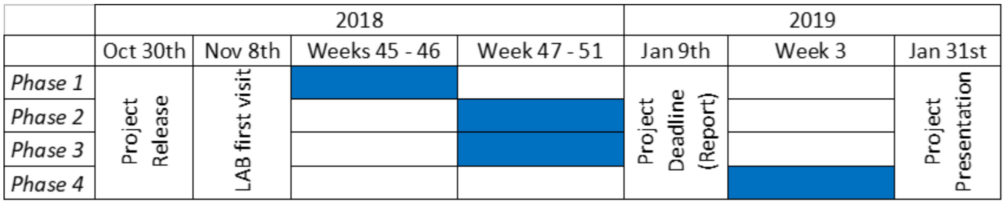
In relation to the last project outcome, each team faces the Buffer Allocation Problem (BAP) in *Phase 3*. Buffer capacity $x_s | s = 1, \ldots, S$ needs to be allocated along the line in order to maximize system throughput $\psi(\mathbf{x})$, respecting maximal total buffer space allowed $B_{\max}$ and the domain of each single buffer capacity $[L_s, U_s] \cap \mathbb{Z}$. We obtain the following BAP:

$$\max \left\{ \psi(\mathbf{x}) | \sum_{s=1}^{S} x_s \leq B_{\max} \ ; \ L_s \leq x_s \leq U_s \right\} \tag{1}$$

In the project, $B_{\max}$ is equal to 42, and L_s and U_s are equal to 2 and 15 for all $s = 1, \ldots, S$, respectively, except for Station 2 and Station 3 that cannot be separated (i.e., $L_2 = U_2 = 0$). Students were required to identify a set $\mathbb{X}$ of candidate solutions $\mathbf{x} \in \mathbb{X}$ and, then, choose the best among the candidates. Simulation was used to evaluate $\psi(\mathbf{x})$. Including other performance indicators of interest (e.g., system time) for decision making was encouraged. Same as the bottleneck identification problem, students are free to choose whatever approaches they found in the literature since the optimization is not the content of this course.

Phase 4 includes a laboratory visit where each team implemented the solution chosen in *Phase 3* in the LMS and acquired new data for assessment of the action within 45 minutes. The performance obtained from this visit should be compared to those obtained from the DES model and in the second visit.

Table 3: Project phases and scheduling of LAB-visits in the semester (AY 18/19).



	2018				2019		
	Oct 30th	Nov 8th	Weeks 45 - 46	Week 47 - 51	Jan 9th	Week 3	Jan 31st
Phase 1	Project Release	LAB first visit	■		Project Deadline (Report)		Project Presentation
Phase 2				■			
Phase 3				■			
Phase 4						■	

Table 4: Nominal information: average processing times [s] of manual operations and deterministic processing times [s] of automatic operations.

Station s	1	2	3	4	5	6	7
Nominal processing time [s]	4	2	2	4.4	5.4	2	2

5.2 Input data

Students were provided with some nominal information about the system and with the data collected during their own experiments. In particular, LOG files are extracted from the LMS.

The descriptive document that the students received was a one-page document including the nominal processing time of each station. The nominal times are shown in Table 4. It should be mentioned that the students would not know whether a station was automatic or manual before they properly conduct the input analysis on the data. The students should observe by themselves the layout, the pallet number, the actual buffer capacity, the blocking after services rule, the unreliability of automatic stations, etc. Based on the document and observation, assumptions should be made and the modeling is enabled.

An explanation of the LOG-file that can be extracted from EV3 was also provided. In particular, the LOG-files for input analysis at each station are two **.txt* documents recording respectively the entering times and the finishing times of pallets. Therefore, 14 **.txt* files were provided. Inside a file, there are three columns: date, time, progressive ID.

Also, a data set acquired during 3-hour production was provided for simulation model validation. Data available were the inter–departure times of Station 1, i.e., system throughput, and system lead time acquired from the LMS. The LOG-file for model validation is also a **.txt* file including the inter-departure times and system lead times of a series of sequential pallets as recorded at Station 1.

6 EVALUATION AND DISCUSSION

In the followings, a complete discussion of results is reported. Evaluation criteria and difference compared to previous years of course are highlighted. A section is dedicated to the interaction between students and physical system. Some remarks follow:

- Students encountered difficulties in choosing the level of detail of DES model. At the beginning they have tried to model every details of the physical system including white noise of processes and rare events (e.g., pallets getting stuck, conveyor variable speed). The model of conveyors was particularly critical. Conveyors have two functions: part handling and part holding. Students analyzed different conceptual models for conveyors and selected the most appropriate according to different criteria: some prefer the reduction of computational time and chose to model the holding function only, others modeled also the transportation time using the buffer length and the conveyor speed by representing the transportation time as a linear function of buffer occupancy. All students faced with the trade-off among model detail level and simulation time.
- As mentioned previously, because of sensor unreliability, students faced with data-post-processing issues and they needed to understand between acquisition errors and natural variability. Further, each

Team dealt with the trade-off between uncertainty of measures taken manually (e.g. chronometers and video recording) and the magnitude of modeling approximations. Also, it might happen that the physical system suffers of real failures because of natural unreliability (e.g., motor overheating). The students were able to handle such variability with our support.

- The interaction with a physical system and its observation increased student involvement. Further, students were satisfied to implement their own solution and to verify that the performance have improved.

6.1 Evaluation

The deliverable for evaluation included a technical report, a 10-minute presentation, both in English, and the developed DES model. The technical report should contain all methodologies and techniques used to obtain results within 20 pages. Report structure is provided to guide the students. The Project Work has been evaluated according to the following criteria:

- A1 - System modeling and validation (38/100) including the conceptual model of the system, the implementation in ARENA and input analysis;
- A2 - Performance analysis using DES (15/100) according to project requests, i.e., bottleneck identification and pallet analysis;
- A3 - Selection of alternatives and validation of the final choice (26/100) after a proper problem definition;
- A4 - Communication of results (21/100) in terms of clearness, language, and logic of project report and student presentation.

The use of proper methods has been considered in the evaluation as well as student understanding of the numerical results.

The grades of each criterion can also be seen in Table 5, and both mean and confidence interval are reported. Criterion A1, related with the physical experience, represents the majority of the grade and students relative score is the highest among all criteria. This result shows the effectiveness of a practical experience. According to a detailed analysis of criterion A3, the students had poorer performance on the *validation*. It seems that the validation with a physical system was more difficult, since the data set from the LMS is quite limited. This situation requires students to carefully design approaches for data acquisition and statistic test, which many students fail to do. According to our experience on several industrial projects, limitation in the amount of available data is quite common. Considering that our students major is in mechanical engineering, the project is a good imitation of their future work. A specific teaching module on validation will be addressed in next years.

Table 5: Project evaluation (95% CI, average of 9 teams).

Criterion	A1	A2	A3	A4	total
Weight	38	15	26	21	100
Mean grade	32.3±2.3	11.7±2.1	19.0±1.6	18.1±1.5	84.0±8.2

6.2 Student Interaction during LAB Visits

The Project Work included three visits: two during *Phase 1*, and one in *Phase 4*. The first visit was limited to Team Leaders with the goal of providing an overall view of the LMS such that they could prepare their Team for the second visit. In the first visit, all Team Leaders observed the LMS simultaneously such that students exploited a collaborative approach. Different information have been observed by different students and, by asking questions, sharing information and discussion, all teams had a good understanding on the system.

The second visit was individual per Team, such that Team members worked together to set the experiments. Although all teams were organized for the visit, we have experienced a high variability of approaches in this phase. For example, one prepared sticks to label pallets so they are easier to be tracked, some brought a camera to record specific stations that they think should be noted, some used chronometers to record timing. Also, each Team member was assigned tasks before the second visit.

During experiments in *Phase 1*, the students were free to decide the initial state of the system (i.e., the positions of pallets along the line) and to interact with the running system, e.g., by moving pallets in the system. As a consequence, students interacted with the system in order to focus the attention on peculiar behaviour of stations. For example, students manually accumulated several pallets to check the blocking conditions of machine. Also, students used additional sensors to record additional information, e.g., the conveyor speed, the blocking time.

In *Phase 2* experiments, all teams randomly chose the initial condition, whilst most of teams designs the initial condition in *Phase 4* experiments. Some teams used the average buffer occupancy obtained by steady-state simulation. Others used the same initial condition as in *Phase 1* for comparison purpose.

7 CONCLUSIONS

In this paper, we have presented a LEGO® -based learning system developed in the Mechanical Engineering Department of Politecnico di Milano for the course of Integrated Manufacturing Systems. The system enables practical experience while teaching to engineering students. The feedback obtained was positive and the students found the subject very interesting. Moreover, students faced with real problems in model building and input analysis more effectively than with traditional lecture-based learning. LEGO® flexibility will be exploited creating different systems in future projects. Future effort will be devoted to create production systems where other decision making problems can be experienced, e.g., machine loading rules, routing of pallets, scheduling. To achieve this goal, the LMS will be improved both from the hardware and the software point of view, for example by providing a higher integration between the stations and a centralized logic.

ACKNOWLEDGMENTS

The research has been partially funded by *Sme.UP Group* (https://www.smeup.com/). The Authors also thank the Italian LEGO® Users Group (ItLUG) and Davide Travaglini for their contribution in physical model building.

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