Active Learning using Physical Prototypes and Serious Games

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Abstract

It is widely accepted that the "learning by doing" approach results in higher levels of knowledge retention. This paper describes how this subject is addressed in the Integrated Master degree on Industrial Engineering and Management (IEM) at University of Minho, Portugal. Serious games are used as a learning tool in different years of the IEM degree to illustrate and consolidate important concepts, namely production dynamics and performance issues. To reinforce "learning by doing" the development of physical prototypes was included in one of the IEM Project-Led Education semesters involving the design of a production system using Lego® Mindstorms® NXT building blocks. This paper provides a reflection on the use of serious games and physical prototypes, mainly in terms of learning outcomes and, to a lesser extent, on students learning styles. Moreover, it provides some hints on the integration of the tools on the curricular structure and on its practical implementation.

Keywords: engineering education, project-based learning, serious games, physical prototypes.

1 Introduction

In terms of human resources, the gap between industry requirements and the competences of the newly graduated industrial engineers has always been a problem with greater or lesser impact. At worst, the consequence for the companies is the need to ensure a significant period of adaption/training to the newcomer engineers. This is not the most efficient approach, both in terms of time and money, due to the ever-growing competiveness enforced by the current markets. Obviously, it is utopian to think that universities can provide its students all the knowledge they will need in their professional lives. However, universities can, for sure, minimize the above mentioned gap by preparing professionals with the best possible set of skills. This implies not only the restructuring of the curricula, but also the adoption of new forms of teaching/learning. In fact, besides the definition of adequate learning outcomes, effective and efficient ways to achieve them are necessary.

Several studies recognize that the traditional methods of teaching/learning are not the best way to consolidate knowledge. For example, according to O'Sullivan, Rolstadas and Filos (2011), students involved in the passive activities inherent to the traditional teaching approaches (e.g. listening and reading) only retain 10% to 30% of the knowledge. On the other hand, the knowledge preservation rises to 70% when students perform active tasks (teamwork, tasks involving physical components, serious games, etc.).

Thus, the adoption of new teaching/learning methodologies, properly supported by adequate tools, becomes an inevitable need for higher education institutions wishing to train highly qualified professionals. Aware of these facts, the Department of Production and Systems from University of Minho, Portugal, has implemented, since 2004/2005, the active learning methodology Project-Led Education - PLE (Powell & Weenk, 2003) in the 1st, 7th and 8th semesters of the IEM degree (Lima, Carvalho, Sousa, Alves, Moreira, Mesquita & Fernandes, 2012; Alves, Moreira, Sousa & Lima, 2009), which includes, in the 1st semester, the design and implementation of physical prototypes of (part of) manufacturing systems using Lego® Mindstorms® NXT building blocks. Additionally, to strengthen the "learn by doing" approach, serious games are conducted in several IEM semesters in order to consolidate fundamental aspects inherent to the industrial engineering area.

1.1 Objectives

The main objectives of this paper are: (i) describe two of the active learning practices implemented in the IEM degree at University of Minho, Portugal, namely the use of serious games and the development of physical prototypes of manufacturing systems, (ii) reflect about the use of these practices, namely in terms of students learning styles and learning outcomes, and, (iii) provide some hints about the concrete implementation of these tools and their integration into the IEM degree curricular structure.

1.2 Methodology

The methodology adopted in this work began with a brief literature review concerning the main fundamentals needed (learning styles, learning outcomes, serious games and physical prototypes). Then, based on the several experiments carried out in the IEM degree, the perceptions of teachers and students were informally gathered. Finally, these results were analysed and discussed, leading to the paper's conclusions.

2 Active Learning – some Concepts and Tools

The designation "active learning" applies to the learning approaches where students are the main responsible for their learning process (Bonwell & Eison, 1991), i.e. student-centred learning approaches. A well-known example is the already mentioned PLE approach, which is characterized by a deep involvement of the students in the project's activities. This section provides a brief overview on learning outcomes and students' learning styles, and also on some fundamentals concerning the two active learning tools implemented: serious games and physical prototypes.

2.1 Learning Outcomes

According to European Union (2004), "…learning outcomes are verifiable statements of what learners who have obtained a particular qualification, or completed a programme or its components, are expected to know, understand and be able to do". Thus, a proper establishment of the learning outcomes is fundamental for the quality of a given degree/subject and special attention should be given to their assessment (Adam, 2004).

Learning outcomes and learning objectives are frequently considered as synonymous, but, although closely related, they are different (European Union, 2004; Harden, 2002; Allan, 1996). The learning objectives reflect the perspective of teachers (e.g., establishment of the contents to be taught) while the learning outcomes are focused on what students should be able to do by the end of the learning process. In fact, the learning objectives may be written in terms of learning outcomes (Krathwohl, 2002) and, in that sense, many scholars do not distinguish them. Further discussion about learning outcomes vs. learning objectives can be found in Harden (2002).

For this paper's purpose it will be considered the Bloom's taxonomy (Bloom & Krathwohl, 1956), which classifies the learning objectives of the cognitive domain into six levels (Figure 1).

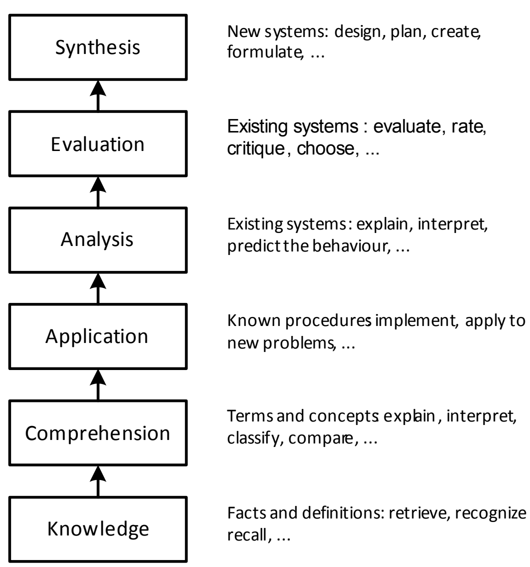

Figure 1: Bloom's taxonomy of learning objectives in the cognitive domain (adapted from: Felder & Brent, 2007).

Felder and Brent (2007) reported that graduation degrees are usually focused on the learning objectives of the three lower levels, but it is advisable that all the levels are addressed, not necessarily in a sequential manner. In fact, they argue that there are benefits for students if the learning objectives of the upper levels - analysis, evaluation and synthesis - are already considered in the first year. On section 4 it will be shown how the PLE implementations at IME seek to follow this approach.

2.2 Learning Styles

The Felder-Silverman model (Felder & Silverman, 1998) characterizes the learning style of a student in four dimensions: (i) sensing/intuitive; (ii) active/reflective; (iii) sequential/global and (iv) visual/verbal (Figure 2).

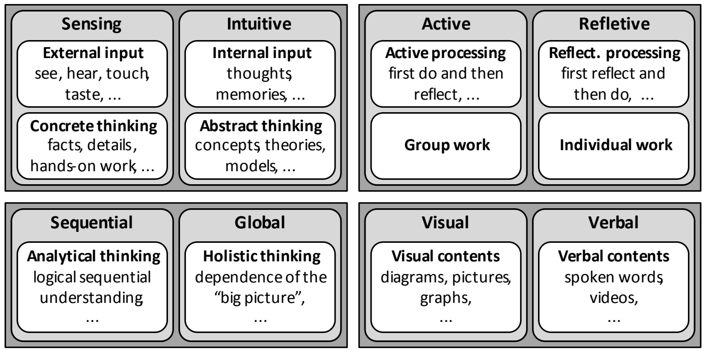

Figure 2: Felder-Silverman's model of learning styles (based on: Felder & Brent, 2007).

According to the model, all students are both sensorial and intuitive, but the weight of each component depends on each student (ranging from weak, moderate and strong). The same applies to the other dimensions. Obviously, for any particular student, the learning process is more effective and efficient if the teaching process is aligned with his learning style. The problem lies on the difficulty to meet the needs of the different learning styles.

2.3 Serious Games

The designation "serious games" can be applied to any game whose main purpose is to make the actors learn specific serious contents (Charsky, 2010). As the students' motivation level tends to be high when they are involved in this kind of activities, serious games are commonly recognized as an important tool to improve any learning process. Thus, the so-called "game-based learning approach" is being implemented in several degrees, namely, among others, in science (Sung & Hwang, 2013) and management degrees (Yalabik, Howard & Roden, 2012). The manufacturing systems' area is a first-rate context to implement serious games but only a few cases are reported in the literature, e.g. Pourabdollahian, Taisch and Kerga, (2012).

Serious games, especially those involving the handling of physical elements/components (as usually happens in the manufacturing systems' area), can be considered as a hands-on learning approach. This kind of approach promotes a deep and intuitive understanding of complex subjects (McManus, Rebentisch, Murman & Stanke, 2007; Peter, 2010). Some important advantages of serious games implementation are the students' engagement and the already mentioned motivation's increase, both leading to the improvement of the learning outcomes. However, it is important to note that, according to Sung and Hwang (2013), complete demotivation and self-alienating behaviours may happen when poorly-designed serious games are applied.

2.4 Physical Prototypes

Prototypes provide a realistic approach towards real world phenomena, by delivering functional apparels that replicate key features of a product/system (or service). The activity of devising, designing and implementing a physical prototype requires the design of strategies to best encapsulate system/products specifications (aesthetics, functionality, performance, human-machine interface, mechanical, electronic, information technology features, etc.), a good deal of deep knowledge on the product/system specifics and a practical attitude towards designing and doing real things in a given timeframe with limited resources. Prototype building is considered to be an active learning strategy that promotes long term knowledge retention, and requires a number of high level activities, such as those of designing, simulating, building and rigorously assessing the performance of a product/system. Such a strategy broadly outpaces the breadth and depth of the learning experience within common activities developed in traditional teaching classrooms. Doing real things with multiple constrains, such as those of time and financial resources, is much closer to the real world engineering practice than that normally exercised within classrooms. Therefore prototypes also close-up the gap between the practices observed on universities and those in use in industry.

Physical prototypes also serve as test beds prior to implementation, and lays down just before realisation stage, offering key opportunities for discussion and enhancement of the proposals. Prototypes can also be used to fast track teaching on key aspects of engineering activities. The process of building prototypes commonly requires new knowledge and new tools, and building them is becoming more frequent, especially because products/systems are getting more complex and it is risky to introduce them to the marketplace without a trustworthy proof-of-concept.

3 Implementation of Active Learning Tools in the IEM degree

This section describes the implementation of two serious games in the 4th and 5th IEM years (one related to production cells' design and operation and the other about equipment setup processes) and also the development process of physical prototypes of manufacturing systems, applied to the IEM project teams of the 1st year. In practical terms, some important aspects must be considered. The involved teachers have to ensure that the right conditions are met, namely in terms of space, material resources and documentation. In the particular case of the serious games, it was important to conduct a first trial before proceed to implementation with the students' teams (at IEM this was done with several teachers). Thus the responsible teachers were able to fully understand the game dynamics, identify potential difficulties/problems and make some adjustments to overcome those issues (e.g. modify the duration of the game and the detail of the demanded activities, depending on the size of the class).

3.1 Cells Design and Operation Game

In the context of the IEM 5th year curricular unit "Design of product-oriented production systems", a serious game designated "Cells design and operation game", involving the assembling of a product (hands-on approach), was applied to strengthen the learning of new concepts. The concepts to learn in this context were the different operating modes that can be implemented in a production cell (Carmo-Silva & Alves, 2006; Oliveira & Alves, 2009). An operating mode is the internal organisation and distribution of the operators by the workstations, i.e., how people work and flow within a cell (Hyer & Wemmerlöv, 2002). The main topic of the referred curricular unit is the design of production cells which are production systems layouts that could be projected as a "…small organizational units which complete all the set (or family) of products or components which they make, through one or a few major processing stages, such as metal casting, machining and assembly, and are equipped with all the machines and other processing equipment they need to do so." (Burbidge, 1989).

The students were organized in teams and invited to prepare a potential training session about operating modes, for operators in a work environment. Each team ran a different operating mode, using the same product, in a plenary class where everyone sees, question and learn, not only the other operating modes, but also how to distinguish them.

This experience had been implemented since 2010/2011. The first edition involved seven teams (21 students) and the results were published by Alves and van Hattum-Janssen (2011). The 2011/2012 edition involved five teams (15 students) and in 2012/2013 five teams (25 students). Each team executes a different operation mode: Baton Touch; Bucket Brigades; Rabbit Chase; Working Balance, Toyota Sewing System (Alves, 2007). When more than five teams were involved, some variations of these modes were allowed (Bucket Brigades in line; Assembly Line).

The products assembled by the teams were small electric torches (Figure 3). Each team studied the assigned operating mode and its characteristics, and presented, in a plenary session, how that mode works. All teams received documentation with theoretical contents about operating modes.

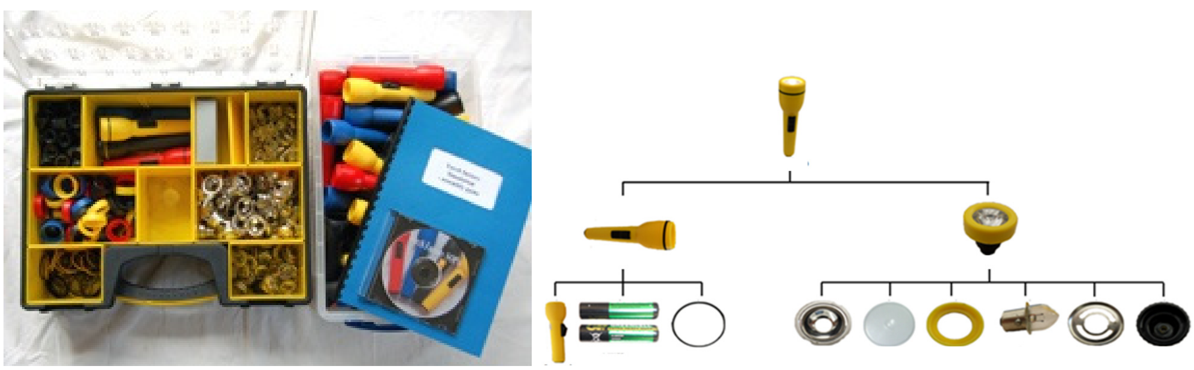

Figure 3: Torches' game and the bill-of-materials of the torch (Lean Games, 2006).

The objective is that students learn to differentiate the operating modes, so, initial data is provided, namely: operations type and time (9 operations), run time (5 minutes) and theoretical number of operators (5). Performance measures such as cell output, number of cells with defects, work-in-process level, productivity, efficiency and lead time for obtaining the first product, are registered and used to compare different operating modes. All sessions were video-recorded and became available to the teams in the end of the sessions and, additionally, some photographs were taken to allow further discussion, especially regarding the differences between the operating modes (Figure 4).

Figure 4: Aspects of the operating modes experienced by three different teams.

More important than the quantitative results (which are not relevant for this paper's purpose), the use of the hands-on approach allowed the recognition of some problems related to the kind of the product assembled, layout used and people involved. The assembling of the electric torch involves nine assembly operations, which implies different subassemblies. In the operating modes without a buffer, it was difficult to pass in hands the small parts and the subassemblies, and, thus, it was very frequent to see some parts lying on the floor. If this session was carried out with software simulation, this kind of problem would never appear. Additionally, the students could realize the layout influence in their performance and quickly concretize the change to a different layout. For example, a team recognized that a U-shaped cell, with all operators inside the cell, was not appropriate and proposed a different arrangement with two operators inside the cell and three operators outside. Not satisfied with this layout, the team proposed a different layout with the same number of operators (five operators), in order to have a perfect balance. All measures were improved, except the lead time for the first torch which remained unchanged. The other teams also wanted to improve the results and because they noticed that five operators were an excessive number (due to mutual disturbance), they reduced the number of operators to three and the measures were improved or maintained.

With methods or techniques (e.g. software simulation) other than the hands-on approach it would be difficult, or even impossible, to recreate aspects related with people, like motivation or confusion and to recognize some problems arising from the synergy (or conflicts) between the operators or difficulties in assembling the product, like the ones described above. Those problems are the kind of problems students will find in the industrial environment.

3.2 SMED Game

SMED stands for single-minute exchange of die (Shingo, 1985), a proven methodology to reduce equipment setup/changeover time (time period necessary to prepare a workstation/production system to produce a different kind of product). The SMED game (Figure 5) is usually applied to the IEM 4th or 5th year and it is particularly relevant as a substantial number of last year students face the setup time reduction problem while developing their master thesis on industrial environment.

The game session is carried out with three teams (three game sets are available) and each team may have from one to five students. Obviously, the roles' assignment depends on the size of the team which also influences the total duration of the game, so equally sized teams should be constituted for each session. The game involves several stages.

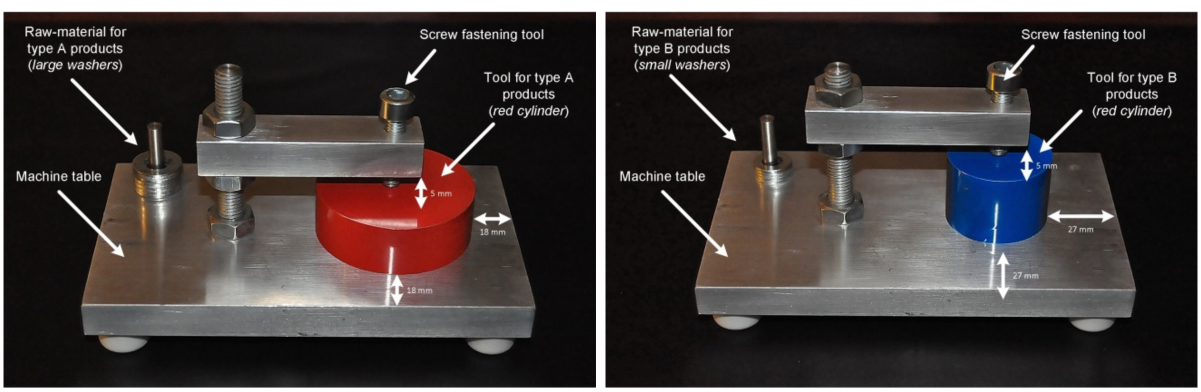

Figure 5: The SMED game - machine prepared for product A (left) and for product B (right)

The teams execute a first changeover (product A to product B) and analyze in detail the entire process, including the setup operations' classification (internal or external) and the measurement of the total changeover time. Then, they discuss the findings and develop improvement proposals by applying the techniques / tools inherent to the SMED methodology. Based on these proposals, each team conducts a second changeover of the machine and, again, they measure the setup time and discuss the results. Next, an additional set of elements (e.g. functional clamps and intermediary jigs) is provided and the teams carry out the last changeover. Finally, it is made a comparison of the results achieved by each team and the session is completed with a discussion on the learning outcomes acquired. A healthy competition atmosphere was observed during the sessions, the level of motivation and effort was very high and, in the end, the teams unequivocally increase and consolidate their knowledge about equipment setup/changeover time reduction.

3.3 Physical Prototypes of Manufacturing Systems

The requirement for construction of production system prototypes targeting 1st year student teams of the IEM degree, at University of Minho, was initially proposed and discussed in 2004/2005 under the Interdisciplinary Project-Led Engineering Education proposal, and has ran annually since (Moreira & Sousa, 2008). Initially some funding was granted to acquire an adequate number of sets of equipment that could provide easy construction of dynamic physical models. The chosen sets were Lego® Mindstorms®, later on upgraded to Lego® NXT, as depicted in Figure 5, which provided programmable controllers, sensors, actuators, communication devices, programming software and technic bricks. These sets were used to construct prototypes of several types of production systems, since each year a new kind of production system was issued. This was done for about eight consecutive years. The development of the prototypes was mainly intended to consolidate fundamental concepts within the field of Manufacturing Engineering.

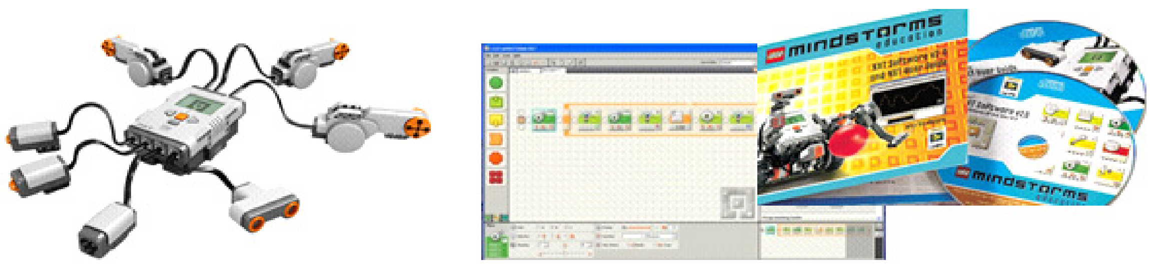

Figure 5: Lego® NXT controller with sensors and actuators (left) and programming resources (right).

Fresh IEM students doing their first Interdisciplinary PLE experience are required to design a conceptual model of a manufacturing system (MS). This involves the layout, main stations and transportation systems, the production paradigm, workforce and a number of production metrics. After designing the MS, the teams conceive a dynamic physical prototype which should encapsulate the key features of the MS, while offering an experimental basis for possible improvements to the original proposal. The system dynamics is coded into both mechanic and logic actions which replicate most of what should be happening on the shop-floor. Each team receive one Lego® Mindstorms® kit and is instructed on the task and key aspects to start building and programming the NXT controller. The instruction provided is minimal, since Lego® block construction and the respective programming language are quite easy, modular and intuitive, allowing a fast learning curve and a rather autonomous work. The students learn on a different way key manufacturing concepts, such as bottleneck, cycle-time, throughput time, material flows, work-in-process, system dependencies, among others, by having to uncover and settle the logic beyond those, on key elements and at the system level. They are also offered the opportunity to reflect on the overall system performance and uncover possible alternatives to performance improvement. Figure 6 depicts prototypes of two IEM students' teams.

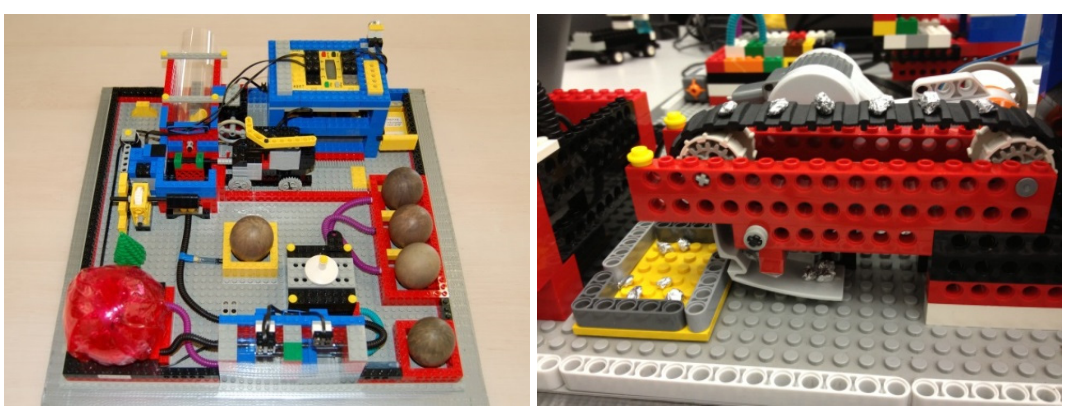

Figure 6: Prototype of an H2O Desalination plant (left) and detail of a recycling plant prototype (right).

The teams also discuss and cooperate on specific issues relating the programming task, structuring a mechanical proposal to represent things, and on exchanging building blocks. The teams are free to incorporate out of the box components/solutions that do not pertain to the standard kit, which normally does happen every year. Teams are also free to find innovative ways to showcase the prototypes, which have resulted in several real-time imaginative multimedia presentations which normally captures the audience attention. All of these have resulted on surprising prototypes that denote a hardworking attitude towards work and denotes fully commitment to the task in hands. This corroborates the idea that prototypes raise students' motivation to learn and are a great communication tool.

4 Discussion of Results

With the cells design and operation game, students were able to consolidate some key concepts associated to the field of industrial engineering, previously covered in theoretical and theoretical-practical classes. Although not formally scrutinized (e.g. using interviews and/or surveys), the students' opinions were gathered after the games' sessions. In general, they found that the use of the cells design and operation game allowed a clear illustration of fundamental concepts such as layout's organization, production flow, line balancing, bottleneck, as well as key performance indicators like production rate, productivity, efficiency, lead time and work-in-process. It was even possible to identify a real problem (the fall of parts referred in section 3.1), impossible to detect without the hands-on approach inherent to the game.

Similarly, the implementation of the SMED game as clearly contributed to a much more detailed knowledge on equipment setup time reduction. The stages of the SMED methodology implementation were properly addressed by the game and the students' teams were able to experimentally understand not only the difference between internal and external setup operations, but also how the most important SMED techniques/tools can be applied in practice in order to reduce equipment setup time. In fact, despite its apparent simplicity, the game is quite effective to demonstrate the following SMED techniques/tools: check tables, function checks, advanced preparation of operating conditions, function standardization, improvement of parts and tools transportation, intermediary jigs, functional clamps and elimination of final adjustments.

It can be said that both the cells design and operation game and the SMED game promoted learning outcomes inherent to all the levels of the Bloom's Taxonomy (Figure 1), although the first one has more impact in the higher levels. Besides that, by playing the role of operators in a company, the students realized the importance of the interaction with other workers, teamwork, mutual assistance, personal involvement, conflict management, etc.

The perception of the involved teachers points out the development of production systems' physical prototypes carried out by the 1st year teams, as one of the phases of the project (PLE semester) in which students' reveal great commitment and motivation, contributing a lot for the project success (Alves et al., 2012). Teachers are constantly being surprised by the prototypes' levels of originality, functionality and layout details. Clearly, the students developed some learning outcomes inherent to the high levels of the Bloom's Taxonomy (Figure 1), especially the ability to synthesize new systems (design, plan and create). The perceptions of each team were collected at the end of the prototypes' demonstration session. Almost all students recognized that their involvement on the prototypes' design and construction as promoted the knowledge retention of important contents such as layout's organization, bottleneck, cycle-time, throughput time, material flow and work-in-process. In terms of fundamentals of industrial automation, one student referred "…now I will not forget what a sensor is and what an actuator is" and other said "… after utilizing gears in the prototype, I understood the importance of the gear ratio when we need more torque in a shaft".

In terms of students' learning styles (Figure 2) it is worth to mention a particular occurrence in the cells design and operation game: two students from the same team had different approaches to experiment a new layout. One wanted to sit down and think about how would be the system behaviour with the new layout (reflective learning style), while the other wanted to try the new layout immediately and then analyse what happened (active learning style). As each approach can be easily executed, this shows that the game is adequate to both learning styles. It also becomes clear that the two serious games and the development of physical prototypes were perfectly adequate to students with sensing learning style. Students with a strong component of the visual learning style are also comfortable and motivated with these active learning tools.

5 Conclusions

The use of two active learning tools – serious games and physical prototypes of manufacturing systems – have shown to be effective instruments to induce high levels of knowledge acquisition and retention, and consequently, to enhance the students' learning outcomes. As shown on sections 3 and 4, these tools can be classified as hands-on approaches and are suitable for a number of different learning styles. Accordingly, their use is capable of attracting a larger audience than that of traditional lectures. In fact, the motivation and engagement level of the students' teams was very high (somehow, almost full class attendance observations corroborates this) and the results were clearly positive. For example, the design and construction of physical prototypes conducted by 1st year IEM student teams induced the ability to synthesize new systems, which corresponds to the highest level of learning objectives according to Bloom's taxonomy. The existence of a functional physical prototype allows a different view over the production systems, but, besides that, its development catalyses the search for knowledge.

In terms of integration in the curricular structure, there is no special limitation to the adoption of the above mentioned tools. Even tools especially aimed at learning outcomes of the upper levels of Bloom's taxonomy (e.g. synthesis of new systems) can be included on early stages of the studies (e.g. on the first year). In fact, the main decision factors regarding the use of such tools are the subject syllabus and the teachers' motivation. The authors consider as well that advanced serious games should be implemented in the last stages of the studies (e.g. last years) because, additionally to the learning of new concepts, they are predictably the most effective way to consolidate learning contents introduced in previous years.

Further developments will likely focus on defining an assessment model for measuring the effectiveness of use of the active learning tools hereby reported. This model will potentially allow comparisons to be made among different learning strategies and tools, and could be used for selection of prospective learning strategies and deployment of strongly bounded active learning tools.

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