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A Project Based Approach for Teaching Product Development to Graduate Students*

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Project-based learning (PjBL) activities let students deal with authentic engineering problems where other abilities are trained instead of rote memorization or simple algorithmic substitution. In this paper, we propose a PjBL approach in a master degree of design and manufacturing where the students have to develop a lighting product from the conceptual design to the manufacturing and promotion of the product, finishing with a physical prototype made by 3D printing. The goal of the paper is to analyze the benefits of conducting a PjBL approach within a group of subjects that can be coordinated under the same project and where the students can put into practice the fundamentals of each subject for the physical realization of a real product. The paper describes the evolution of the PjBL experience throughout four years, the improvements and changes made according to students' and instructors' perceptions. As a result of the improvement of the project along the 4 year experience, the student's performance and the student's satisfaction related to the project increased from 7.2 to 8.9 out of 10 and from 3.7 to 4.8 out of 5, respectively. The motivation and engagement of the students were also improved according to the quality and dedication of the resulting products manufactured by the students.

Keywords: active learning; project-based; engineering education; product development; 3d printing; design

1. Introduction

Nowadays, current engineering curricula are too focused on fundamental engineering science and several agencies and researches have reported the lack of integration of these topics into industrial practice [1]. In higher education, the dominant mode of teaching and learning is still based on "teaching as telling; learning as recall" [2], and real engineering experiences where the student acts as the main actor are not sufficient in current programs [3]. This teacher-centered approach, also called passive learning approach, may prepare the students to pass the exam in short term but it presents important issues related to low knowledge retention, difficulties in the engagement of the students, lack of motivation, and low preparation for the 'practice of engineering' [4].

To overcome these deficiencies, professional bodies such as the European Networks for Accreditation of Engineering Education (ENAEE) in Europe have defined a list of expected graduate attributes or outcomes that should be incorporated in the educational programs in order to obtain the accreditation of an Engineering Program. For instance, ENAEE sets the program outcomes in terms of knowledge, understanding, skills and abilities that a graduate must demonstrate within an accredited engineering degree program. The program outcomes are described with reference to the following eight learning areas: knowledge and understanding; engineering analysis; engineering design; investigations; engineering practice; making judgments; communication/team-working and lifelong learning [5].

These engineering accreditation programs promote the use of active learning methodologies such as project-based or problem-based learning in order to make the student an active participant in the process of assimilating new information. Prince et al. [6] and Freeman et al. [7] proved that these active learning methods present positive aspects such as higher motivation and persistence due to authentic problems and case studies, deep learning instead of rote memorization and simple algorithmic substitution, and higher levels of student attendance and knowledge retention in comparison to traditional lectures.

Several research works on PjBL in the field of product development have been reported in the literature with interesting aspects to be considered in similar experiences. In [8], the authors introduced the PjBL approach in an introductive course on mechanical engineering with the aim of simulating the process of design and development of a new product, and emotionally engage students in this process. During the course, students worked in small groups to design and built a device that performs a specific task and the quality of the designs was evaluated through a competition among all groups. After the competition, each team was required to submit a final technical report detailing the research and development process, the engineering considerations that led to the final design, a review of the relevant engineering literature, and the team's conclusions. The authors gathered data from

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students and instructors interviews, observations in the classroom and students' reports to study the students' perceptions in a PjBL environment. According to students' opinion, the course helped to develop their engineering thinking and their intuition, increased motivation to study and made them feel like responsible collaborators in the learning process. However, the study was only based on students' perceptions, with no objective evaluation of the benefits of the PjBL approach. Hadim et al. [9] presented the implementation of the PjBL approach in a first-year course on Mechanics of Solids and a second-year course on Mechanism and Machine Dynamics. The project was related to the design and analysis of a tower crane used for lifting heavy loads and it was monitored by periodic reports and instructor's feedback. The implementation of the PjBL required the reduction of homework assignments to 50% and the material covered by lectures was also reduced to 25%. The assessment of the educational experience was conducted through a survey of the students at the end of the semester. The students increased their motivation and interest of real-life applications but they demanded more guidance in completing the project, which is a critical issue in this kind of learning methodologies. The analysis about the exam performance showed a measurable improvement of the students especially in the examination of design components. Palmer and Hall [10] applied the PjBL approach in a first-year engineering of a bachelor of Engineering Technology, however, they did not find any significant difference in the students' performance although they observed a high students' satisfaction. After administering a questionnaire they pointed out that the best aspects of PjBL according to students' perception were team working and practical approach and the worst aspect was the necessity of more time to work on the project.

Vila et al. [11] showed an educational experience in a 5-year engineering course on Integrated Manufacturing Technologies. The purpose of the project was: i) design a new component for a given toy car, ii) prototype the component in a 3-D printer in order to validate the component and its assemblability and iii) design the mold cavity for the injection process. The project was conducted through a Product Lifecycle Management (PLM) software and the students/instructors worked following a predefined workflow. The instructors reviewed the students' designs and, using the PLM and a web-browser visualizer, made annotations to correct the designs. The approval for the next stage of the project was given when all corrections were made and no design errors were detected by the instructors. After the project, the students were asked to complete a questionnaire and the authors reported a high engagement where students evaluated positively the experience and acknowledge their high improvement in abilities related to computer aided design, computer aided manufacturing and product data management. In [12], the same authors evaluated different PLM software to support the execution of collaborative practices during the development of project-based learning activities in higher education. More recently, Abellan-Nebot [13] showed a PjBL experience in a mechanical engineering course where a part was manufactured from the scratch, creating pattern plates by 3D printing, sand molds, CNC machining programs and conducting product inspection and verification activities. According to his experience, the students are highly motivated in this type of learning approaches where they create artifacts and apply the course contents in real products.

Additionally to these academic experiences, excellent reviews of PjBL reported in [14–16] showed the main factors influencing the success of project-based learning experiences at higher education such as those that are likely to affect motivation and thought, difficulties that students and teachers may encounter with projects or how to effectively design the project experience. However, it should be pointed out that some authors are skeptical about the usefulness of these approaches. Kirschner et al. [17] discussed that minimally guided instruction such as the active methodologies presented above may be less effective and less efficient than instructional approaches. According to their study, only a less guidance of the student learning process is effective when learners have sufficiently high prior knowledge. Therefore, it is critical to consider a good trade-off between guidance and self-discovery when designing efficient active learning approaches.

The goal of this paper is to analyze the benefits of conducting a PjBL approach within a group of subjects that can be coordinated under the same project and where the students can put in practice the fundamentals of each subject for the physical realization of a real product. One of the common limitations in PjBL approaches is the limited time students may have to work on the project since real activities for product development are time consuming [13]. By grouping different subjects under the same project the time spent in project activities is more efficient. Furthermore, the timetable of the subjects is rescheduled in order to teach the concepts according to the needs of the project stage which improves the engagement of the students and the application of the concepts learnt on product development. The PjBL experience is conducted in a master degree (Master of Design & Manufacturing) at the Universitat Jaume I, Castellón (Spain) for four consecutive academic years. The goal of the project is the design and development of a product using 3D printing technologies and the promotion of the product (brand and logo creation, promotional video, technical documentation – assembly documents –, etc.). The experience shows the improvement of the project along 4 academic years considering students' and instructors' opinion and provides some recommendations for those instructors interested in applying similar learning approaches in their institutions.

The paper is organized as follows. First, the description of the subjects that are coordinated within the PjBL approach is presented, showing the grading system and the course contents that should be covered by the project. Next, it is described the scope and goal of the project and the changes made throughout the four academic years in order to improve the learning results. Section 4 shows the results of the project taking special attention on project grades, exam performance and students' satisfaction. At this point, some key aspects to be considered and useful recommendations are provided for those interested in implementing similar educational experiences. Finally, Section 5 shows the main conclusions of the paper.

2. Course and Project Description

The education experience is conducted within a group of subjects at the Master of Design and Manufacturing from the Universitat Jaume I (Spain), accredited with the Eur-Ace distinction (2016–2020). The subjects coordinated in the project experience and their contents are:

- SDI222. Digital and Physical Prototyping: rapid prototyping, 3D printing, and rendering tools for product communication.
- SDI223 Multimedia Tools in Industrial Design: video recording for product promotion, creation of technical documentation (assembly manual, etc.).
- SDI224. Trends and Product Promotion: market trends and novel designs, brand and logo creation.

This group of subjects defines 8 ECTS (European Credit Transfer and Accumulation System) and the project activity to work on a product development case defines 2 additional ECTS. In total, the students have 100 hours with the instructor and 150 autonomous working hours. Other subjects are coordinated in the same way with other project activities in order to apply the learnt contents into real engineering experiences and make the learning process student-centered. The master degree is composed of 60 ECTS the first year and 15 ECTS the second year which refers to the Final Master Thesis.

The grading system adopted in all subjects is: 25% exam score; 25% personal activities (homeworks); 50% project score. The project is conducted by groups of 3–4 members and its grade is also divided into two parts: 30% seminars score and 70% final project score. The seminars are monthly meetings where the students show the progress in the project activities and the instructors give feedback and comment potential improvements in the product development process. The final project refers to the final exposition of the project where it is mandatory the presentation of the resulting product with the explanation of all technical details and the multimedia documentation for product promotion. The final project score is done according to a rubric following the Eur-ACE recommendations. In order to avoid problems about students' grades due to different workloads and contributions to the project, the final project score is modified according to the self- and peer-assessment (SAPA) results. The SAPA procedure is conducted by each student in order to evaluate their contribution to the project and the contribution of the rest of the members. Gathering this information, the instructors may modify the scores between the members of the group. Similar SAPA procedures are reported in the literature as a key aspect to consider in PjBL approaches [10].

The topic of the project is a lighting product which should be manufactured by 3D printing processes. The goal of the project is to involve the students in a real engineering activity of product development where the concepts learnt during the classes are implemented. The scope of the project is shown in Fig. 1 and basically it is focused on the following tasks: (i) conceptual and final design according to market trends; (ii) creation of a prototype by 3D printing technologies and product redesign if necessary; (iii) elaboration of promotion documentation such as renders, webpage and promotional video.

3. Continuous Project Improvement: Courses 2015/16–2018/19

The project was implemented in the course year 2015/16, and from that year onwards the project has been reviewed and improved to include the students' and instructor's recommendations. In 2015, the project was focused on the design of a lighting product with a priori no limitations in terms of dimensions and components. The budget per group to buy any additional material for the product (bulbs, electrical cables, leds, etc.) was fixed to 20 €. At that time, there was no 3D printer at the

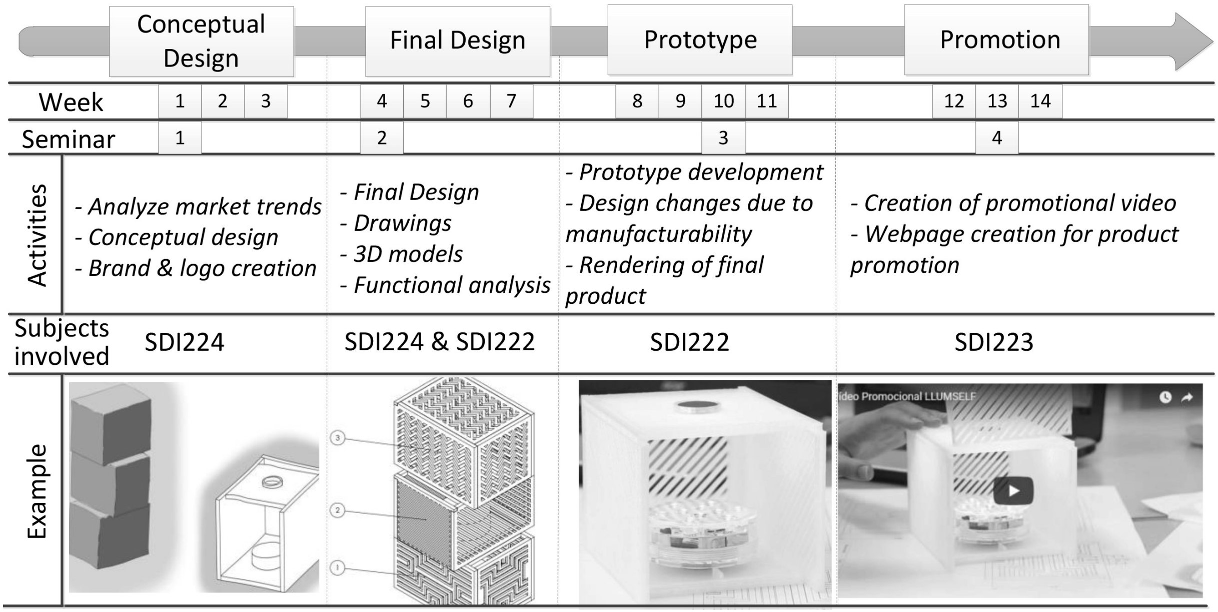

Fig. 1. Project overview. Scheduling and activities conducted.

disposal of the students, so the parts to be printed were sent to the instructor for printing. The students came up with product solutions based on one component with high dimensions (more than 200 mm in height). Due to the dimensions and printing time required, the instructors used a 3D printer from ZCorp (3D printing technology based on powder), and the results were acceptable although the product was not operative. For instance, one design presented a slot for the electrical cable that was clearly impossible to be used since the powder was jammed into it. Additionally, some of the parts should have presented a complex shape in order to justify the use of 3D printing technologies. This point was the negative part of the project, since some of the parts were created with a complex pattern mesh from the software MeshMixer, and the weight and problems of manipulating these files was important.

In order to overcome some of the issues found, the following year the instructors added as product specifications the use of more than one component to force the students conduct an assemblability analysis. Furthermore, a FDM printer (a BCN3D + brand) was bought and the students had access to the 3D printer at any time, so they could print and check specific parts before the final design. At this point, the main problem was still the use of patterns to create complex surfaces. PC reboots and too slow performance of CAD systems were the main complains of the students. In course 2017/18, the main change made was related to the sequence of the subjects taught throughout the semester. To make the concepts taught in class easier to apply on the project, the subjects replaced the sequence of 2 lecturing hours per week with an intensive scheduling where the subject is taught when the project requires it. Therefore, the first 5 hours per week during 4 weeks were used to teach the subject "Trends and Product Promotion", the following 4 weeks were used to teach "Digital and Physical Prototyping", and finally, the subject "Multimedia Tools in Industrial Design" ended the semester. Additionally, the use of complex meshes was limited in order to reduce the problems related to software crashes or excessive time for product modeling. At the disposal of the students it was added a small laser engraving to create the logo of the product in a small wood plate and mount this component with the rest of the 3D printed parts. In this year, the main drawback was related to the 3D printer at the disposal of the students, which was out of service 3 weeks due to mechanical problems.

Finally, in the course 2018/19 the Product Data Management (PDM) software from SolidWorks was introduced in the project. The instructor created different roles (designer responsible, manufacturer responsible, designers/manufacturers) to coordinate the product development. A workflow was created to manage permissions and conduct first the design and functional test, ask for instructor's validation, and finally manufacture and produce the promotion material. The PDM also automatizes the creation of revisions, title blocks in drawings, and so on, so the students can learn by themselves the benefits of PDM systems in product development. Additionally, a second 3D printer based on FDM technology was provided to ensure the availability of at least one printer. This year there was no problem during the construction of the prototype and the instructor considered an adequate setup for the proposed PjBL approach.

For illustrative purposes, Fig. 2 and 3 show some of the product designs and prototypes from courses 2015–2019. Table 1 shows the main changes of the project throughout the courses 2014–2018 and Fig. 4 illustrates the evolution of the project experience in terms of complexity with the main changes per

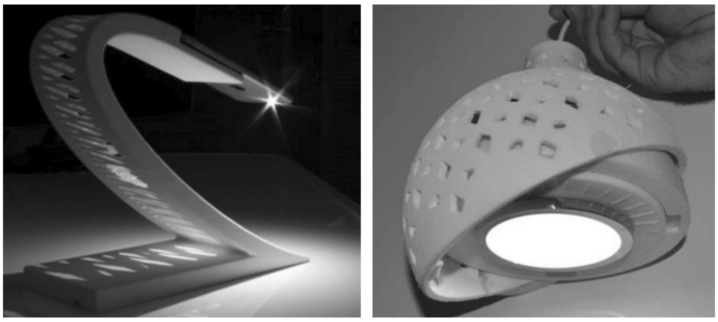

Fig. 2. Examples of product designs. Courses 15/16 and 16/17.

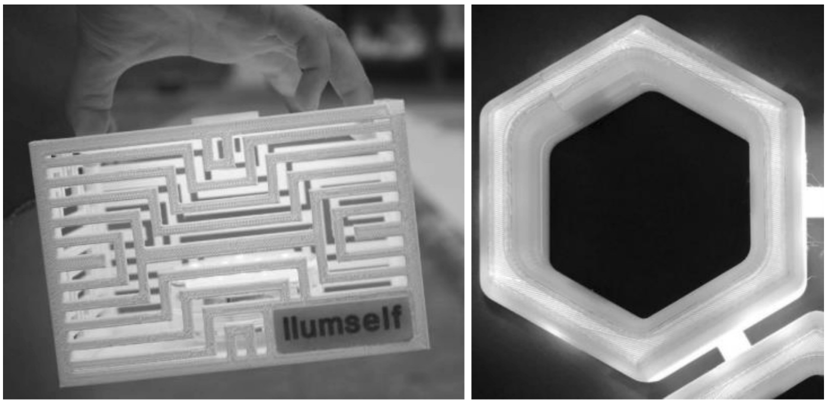

Fig. 3. Examples of product designs. Courses 17/18 and 18/19.

Table 1. Summary of project evolution and issues found along courses 2014–2018

Course	Description / Project changes	Equipment used	Issues
2014/15	No PBjL approach. Students conducted specific tasks related to each subject, without the development of a physical product.	No equipment used.	Low students' satisfaction. Tasks evaluated only through a report
2015/16	PjBL approach is introduced: a lighting product produced by 3D printing technologies should be designed, manufactured and promoted. Subjects are taught 2 hours per week.	3D printers are available only for the instructor to construct students' prototypes.	Dimensions of the parts too large. Products are based on only one part, so the purpose of assembly analysis during the prototype phase is lost. Patterns used too complex and crash issues when manipulating STL files. Instructor printed the parts, which means that the success of the project relies on instructor not students.
2016/17	Dimensions of the parts are limited. The use of multiple parts per product is mandatory.	An FDM printer is available for the students at any time.	Still crash issues due to complex patterns used in design. Coordination issues between subjects and project stage.
2017/18	Subjects are taught sequentially, according to the needs of project. Use of complex patterns is limited.	A laser engraving is added to create a logo on the product.	Unavailability of the 3D printer for 3 weeks due to extruder problems.
2018/19	A PDM software to control revision and permissions along the project was added.	A new FDM printer is added to ensure the availability of at least one printer.	No relevant issues were found.

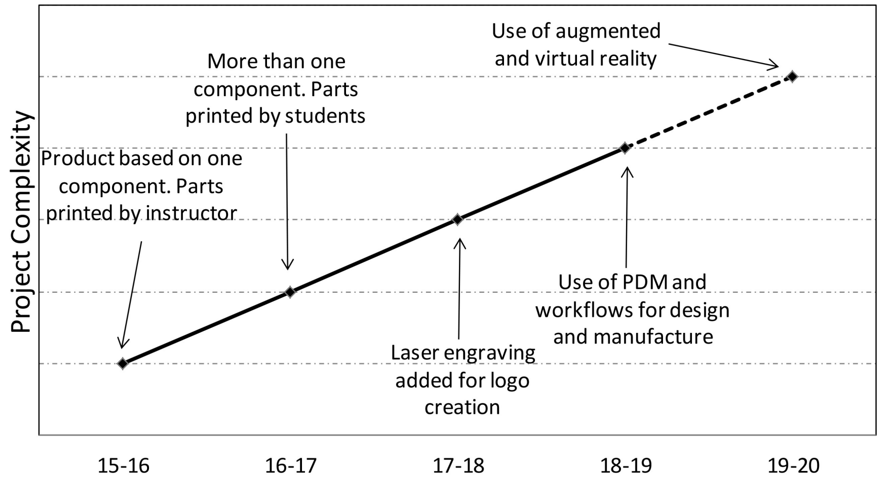

Fig. 4. Evolution of project complexity throughout the years.

year. For next courses, the instructors are planning to include augmented and virtual reality within the tools taught for product promotion.

4. Project Evaluation and Recommendations

The results from the educational experience have been compared and analyzed from course 2014/15 to course 2018/19. The results analyze different aspects such as: (i) the students' satisfaction considering the institutional questionnaire and the students' performance on both project and exam grades; (ii) the students' and instructors' perceptions on the educational experience using ad-hoc questionnaires. These results are analyzed in the following subsections and a final summary of recommendations for practitioners in similar PjBL experiences are proposed.

4.1 Grades and Students' Satisfaction

For comparison purposes, the resulting grades from both project and final exam throughout years 2014–2019 are reported as shown in Fig. 5. The course 2014/15 refers to a course previous to conduct the PjBL method proposed in this paper. At that year, the project conducted was more focused to specific tasks related to each subject, without the development of a physical product. From course 15/16 onwards, the proposed methodology with the improvement reported above was followed. As shown in Fig. 5, the improvement of students' performance at both project and exam grades increased which proves the effectiveness of the educational experience.

Additionally, the students' satisfaction on the course was compared from courses 2014/15 to 2018/19. The satisfaction index is obtained according to an institutional questionnaire which is anonymous and mandatory for all courses taught in official programs. Basically, the questionnaire deals with aspects such as satisfaction with: teaching methodology, course contents, facilities, and instructor's interaction. The final satisfaction

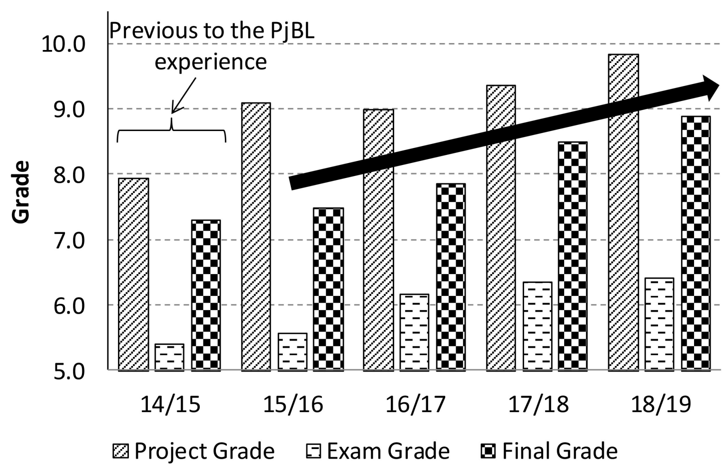

Fig. 5. Project and course grades. The grade system used is from 0 to 10.

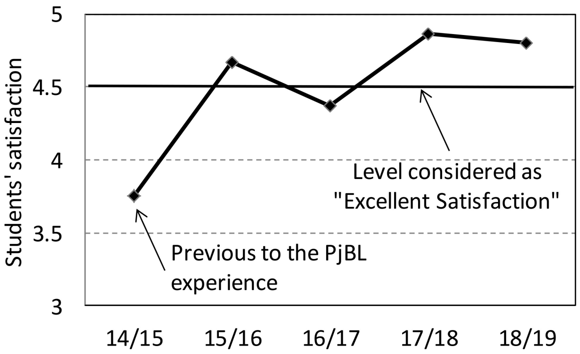

Fig. 6. Students' satisfaction according to the official questionnaire provided by the institution. The score system used is from 1 to 5.

index is an average of all aspects evaluated by the students following a Likert scale from 1 to 5. For engineering programs, an average satisfaction index of 4.5 or higher is considered as excellent satisfaction. The satisfaction values are shown in Fig. 6, and it reports the notably increase of students' satisfaction when the PjBL methodology presented in this paper was applied. As it is observed, the satisfaction results were considered excellent in three out of four academic years.

4.2 Students' and Instructors' Perception

The PjBL experience was also analyzed considering both students' and instructors' perception. On the one hand, a questionnaire about the student's opinion in relation with the project was delivered the last academic year, course 2018/19. The questions about the project were, basically: (i) degree of motivation; (ii) level of project difficulty; (iii) workload of the project; (iv) positive and negative aspects of the project; (v) potential changes for next years. The results from the questionnaire showed that 100% of the students considered the project highly motivating, the difficulty was high according to 75% of the students and the workload required for the project was within the expected hours according to the ECTS system (see Fig. 7). In relation with the open ended questions about positive and negative aspects of the project, Table 2 shows the main responses. According to the answers, the students really appreciate the project conducted where a real product is developed from conceptual design to manufacturing a prototype. The main negative aspects are the time spent in conducting physical test for validating the product, issues related to the operation of the 3D printer and common problems among students when working in group. It should be noted that despite applying the SAPA procedure for correcting the students' work on the project, the values of the SAPA form given by the students provided no grade correction. However, some students considered that working in group is not fair since the contribution and time dedicated to the project is not equal among the students. Therefore,

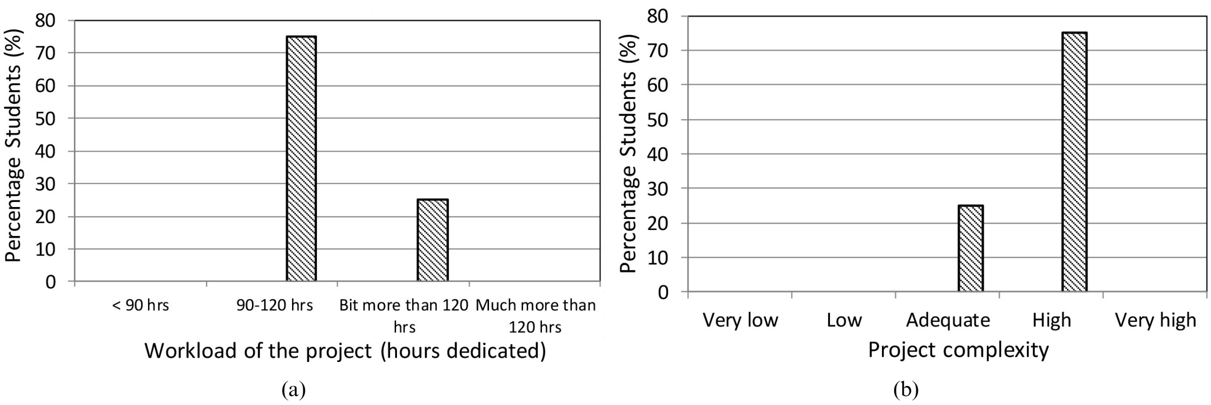

Fig. 7. (a) Results from the questionnaire related to workload of the project; (b) Results from the questionnaire related to project difficulty.

Table 2. Students' perception. Answers obtained in course 2018/19

Students' Perception	
Positive Aspects	**Negative Aspects**
• *Physical creation of our own design* • *All project phases were exciting* • *The project simulates a real product development process.*	• *Working in group is somehow unfair.* • *Limitations of the 3D printers (repeatability and tolerance issues).* • *To validate the product, too much tests with 3D printers are required.*
Potential changes in next years	
• *Increase the hours of Multimedia Tools in Industrial Design and rendering.*	

Table 3. Instructors' perception. Answers obtained in course 2018/19

Instructors' Perception	
Positive Aspects	**Negative Aspects**
• Students are highly motivated due to physical creation of their own product. • Students deal with real problems in making prototypes. • As main users, students learn the capabilities and problems of 3D printing technologies. • The implementation of the PDM into the project gives the students a real understanding of its benefits (control of permissions, design and manufacturing roles, automation of revisions and title blocks in drawings, etc.) • The learning process improves and both grades and engineering skills increase.	• Difficulties in ensuring that all members of the group contribute equally, even if SAPA procedures are used. • Delimiting the complexity of the product proposed by the students is critical to avoid problems and time-consuming tasks at the manufacturing stage. • Project progress should be closely supervised to ensure good results which means higher instructor's workload.

it seems that the students try to avoid the modification of the grades to consider the real contribution of each member of the group and they only use this tool if the situation is really serious. Finally, for the question "aspects you would change", only an increase of hours in the subject "Multimedia Tools in Industrial Design" seems to be necessary for next academic years.

On the other hand, the instructors' perception was evaluated using an open-ended questionnaire where the instructors should remark the main positive and negative aspects of the PjBL experience. The results are shown in Table 3, and it remarks the students' high motivation and the importance of dealing with real problems during manufacturing/prototyping. The instructors also highlighted the performance increase in both exam and project grades throughout the 4-year experience, but they are aware that the complexity and scope of the project should be carefully defined in order to ensure a feasibility product design. The main negative aspect was the additional effort needed with respect to other activities since close project supervision is critical to achieve a functional prototype. Furthermore, the evaluation of the contribution of each member on the project was also difficult to conduct even using the SAPA procedure. The students tend to avoid conflicts and do not penalize each other. The SAPA procedure seems to be adequate when extreme cases are presented, but moderate differences of working load among students are usually not reported within this procedure.

4.3 General Recommendations and Limitations

Finally, the instructors share the following recommendations for those interested in applying a similar PjBL experience in engineering degrees.

- The key aspect of making this experience valuable is a good delimitation of the scope of the project. For instance, a badly delimitation in size, number of parts and complexity may increase too much the effort of obtaining physically the parts without any additional contribution to the learning process. It is critical that the instructor, considering equipment, number of members of the group, and available time, delimits wisely the project to let the students work equally in all project tasks.
- The members of each group are recommended to be from 3 to 4. More than 4 students (even 3) in a group may make some students do not collaborate efficiently and fairly.
- The number of groups should be also kept low. Since this type of project requires the use of equipment (3D printers, laser engraving tools) and constant feedback from the instructors, a large number of students may make the project unmanageable. The instructors believe that less than 15 students is a reasonable limit and they pointed out that this aspect is the main limitation of the project in order to ensure the success of this learning methodology.
- Some kind of overview or monitoring is required to ensure the success of the project. For this purpose, at least a monthly seminar is recommended where the students should report the progress of the project and the instructors can guide the product design and manufacture.
- In order to ensure that the students collaborate fairly during the project, a SAPA procedure is required to compensate workload differences among students, although according to our experience this seems to be only necessary in extreme cases where one student does not cooperate at all.
- The material required (3D printers, laser engraving, and hand tools such as screwdrivers, nuts, bolts, etc.) should be available at any time and thus, possible problems should be anticipated and rapidly solved. For instance, extruder replacement due to material jams, 3D printers maintenance due to out of service, and so on.

5. Conclusions

In this paper we have shown a project-based learning experience on product development where three subjects are coordinated and sequentially taught according to the needs of the project. The project based approach has proved to increase students' performance from 7.2 to 8.9 and student's satisfaction from 3.7 to 4.8 along a 4 year experience. The motivation and engagement of the students also increased according to the quality and dedication of the resulting products manufactured by the students with a clear positive progression according to the changes proposed year by year to improve the PjBL experience. However, it should be noted that the proposed PjBL approach required an important delimitation of the complexity of the product and a close supervision of the progress of the project by the instructors. A reduced number of students (less than 15) grouped in 3–4 is also a key aspect for a successful project.

The author encourages the adoption of this type of PjBL experiences in mechanical and design degrees where the students can develop a product from conceptual design to manufacturing (prototype), allow them to validate, test and manufacture their own designs using low-cost 3D printers equipment.

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