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A New Learning Factory Experience Exploiting LEGO For Teaching Manufacturing Systems Integration

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Abstract

Involving and stimulating students through intensive work in computer laboratories and simulation projects might be a challenging task, often due to the lack of the real manufacturing system that must be modeled and improved. Indeed, studying a manufacturing system that cannot be observed represents a real obstacle for student effective learning. In this paper, we describe the "LEGO FACTORY" initiative, an extra-curricular experience within the Master Degree Study Program in Mechanical Engineering of Politecnico di Milano. The initiative is open to students from any study course of the university. The goal is to exploit learning-by-playing principles to offer scholars the possibility to understand the most common issues in the design and management of manufacturing systems, with a focus on system integration. A miniaturized production system made with LEGO® MINDSTORMS® is provided to students who are asked to accomplish a project aiming at the improvement of the system performances. The participants work in teams and must introduce design modifications and develop technical solutions to address the requirements. The experience is described with the hope that the approach can be replicated in other environments.

Keywords: LEGO; learning factory; system integration; learning-by-play

1. Introduction

Students approaching industrial engineering topics often deal with the design and management of production systems. Typically, students focus on the issues of understanding the problem and modelling the considered system such that alternative solutions can be properly evaluated and selected. Beyond the complexity of techniques and methods that is usually covered with traditional lectures and classworks, students rarely deal with real systems to be observed and modified. The reason is simple, i.e. the unavailability of such real production systems in universities. On the other side, real industrial projects are complex and connected to company requirements making the direct involvement of students unfeasible.

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Recently, the role of practical experience has gained particular attention in Higher Education [2]. Project activities could help to provide students with competences on practical applications and problem solving abilities. Several recent works sponsor the introduction of team-based interactive activities for teaching purposes (e.g., games, laboratory experiences). With such experiences, students can develop team-work and organization abilities, apply mathematical knowledge, and grow programming skills.

Herewith, we describe the a teaching initiative organized by the Master Degree Study Program in Mechanical Engineering of Politecnico di Milano. It is offered as extra-curricular course called "LEGO FACTORY". Miniaturized production systems made by LEGO® MINDSTORMS® are provided to students who are asked to accomplish a project aiming at the improvement of the system performances. Students from any study course of the university work in cross-sectorial teams on topics they can choose, and present the results achieved at the end of the experience. Hence, students merge different competences and previously acquired knowledge for the resolution of practical engineering problems. The key activities often involve finding a feasible working solution or the proper method to achieve a goal.

The paper is organized as follows. Section 2 outlines the contributions in the literature about teaching engineering classes with LEGO. Section 3 describes the basic structure of the physical models used in the course. Section 4 explains the course organization and the learning goals. Section 5 lists the students projects. Section 6 summarizes the lessons learned in this new experience and the concluding remarks.

2. Engineering classes based on LEGO models

The idea of exploiting LEGO as instructional material is based on the belief that effective learning can be established through play [5]. Recently, LEGO MINDSTORMS has been increasingly used as an educational tool for 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, for example in teaching embedded systems [8], MATLAB coding [1], control theory [9, 4, 13], as well as computer science concepts [10], PID control design [17], model checking [6], and data acquisition [3].

In general, the adoption of LEGO in engineering courses that focus on manufacturing systems is less common. Lugaresi et al. [11] developed a discrete event simulation class in which students can learn the dynamics of a 7-station production line model and make experiments with the goal to build the simulation model of the system as project work of the course. Simulation-based decision making to improve the system was also performed. Jang and Josephine [7] developed a flow line consisting in one feeder and two machines with an intermediate buffer. The machines were programmed to simulate failures with different duration. Hence, the system was affected by blocking of the first machine and starvation of the second. The course had three main goals: (1) understanding the processing times and failure rates by collecting data, (2) modeling the system with the objective to optimize the throughput, the cycle time, and work-in-progress, and (3) designing the system in terms of buffer allocation. 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 dynamic behavior of manufacturing systems has improved more effectively than with traditional lecture-based learning. Sanchez and Bucio [15] used a manufacturing system 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. The physical system was a closed-loop line composed by two workstations, two feeding systems, two dispatchers and a conveyor belt system. The project goal was the design and realization of a hierarchical supervisor for the physical model and capable of executing the production schedule, as well as to design controllers to supervise the resource allocation tasks during production. Syberfeldt [16] designed a practical exercise to teach simulation-optimization to students using a physical factory simulating the refinement of raw materials. The manufacturing system was composed by three consecutive stations with dedicated controllers. The goal was to provide students an additional tool for learning and understanding simulation-optimization and performance evaluation. During the project work, students were asked to find the best system configuration in terms of profitability by changing either the product mix or the buffer capacity allocation along the line. In [14], the authors developed a Computer Integrated Manufacturing environment for the design and assembly of products built with LEGO blocks. The aim was to teach students process planning and trajectory planning software to determine the production sequence.

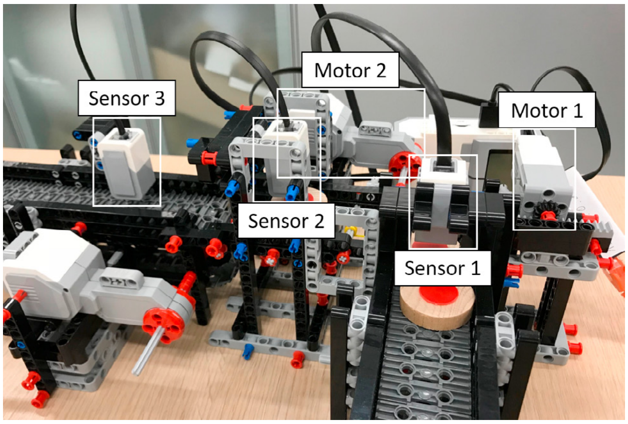


Fig. 1. basic elements of a station in a LEGO Manufacturing System. Sensor 1 detects if a part is queuing at the entrance of the station. Motor 1 lets the parts enter the station one at the time. Motor 2 drives the parts in the station and Sensor 2 detects if a part has entered. Sensor 3 detects if the downstream conveyor has enough slots for the parts to be released.

To the best of our knowledge, literature about teaching manufacturing systems integration exploiting LEGO is scarce. In this work, we developed a laboratory experience to let students understand the main dynamics and issues that arise when designing and deploying elements of manufacturing systems such as assembly lines, robotic cells, or pallet production lines.

3. LEGO Manufacturing Systems

The laboratory experience is based on the construction of physical models called LEGO Manufacturing Systems (LMS), namely miniaturised production lines made with LEGO. All the projects aim at building physical models starting from a baseline that allows for compatibility among different models, as well as easy reconfiguration. The basic configuration of an LMS is composed by sequential stations with intermediate conveyors that also operate as buffers. Fig. 1 shows the basic design of a station. All the stations are controlled by EV3 intelligent bricks. Wooden circles tagged with colored plates represent pallets that load the work-pieces. These must be processed by the stations. The processing times are represented by a time interval that each workpiece must wait in a station before being released on the downstream conveyor. Buffer capacities are defined by the position of a sensor on the downstream conveyor of each station, hence the total buffer capacity is limited. The stations are connected to a local network and a PC through Secure Shell Connection (SSH) protocol from which different scripts can be sent to be executed. All the software is written in *python* and exploits the EV3DEV OS and libraries (www.ev3dev.org) to interface with the EV3s.

The LMS has some limits. For instance, only the pallet presence can be detected with EV3 sensors, while single-piece identification is not achievable. Further, the communication between different devices requires the network design. In order to cope with these lacks, other devices such as Arduino and Raspberry-Pi may be integrated in the system through an IoT software architecture that has been developed for the scope. Additional details about how to build the LMS have been described in [12].

4. Description of the course

"LEGO FACTORY" is an extra-curricular experience offered to students both from Bachelor and Master of Science study courses. The participants have been selected to favour diversity among teams. Two editions of the course have been completed, with a total of 56 participants.

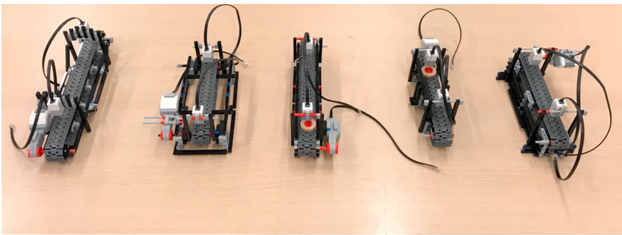


Fig. 2. prototypes of two-station models realized during the introductory class of the first edition of the course.

4.1. Course organization

The course is organized in 8 appointments of 4 hours each. Three main activities are included: an introductory tutorial class to familiarize with the material (both hardware and software), group-work activities with specific requirements, and presentation of results (mid-term and final presentations).

During the introductory tutorial class, the participants are provided with knowledge of: (1) the main elements of integrated manufacturing systems and their relationships, (2) the basic principles of *python* programming language, (3) the basic principles for programming LEGO MINDSTORMS EV3s. In the first class students are also asked to develop a simple prototype of a two-station system. Each station is represented by a sensor and a conveyor that carries parts from the first station to the second. Fig. 2 shows the prototypes developed in the first edition of the course. In the group-work activities, students are asked to gather in teams, to choose a project among a set of proposals, and to work autonomously toward the accomplishment of project goals. In the mid-term and final presentation, the teams have to discuss the applicability of their solutions in the integrated system.

4.2. Learning goals

The “LEGO FACTORY” initiative aims at exploiting the learning-by-playing principles to give students the possibility of understanding the most common issues in the design and management of production systems. The learning goals are not related with the choice of LEGO as hardware.

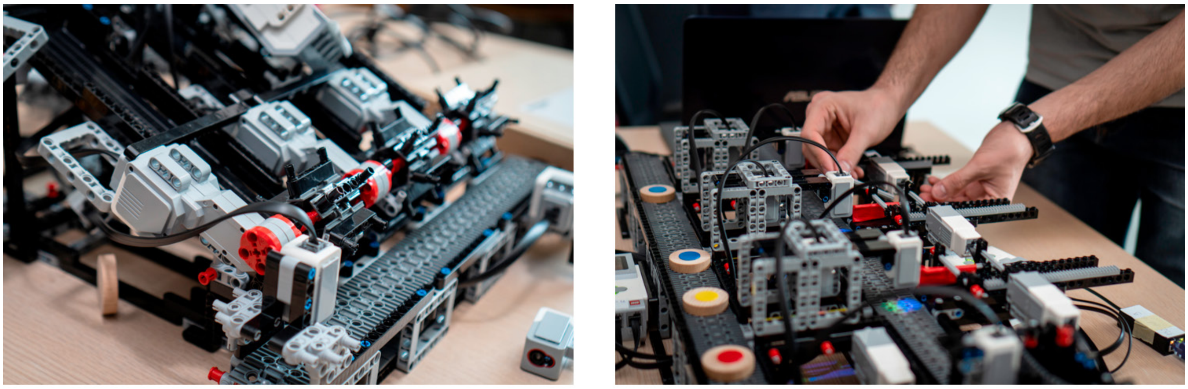
In the group-work activities, students develop the ability to handle complexity of manufacturing systems, to integrate knowledge acquired in other courses on productions systems and industrial plants, and to work in a manner that may be largely self-directed and/or autonomous. Students also develop the ability to communicate their choices and conclusions to each other. The group-work activities allow students to:

- Design an integrated manufacturing system in a context of partial information. Students are required to retrieve the rest of information from either external resources or through cooperation among teams.
- Observe the most common issues for designing manufacturing systems (e.g., cycle time constraints).
- Obtain additional soft skills such as the ability to overcome conflicts and critical issues.

5. Proposed projects

The following projects have been successfully completed in the group-work activities of the course:

1. **Traceability**. Development of a system for tracing parts along the system. The target is to record the passage of parts along the line and to write a system log file with at least three information labels: part ID, timestamp, and activity ID.
2. **Machine-to-machine Communication**. Development of a distributed control system made with EV3s able to communicate with each other and with a central controller through a local network.
3. **Load/Unload Station**. Realization of a station for loading and unloading the parts from the line and its related management logic. The objective is to be capable of deciding the sequence of parts flowing in the manufacturing system. Fig. 3a shows the system that has been developed.



(a) (b)

Fig. 3. two projects realized in the course: (a) buffer system allowing load/unload of pallets; (b) manufacturing system with three parallel stations.

4. **Quality**. Construction of a quality control station with its parts re-routing system. The intent is to halt pieces outside the main route to simulate the detection of a bad part.
5. **Robotic Arm**. Development of a material handling system consisting of a robotic arm. The goal is to be able to add and remove pieces from the line.
6. **Guided User Interface**. Development of a software interface for controlling the physical system. The goal is to send commands to the system with a user-friendly interface, so that also people with no programming skills can use the system.
7. **Image Recognition**. Development of an image recognition system able to recognize parts location. The ambition is to be able to count the number of parts in a buffer or in the whole system in real-time.
8. **Parallel Machines**. Development of an system able to process parts in parallel. Fig. 3b shows the prototype that has been realized.

At the beginning of each project, the teams are provided with general specifications. Then, they are encouraged to brainstorm and gather additional information that they need. They may also buy additional hardware within a fixed budget (EUR 100). During the whole course duration, students are supervised and provided with technical help.

6. Concluding remarks

In this paper, we have presented a LEGO-based learning system. The practical experience facilitates teaching manufacturing systems integration basics. The introduction of this innovative course methodology brought insight on several aspects of the learning experience, both from the students and the teachers perspectives. Following we summarize our thoughts and considerations.

- Several aspects of manufacturing systems integration can emerge autonomously through group work activities. For instance, several groups might search for solutions to the same problem (e.g., parts movement, sequencing). In this case, they have to decide which team will be in charge of a certain operation such as deciding where to position the sensors. Further, they might encounter design decisions, such as the definition of of the pick up point from robotic arm outside the line. Also formalization issues are experienced, such as the selection of which file formats to use.
- Students autonomously recognize the existence of trade-off to resolve (e.g., between versatility of movements of a robotic arm and its weight and vibrations). They can understand the importance of the final outcome, hence they are comfortable in criticizing their own solutions in favour for more efficient ones.
- Most of the students are experiencing for the first time in their career working together with teams of people from different ages and diverse background.

In the next editions of the experience, we aim to introduce new projects related to the improvement of several performance measures of a production system (e.g., productivity, sustainability, profitability). Further, different types of manufacturing systems will be included in the course.

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