Project-based learning approach: improvements of an undergraduate course in new product development

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Abstract

Product development is considered as an interdisciplinary undergraduate course with a central role in engineering education. In this sense, this paper demonstrates an experience of a product development undergraduate course based on a project-based learning (PBL) perspective. PBL has been discussed in the literature as one of the most effective teaching frameworks for engineering courses, but there is still scarce research on PBL implementation in engineering education in developing countries. The course scope was reviewed to include engineering management content and to face some barriers for PBL implementation highlighted in the literature. The student activities were organized in four development phases following a structured stage-gate development process. The results achieved include a higher level of learning perception and increased complexity of products generated by students. Besides demonstrating the improvements in the course, this paper contributes to PBL empirical body of knowledge by exploring a successful initiative and its outcomes.

Keywords

Engineering education. New product development. Design process. Project-based learning. PBL.

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1. Introduction

Engineering education remains similar to that practiced in the 1950's, with the lecture-based approach dominating the educational methodologies, presentation and teaching in most engineering courses (Baytiyeh & Naja, 2016; Palmer & Hall, 2011). However, nowadays engineers are expected to solve more complex problems that require them to be able to develop questioning and critical thinking skills (Li & Faghri, 2016), as well as the ability to communicate effectively and work on multidisciplinary teams (Baytiyeh & Naja, 2016). Industry requirements for engineering graduates have evolved, and demand changes in the educational approaches used (Uziak, 2016). More contextualized, autonomous, interdisciplinary learning and student-centered process can contribute to a more effective learning process (Lima et al., 2007), providing students with experiences that are similar to what they will encounter in the working world (González-Marcos et al., 2016).

With the Bologna Declaration, all European universities started using new active teaching and learning methods to help their students be successful in their professional careers (Terrón-López et al., 2016). The Bologna process has been driving forward the most important reforms in higher education in the modern era, which has implied many changes in the curriculum, structures, and educational paradigm (Alves et al., 2016). In this context, the Project-Based Learning (PBL) is one of the active learning approaches which have become very popular within Engineering Education (EE), due to its positive impact on students' learning and engagement (Alves et al., 2016). Project-based learning is a method centered on the learner. Instead of using a rigid lesson plan that directs a learner down a specific path of learning outcomes, project-based learning allows in-depth investigation of a topic (Grant, 2002). The method has been discussed in the literature as one of the most effective teaching frameworks for engineering courses (Carpenter et al., 2016). Learning under this approach occurs via developing cognition (critical thinking), skills (e.g. teamwork, good oral and written communication, time management, etc.), and attitudes in the students (Terrón-López et al., 2016).

Many successful cases of PBL implementation in EE have been discussed in the literature (e.g. Li & Faghri, 2016; Song & Dow, 2016; Terrón-López et al., 2016), but most of them in European Universities, due to the requirements of the Bologna Process. In developing countries, the application of PBL in EE is still little addressed. However, the economic growth in developing countries enhances a demand for a multidisciplinary background of professionals in technology-related areas, and demands for reforms on current teaching methodologies used in degree programs (Ferreira et al., 2015). In this sense, this paper aims to describe the experience of PBL implementation in a university located in an emerging economy (Brazil). The paper focuses on the experience of the course "Product and Process Design" offered by the Polytechnic School at the University of São Paulo. The course is part of a curriculum of a five-year production engineering undergraduate program, and it is delivered during one semester (around eighteen weeks, depending on the academic calendar). The implementation of PBL in the product and process design course has enhanced the learning process and may bring benefits for the country as new engineers may be better prepared for the industrial environment. Indeed, employers recognize that PBL education is important, and it allows graduates to work from day one (Edström & Kolmos, 2014).

In fact, product development is a key topic for many engineering courses and educational programs (Fredriksson et al., 2014), and is a core competency requested in the job market of engineers. The engineering undergraduate education for product development, however, faces two main challenges. Firstly, whereas product development in the industry is highly interdisciplinary, most undergraduate engineering courses are tied to a specific university functional department and therefore have a main subject emphasis. Secondly, product development practice in industry demands not only knowledge of specific methods and tools, but also a complete view of the information flow that enables ideas to be developed into real products. The lack of an overall picture also hinders the multidisciplinary view, as students work mainly in isolated tasks. Project-based learning is the most-favored pedagogical model for teaching design (Dym et al., 2005), and it allows students to relate disciplines to each other in the problem-solving process (Edström & Kolmos, 2014). Thus, PBL is suitable to address the challenges associated with the product development course.

Moreover, the implementation of product design activities in the engineering curriculum is an arduous initiative in the context of developing countries due to due local constraints, like the shortage of financial and skilled human resources (Kojmane & Aboutajeddine, 2016). The exploration of PBL implementation in the analyzed context, therefore, aims to contribute to the empirical body of knowledge by demonstrating PBL successful implementation in a developing country involving a product design course that is one of the most important courses in EE. In developing economies, there is a higher need for problem solvers, critical thinkers, and independent learners given that the industrial sector is under development (Khalaf & Newstetter, 2016). Thus, improvements in engineering education in those contexts are of paramount importance. In addition, since it has been pointed out in the literature that there is a lack of evidence in research on the short-term and long-term effectiveness of PBL approaches (Alves et al., 2016), the paper intends to contribute to the body of knowledge in this sense by exploring student opinions (short-term) about the new learning method. Exploring the implementation of PBL also contributes to the empirical body of knowledge in the national context, because in Brazil the traditional teaching methods are still applied in engineering courses (Santos, 2003), and it has been recognized that it necessary to replace these models with others that enhance learning in the country (Santos, 2003; Silva et al., 2016).

The remainder of this paper is organized as follows. After this introduction, the next section presents a brief literature review on PBL. Section 3 describes the course structure and content. Section 4 presents some examples of projects conducted and an analysis of results achieved. This includes an analysis of how some of the main barriers to PBL implementation in engineering courses reported in the literature were overcome. The impact of PBL on the pedagogical experience of the students is also briefly discussed at the end of the section. Finally, Section 5 draws the conclusions of this work.

2. Project-based learning: a brief review of the literature

Project-based learning can be defined briefly as 'a model that organizes learning around projects' (Hugerat, 2016). Thomas (2000) identified a set of criteria to capture the uniqueness of PBL. According to the previously cited author, PBL projects: (i) are central, not peripheral to the curriculum; (ii) focus on questions or problems that drive students to encounter (and struggle with) the central concepts and principles of a discipline; (iii) involve students in a constructive investigation; (iv) are student-driven to some significant degree; and

(v) are realistic, not school-like. In PBL, students go through an extended process of inquiry in response to a design question, a problem, or a challenge that usually requires more than an individual effort to handle and overcome (Chua et al., 2014).

In terms of advantages of the PBL approach, learning by means of a project is likely to increase motivation (Fernandes et al., 2014), and give the students a sense of satisfaction, it is helpful for developing long-term learning skills (Edström & Kolmos, 2014), to develop deep, integrated understanding of content and process, it allows students learn to work together to solve problems, and it promotes responsibility and independent learning (Chau, 2005; Chua et al., 2014; Frank et al., 2003). PBL also contributes to bringing the classroom close to the profession through the acquisition of knowledge while solving practical and real cases closed to the professional world (Terrón-López et al., 2016). In fact, PBL works to integrate and apply (Song & Dow, 2016): (i) structured new knowledge covered in the course, (ii) knowledge learned in other courses, (iii) prior life experiential based knowledge, and (iv) new self-taught knowledge.

PBL models present a number of characteristics (Graaff & Kolmos, 2003). According to the previously cited authors, in general, the curriculum is structured in thematic blocks and disciplines are integrated through relating the case to professional practice. The learning process focuses on self-directed study groups that discuss and analyze selected cases (Graaff & Kolmos, 2003). The role of professors is mainly to facilitate the learning process; they assist students to understand the project problem, develop potential solutions, apply solutions to meet specifications and criteria, and when possible to construct new knowledge (Chua, 2014). Moreover, the assessment methods should be compatible with the learning process (Graaff & Kolmos, 2003). Team work and assessment of team work are important issues related to project approaches (Fernandes et al., 2012).

There are many examples of the application of PBL in higher education. In the case of engineering courses, PBL does address one of the key components of engineering competence development, i.e. the ability to extend what has been learned in one context to other new contexts (Dym et al., 2005). The design is considered as one of the central functions of engineering practice, and project-based learning is a well-known methodology for engineering design education (Palmer & Hall, 2011). The achievement of evaluative skills critical in the design methodology is challenging; students should recognize that design involves a range of decisions with the validation of assumptions and justification of choices made (Kunberger, 2013). In fact, it is expected that students practice the design of solutions under realistic conditions (Dym et al., 2005), and PBL is valuable for that; however many engineering curricula are still predominantly based on the traditional model that is heavy in mathematical analysis, and where design, if present, is often segregated (Palmer & Hall, 2011).

Although PBL has been discussed as valuable for engineering design education, PBL experiences also entail certain difficulties that can lead to educational gaps and imbalances when considering each stage of PBL (i.e. planning, organization, development and assessment), including (Lantada et al., 2013): (i) designing projects that properly reflect how the subject evolves, preparing questions of equivalent difficulty, (ii) planning projects to fit the time allocated to the subject, (iii) searching for realistic approaches, (iv) setting milestones throughout the process, (v) taking action to adapt students' starting-out levels, motivation and follow-up to avoid deviations in the results, (vi) setting an adequate system to evaluate knowledge, etc. Those issues should be addressed by professors in many fields of engineering who wish to apply this kind of teaching strategy and design specific actions for their subjects (Lantada et al., 2013).

Moreover, some studies have evaluated the impact of project-based education on students' learning processes and outcomes (e.g. Carpenter et al., 2016; Fernandes et al., 2012; Holmes & Hwang, 2016; Lima et al., 2007; Song & Dow, 2016; Terrón-López et al., 2016). Nevertheless, there is a limited number of studies that explore PBL implementation in developing countries and the respective outcomes (e.g. Du et al., 2013; Hugerat, 2016; Xu & Liu, 2010), and that also report how the main challenges associated with PBL implementation in EE have been overcome. Thus, this study focuses on PBL implementation in an emerging economy (Brazil), and how the course was structured to overcome some implementation challenges. Next section starts presenting the proposed PBL approach in the analyzed course, providing an overview of its structure and content.

3. Overview of the proposed course structure and content

The "Product and Process Design" course under analysis remained until 2004 around design activities, with a strong emphasis in mechanical engineering technology. Between 2005 and 2012, a progressive course improvement initiative was conducted to expand the approach in order to consider a holistic perspective, from idea generation to final product prototyping, including engineering management content. A specific product development reference model was selected to be applied. The selection of the reference model aimed to obtain a deeper learning through the application of active methods. The selection of the reference model considered mainly two criteria. Firstly, a detailed description of the reference model should be available for teaching purposes, as many as of such models might contain companies' rights and confidential information. Secondly, the model should encompass the methods and tools and the engineering management perspective needed for the course. As a result, a reference model for a new product development proposed by Rozenfeld et al. (2006) was selected to compose the undergraduate course backbone.

The selected product development reference model is structured in three macro-phases: (i) pre-development, (ii) development, and (iii) post-development. The pre-development macro-phase involves strategic product planning (portfolio definition) and individual project planning. The development macro-phase encompasses five phases, including: (i) informational design, (ii) conceptual design, (iii) detailed design, (iv) production preparation, and (v) product launch. The post-development macro-phase includes activities needed to monitor, improve, and discontinue the product after it has been launched in the market. The process is structured in stage gates, defined as milestones in which design results are completely reviewed (Cooper, 1993). Figure 1 presents the reference model overall structure. For each phase, it is available a detailed description to which specific methods and tools are applied (Rozenfeld et al., 2006).

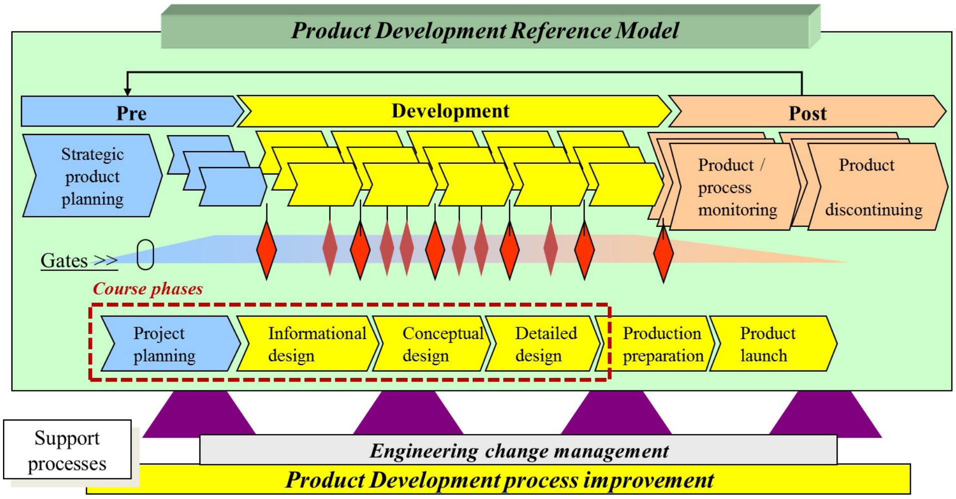

Figure 1. Overall structure of the product development reference model selected for the course (Rozenfeld et al., 2006).

Whereas the reference model addresses the complete life cycle view, from idea generation to end of life, the "Product and Process Design" course focuses mainly on four phases (see dotted box in Figure 1): (i) project planning, (ii) informational design, (iii) conceptual design, and (iv) detailed design, which conduct to a functional prototype construction. This delimitation is needed since actual production preparation activities such as tooling fabrication and factory layout modification in addition to a real product launch are not possible to be conducted considering the course current timeframe and scope. These additional topics, such as factory layout, are covered by other courses.

Within the selected business process activities, methods and tools are applied to support the design process. In fact, during the past decades, several of those methods have been widely discussed. They can be found either in specific publications (e.g. Akao, 1990; Taguchi, 1993). Among several methods and tools for product design that have been described in the literature, many of them contribute to some extent to a more effective design process. The following sections present more details of the current course structure, including the educational methodology applied, the development phases and stage gate report content.

3.1. Educational methodology

During the entire semester, teams of about five students structured at the beginning of the course conduct a product development project from idea generation to prototyping, following the business process reference model activities proposed by Rozenfeld et al. (2006). The course progress is therefore bound to the reference model content, which is delivered twice a week in two-hour lectures held between each stage gate report delivered by the teams. A package of activities is developed and delivered at the end of each stage. Gates are decision points to check whether the activities were performed, aligned with the phase. Each team is responsible for one development project, from idea identification, through market analysis, conceptual design, detailed design, and final physical prototyping. The course also has an integrative role within the whole undergraduate program, as it applies concepts from other courses such as introduction to mechanical design, industrial cost accounting, quality assurance and control, and factory planning. Teaching activities involve lecturers and mainly the continuous development of the project. The proposal is an attempt to integrate different areas of knowledge. It is a course replicating traditional industry practices by including elements of engineering design and management.

The main course task for students is to develop the practical project, whereas lectures serve as a source of information and discussion panel to provide the necessary information, methods and tools while students develop their own practical project conducting the business process activities, similar to the findings of Reeves & Lai-Yuen (2010). The total time the students spend in the classroom weekly is four hours (two-hour class twice a week). It is expected the students to work on the projects at least four more hours outside of the class per week. As stated by Thomas (2000), PBL incorporates more student autonomy, unsupervised work time, and responsibility than traditional instruction and traditional projects.

The students are in the first semester of the fourth year (it is a five-year engineering course). The students in this phase already have experience, which is important because it has been stated in the literature that the PBL approach works well with students who already have a deep conceptual knowledge of the subject matter (Holmes & Hwang, 2016). However, some studies have also demonstrated that PBL can be an effective strategy to avoid dropout and underachievement problems usually faced by first-year engineering students (Fernandes et al., 2014). Its implementation in the fourth year, nevertheless, may bring benefits in terms of the level of knowledge students already have, obtained from previous courses. Although the course is offered in the fourth year, there are no formal course prerequisites. A fixed stage gate schedule is defined upfront at course beginning (Figure 2), and it serves as a milestone definition for teams.

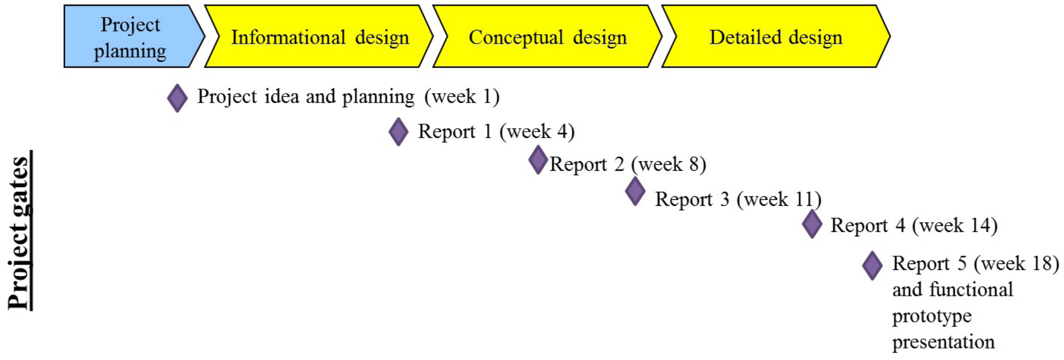

Figure 2. Course schedule and stage-gate milestones (reports) related to business process phases (may vary slightly depending on the year's calendar).

Since every team should follow the same schedule, project complexity in terms of technical feasibility and number of items in the product structure should not differ too much between project teams. The idea generation by students and its evaluation by the faculty is, therefore, a critical step to balance team effort. The idea is usually developed by the students considering consumers and market needs, e.g. (i) a need not yet or poorly fulfilled by a product, (ii) a need fulfilled by an old product technology and design, or (iii) a need fulfilled by a high-cost product. In addition, students are also encouraged to develop a product that has social or environmental positive impacts. This is aligned with the principles of PBL stated by Thomas (2000), in the sense that PBL projects are focused on questions or problems that 'drive' students to encounter and the projects are student-driven to some significant degree, i.e. the students develop the product idea. At the end of week 1, the teams present their project ideas, which are then assessed by faculty in order to balance project effort. Since the definition of questions with equivalent difficulty for all teams has been reported as a barrier to PBL implementation (Lantada et al., 2013), the assessment is performed carefully by the lecturers.

Afterward, the development of the product idea starts following the activities defined in the product development reference model. Each new development phase (i.e. informational design, conceptual design, and detailed design) is kicked off with a lecture focused on providing the overall view of the entire phase and deliverables required. The lecturers focus on specific method and tools (e.g. DFMA – Design for Manufacturing and Assembly), and discuss how to apply these methods and tools on practical team projects. At each phase, when possible, one lecture on average is provided by a professional from industry in order to provide the industry view of the phase, and on specific methods and tools applied by industry during this phase. In addition, in semesters with a lower number of industry lectures, students are encouraged to seek for industry feedback from various stakeholders, including potential suppliers. As an example, students frequently seek for support from plastic parts suppliers to check for the feasibility of their plastic parts design and volume estimates. The professor supports the identification of potential practitioners from industry. In fact, it has been stated that project-orientation especially with industry involvement may have a clear positive impact on students' problem-solving skills and student motivation (Daun et al., 2016), and for this reason the involvement of the industry in the course became one of the goals of the PBL program. The integration between companies and the university is also important for professionals in those companies be aware of the solid training received by the students, which may result in an increase in the employability of the students (Terrón-López et al., 2016).

As the development is being carried out, technical and managerial reports should be delivered by teams at the defined stage gate milestones to document results from each development phase, including decisions reached considering market needs and technical possibilities. Reports should demonstrate the application of design method and tools appropriate for the design phase under development. Since there is no agreement on how to integrate different dimensions of learning, knowledge, skills, etc. (González-Marcos et al., 2016) a continuous assessment was adopted. A feedback document is issued by the lecturers for each group report in order to review its contents for the final project brief. The feedback document is reviewed with each team in feedback sessions. This is also important in order to continuously provide insights from the lecturers (Alves et al., 2016).

In order to have exposure to more input and references, project teams have free access to project documentation from previous years. This simulates the actual situation at the industry level – and project teams may use previous experience – and also encourages continuous improvement based on existing knowledge. Providing access to example projects from other courses is a way of showing the stages to be followed and what is expected of them, being important to stimulate them to work (Lantada et al., 2013). The best project's reports of each year are available online on a course-specific internet platform. As the product is being developed, a prototype is constructed considering the main product attributes regarding product dimensions, functionality and, in most cases, a simulation of its operation.

To motivate students, best projects receives an award at the beginning of the following semester, in order to show to the students that are starting the course the best projects from the last semester and motivate them to work. The award ceremony is conducted through a partnership with a company (Procter & Gamble). The selection procedure of the best projects varied across the years, with different procedures being experienced. In most of the years covered by this study, the top twelve projects selected by the lecturers based on the final project grade were sent to professionals from Procter & Gamble (usually marketing and product development professionals) in addition to three more faculty members in order to be assessed. The six best projects were then selected to be presented during the award ceremony in which the best three projects were elected. In other years, the projects to be presented at the awards ceremony were selected as a result of their superior deliverables grading during the course. It is worth mentioning that this is not only a technical presentation, but it also has a strong marketing emphasis to 'sell' the product for the evaluators and the audience, stimulating the development of other skills. This is a positive aspect, because is this way, as in the professional world, team competitiveness is promoted (Ríos et al., 2010). Next section provides more details about the project development process.

3.2. Development process phases and content of stage gates reports

The development follows the four phases defined by the business process reference model (Figure 2), which integrates concepts associated with marketing, engineering, and production. The consideration of the four phases of the reference model (from the market research and product planning stage, up to the preproduction stage, that is, working from the general to the particular) is valuable to ensure a sufficiently complete PBL experience, as recommended by Lantada et al. (2013). Each phase encompasses a set of activities which are summarized next.

The project starts with idea generation and analysis on how the product could fulfill market needs in a given segment. To do so, concepts related to creativity, market target analysis, and segmentation must be considered. Consumer interviews and surveys might be carried out to identify needs. Consumer requirements are deployed in technical requirements resulting in target technical specifications. One of the outputs of this phase is a first product draft (usually a sketch).

Then, an initial product functional analysis is carried out in addition to a check if customer requirements are met. A benchmarking study is also conducted to compare the proposal to other existing products or functions from similar products. Technical solutions for each functional challenge are selected, and product architecture is established. Based on product architecture, a first and second level product structure is defined. At the same time, product drafts are refined. Critical materials for main parts are pre-selected. DFMA activities can be implemented at this early stage to guarantee manufacturing and assembly effectiveness.

The next phase involves the detailed development, including the refinement of the product structure to include all product items. Detailed product specifications are defined. In addition, aspects of manufacturing and assembling should be detailed (process planning, tooling, etc.) as well as quality control points. Production scale and sales volume should be defined based on consumer and market segmentation from the previous stage. Critical design and manufacturing points should be analyzed through FMEA (Failure Mode and Effect Analysis). Other aspects such as packaging and distribution are also defined. A technical and an economical product assessment is performed. Product costs are calculated and compared to estimates developed at early development stages. Value engineering may be used to support this analysis. If necessary, a cost reduction is proposed as well as the opportunities for improvement are identified to retro-feed the new product development. The project is concluded by delivering a prototype as close as possible to a functional product. The final stage is revised by having the award ceremony where the students have 'to sell' the product to the practitioners from industry.

Until 2012, five reports were due according to the project schedule (Figure 2), to record all the achieved results. The reports monitor the development of a given product according to the product development cycle. The report contents are summarized in Table 1.

Table 1. Content of each stage gate report.

Report	Stage gate report content
1 – Informational design	• Market definition • Customer needs identification • Technical requirements and target specifications using Quality Function Deployment (QFD) • Product sketch
2 – Conceptual design part 1	• Functional analysis • Product draft • Differentiation study • Distribution channels • Product market value
3 – Conceptual design part 2	• Product structure (first 2 levels) • Main materials • DFMA documentation • Macro process plan for final assembly
4 – Detailed design	• Product structure – complete bill of materials • Blueprints • Specification of standard and outsourced components • Process plan and tooling • Product and process FMEA • Quality control plan
5 – Final report	• Packaging • Product cost analysis • Functional prototype

The PBL approach was designed to overcome some of the main barriers outlined in the literature when implementing it and to achieve better results when compared to the conventional methods. Next section presents some results of the experiences with PBL, provides an overview of the program structure to overcome the main barriers, and discusses some positive outcomes.

4. Results and discussion

The products developed are quite diverse. They involve different technologies, materials as well as manufacturing processes. There is a prototype for all of them, which simulate product concept and functionality. One example of a product developed when the first efforts to improve the course were carried out is shown in Figure 3.

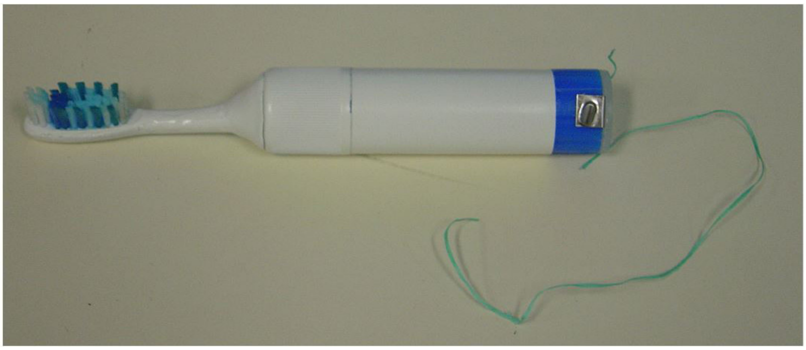

Figure 3. A prototype developed by a team in 2005.

The product, called "tube", is a toothbrush that includes toothpaste and dental floss, conveniently developed for traveling, camping, etc. Most parts are made of plastic (high-density polypropylene). The engineering drawings for all components were developed as well as the respective manufacturing process, including process flow, equipment, tools and dies, and quality control devices. All specifications were based on a given volume production obtained through a market estimate (based on market research conducted in a specific segment). Throughout the product development, a number of methods and tools have been applied, including QFD, Functional Analysis System Technique (FAST), FMEA and value engineering.

Another example focuses on a product developed during the latest course improvement round (2012). The product is a modular food plastic container kit (multiple containers) with a novel functionality to measure food level inside the containers and provide this information to the users on their smartphones. The goal is to allow users check the need for a specific item as they are shopping around. The development involved multiple engineering disciplines, including mechanics, electronics, and software. Figure 4 presents a sample of project team deliverables during the development phases as a result of the application of specific methods and tools, such as QFD and DMFA. The final product documentation report provided all the information needed to manufacture and distribute the product, including manufacturing process plan, quality control plan, and packaging. A product prototype was built based on the Arduino open-source electronics prototyping platform, and the software was developed for the Apple iPhone. The prototype also included parts manufactured using additive manufacturing (3D printer). The customer can choose to use one or multiple containers from the modular container kit and the software displays the content level information for each container individually.

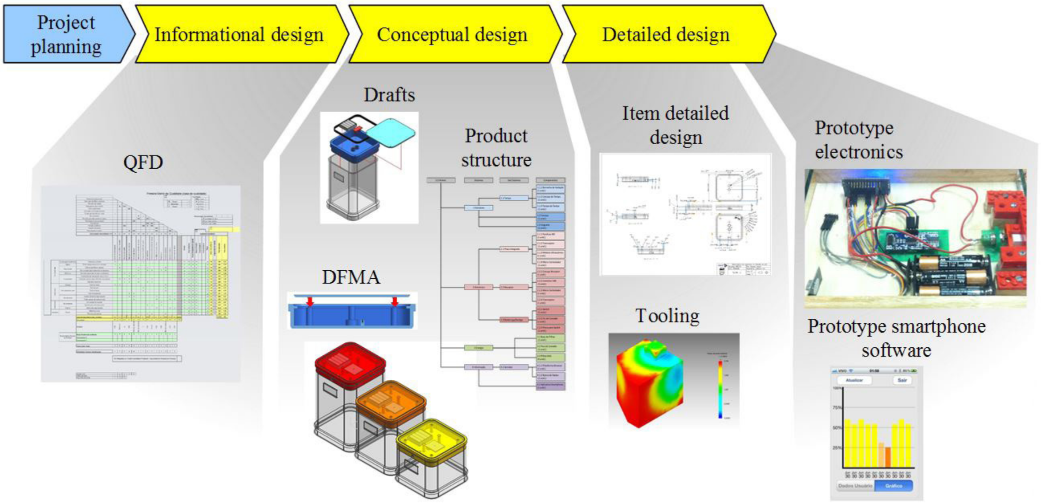

Figure 4. A prototype developed by a 2012 team.

The course has evolved from the past years. A more recent calendar of the course (2015) is showed in Figure 5. It presents the main course phases and students' deliverables.

As can be seen in Figure 5, the course structured is similar to the phases showed in Figure 1 (i.e. informational project, conceptual design, and detailed project). Reports R1 to R4 are due on each of the "gates" for phase progress. Exceptionally, R2 is an intermediary "gate" to avoid an excess of work to progress to the final concept (R3) without an intermediary verification. In terms of deliverables, the course requires eight deliverables. More important than the number of deliverables is their type and nature. The course demands five technical reports, one prototype, and two presentations. An updated description of students' requested deliverables pictured in Figure 5 is presented in Table 2.

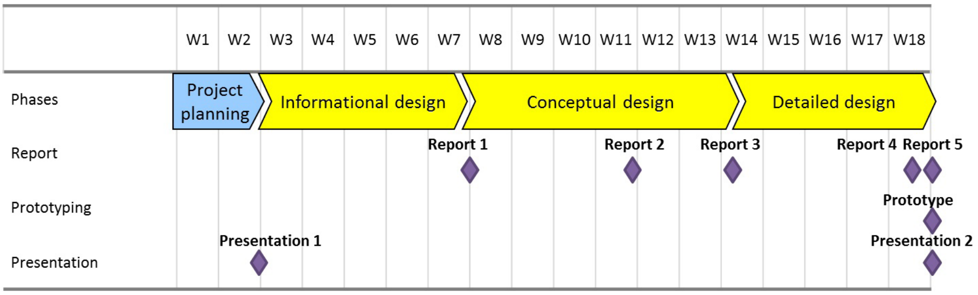

Figure 5. Course schedule (2015).

Table 2. Description of students' deliverables.

Deliverable (according to calendar)	Content description
Presentation 1	• Problem to be addressed • Hypothesis for market demand • Project briefing
Report 1	• Market segmentation and focus • User needs • QFD matrix – product requirements • Preliminary sketches
Report 2	• Technical benchmarking • Commercial benchmarking • FAST (Function Analysis System Technique) Diagram • Product concept draft • Distribution and logistics strategy
Report 3	• Product assembly draft • Product structure (preliminary) • Materials selection • Design for Assembly and Manufacturing (DFMA) • Macro manufacturing process planning (for critical items)
Report 4	• Technical drawings • Sourcing specification for buying items • Manufacturing process planning and tooling • Product FMEA and process FMEA • Quality control plan
Report 5	• Executive summary • Final items from R1-R4 • Product costing
Prototype	• Functional Prototype
Presentation 2	• Final solution presentation

The course follows a linear approach, and it is offered once a year. Students commit earlier (between weeks 7 and 11) on a conceptual solution that is progressively detailed through the conceptual project and detailed project phases. A final prototype is presented at the end of the course, as a recent project illustrated in Figure 6. The product is a low-cost rain gauge, and the prototype involves the development of all mechanical

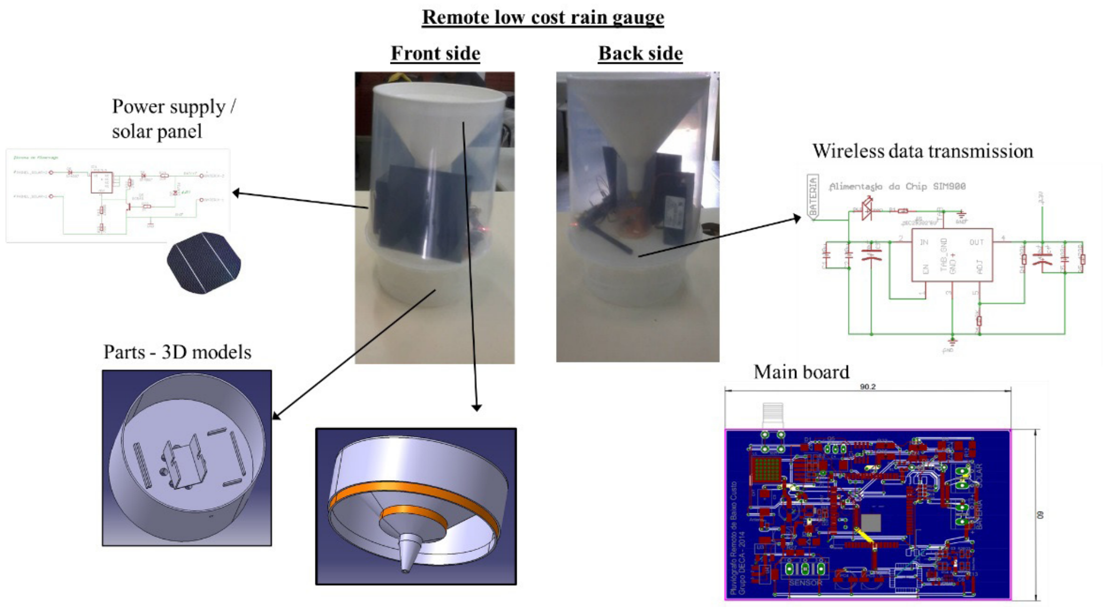

Figure 6. A prototype developed by a team (Bacarin et al., 2014).

and electronic components. The components that constitute the products are (i) plastic parts (body and filler), (ii) power supply system (solar panel), (iii) data acquisition and transmission systems, and (iv) electronic board. The students worked in all component development processes, and a range of tests was undertaken.

Table 3 summarizes the main course characteristics and demographics from February 2014 to July 2015. During this period, the product and process design course had a total of 141 students working on 28 different projects.

Table 3. Course characteristics and demographics (from February 2014 to July 2015).

Course characteristics	Main figures
Semester offerings analyzed – semester/year (number of students)	2014 (69) 2015 (72)
Multidisciplinary prevalence	Monodisciplinary
Number of engineering majors represented	5
Engineering students' most frequent major: number of engineering students in most frequent major (% of total)	Industrial engineering: 127 (90.1%)
Number of non-engineering students (% of total)	1 (0.7%)
Average students' semester cohort (std. dev.)	7.4 (2.5)
Average team size (std. dev.)	5.0 (0.4)

There are, actually, a number of problems and difficulties that may affect PBL experience in engineering courses reported in the literature. Table 4 summarizes the strategies adopted when the PBL was structured to overcome some of the main barriers reported by previous studies (e.g. Lantada et al., 2013).

Regarding the planning and organization phase, the coverage of all development stages was assured by the adoption of the reference model that guides the process and involves all relevant phases of product development. In addition, to guarantee that all PBL experiences arisen are equally complex and require similar efforts, each idea developed by the teams (to fulfill real market needs at the same time that should be feasible for students) is carefully assessed by the lecturers. The reports and activities are planned carefully following the stage gate schedule to fit the time of the course. The activities are also planned considering the total time the students spend in the classroom and considering pre-determined additional working hours outside the class. With regards to the development phase, the design results are reviewed at the gates. For a development free of unforeseen events, the interim milestones are clearly defined with planned dates. The feedback sessions allow students to

Table 4. Main difficulties and problems of PBL and solutions adopted to achieve success.

Stages	Main factors that can limit PBL experiences (according to Lantada et al., 2013)	Actions taken
Planning and preparation	Designing projects that properly reflect how the subject evolves	Use of a reference model in the development process that covers the main phases of the product development process going from the general (market analysis) to the particular (prototype)
	Preparing questions of equivalent difficulty	Careful assessment by faculty at the beginning of the course to ensure that the project proposals have similar complexity and require similar efforts (e.g. the number of items in the product structure should not differ too much between project teams)
	Planning projects to fit the time allocated to the subject	Project activities are planned considering the gates structure of the reference model. A fixed stage gate schedule is defined
	Searching for a realistic approach ('real' projects) but feasible for students	Students should consider market and customers needs, following when possible sustainability principles
Assignment and organization	Project coordination and time scales compared to other experiences in other subjects	The activities are planned in a way that is possible to students perform them over the semester, considering the students will work at least four more hours/week outside of the class
Development	Setting milestones throughout the process	The development process is structured in stage gates, defined as milestones in which design results are completely reviewed
	Taking action to adapt students' starting-out levels	All students are in the same course level (first semester of the fourth year), and although there are no formal courses prerequisites the knowledge necessary involves topics they studied in previous years
	Motivation and follow-up to avoid deviations in the results	Feedback sessions are structured to work as design review sessions after each stage gate to help students improving the project
	Motivation and follow-up to avoid deviations in the time scales	The partial reports required in the gates were structured to avoid delays during the project development
Assessment	Setting a diagnostic assessment system to find the starting-out level	When the teams present the ideas in the first week, faculty evaluates the level and establish a common basis and difficulty level to all students
	Setting an adequate system to evaluate knowledge	There is a continuous assessment as well as assessment of projects' process and results
	Setting an adequate system to evaluate skills	Skills are evaluated regarding the projects' development process (team work) and also an individual assessment is carried out (which includes written tests, practical exercises, presentations)
	Setting an adequate system to individualize group experiences	Students present the ideas in the beginning of the semester and the final projects at the end of the semester. Individual feedback is given after they deliver the reports in each stage gate. Exams are applied at the end of the semester and students should state aspects of their projects related to the theory of the product development process
	Detecting and controlling unacceptable conduct (e.g. copied projects)	Students have access to the projects developed in the previous courses. Each team develops a different project in order to avoid copied projects
	Use of questionnaires to assess the progress of the experience and possible improvements	At the end of the semester students are asked about their experience

improve the projects. The required reports that should be delivered at the defined stage gate milestones intend to avoid delays and deviations in the time-scale.

Concerning the student evaluation, a continuous assessment as well as an assessment of projects' process and results is carried out. Thus, student assessment focuses not only on the product, but also on the learning process (Fernandes et al., 2014). Students' evaluation is divided into two groups of grades: they have project grades and individual grades. Each student receives 15 grades during the course; eight are individual and seven are related to the evaluation of the team project. The individual grades represent 40% of the final grade and the project grade is equivalent to 60% of the final grade. Of the individual grade (40%), 20% is regarding students' evaluation related to the project (specific aspects of each phase of the product development process following the reference model), and 20% is related to a final exam. In the written test, students are asked about aspects of the theory of product and process development to be explained considering their projects. This is important in order to encourage all those in the group to really take part in the project and avoid any personal conflicts arising from any members trying to take advantage of other students (Lantada et al., 2013). Students develop a range of skills related to teamwork and project management. The delivery of a set of reports in each gate and presentations to the faculty during the semester, allows to avoiding problems when evaluating the knowledge and skills developed and controlling students conduct.

Regarding the final project assessment and award, as mentioned before, students receive grades concerning each project development phase, following the reference model. In many years, the final evaluation of projects selected for the award ceremony occurred by a first screen selection by the faculty of the twelve best projects. Those were then evaluated by a committee of three other professors from the Production Engineering Department. The six best projects according to the committee evaluation were selected for oral presentation in a specific award event. In this event, members of industry, the faculty and the other professors that were members of the committee selected the three best projects. In the last years, however, the process has changed. Only the faculty evaluated the projects in order to ensure that the same criteria are applied to the evaluation of all projects.

Moreover, in order to analyze students' satisfaction level with the learning experience provided by the course, surveys are conducted with the students at the end of the semester. In the last survey applied after the improvements in the course - based on Net Promoter Score methodology - NPS (Reichheld, 2006) - students were asked to answer "How likely is it that you would recommend the course as a positive learning experience to a colleague at the University?" on a scale from 1 to 10. Among 32 respondents of one class, 78% ranked equal or higher than 7, demonstrating a moderate to high level of satisfaction with the overall course experience. Among them, 34% ranked 9 or 10, which can be considered as enthusiastic students.

Students were also asked open-ended questions to indicate both positive aspects as well as improvement needs for the course. Current course structure after the improvement cycle most cited positive aspects were: (i) the project work, linked with the business process and the report structure at the stage gates; (ii) feedback sessions that worked as design review sessions after each stage gate; and (iii) availability of design tools (software). Most cited improvement needs were: (i) demand for a longer time available at project beginning for project idea definition; and (ii) availability of additional fabrication tools at fabrication shop floor to support prototyping. Those improvement opportunities based on the survey feedback generated adjustments, which is now being carried out. It is also worth mentioning that one challenge faced by faculty during the course is the difficulty some students face to understand the business process situations and nuances, as most students have only limited industry experience.

Having presented the results, next section outlines the main conclusions of this work.

5. Conclusions

The course takes a new look at what design really is and proposes an approach which makes changes in the way students learn about design, by introducing a holistic perspective. In addition to providing an opportunity to reflect and develop - in practice - the major topics discussed in the course, the PBL approach also permitted students to work in a team environment to produce a deliverable in the form of a functioning product prototype.

The proposed teaching approach demonstrated to be efficient to tackle with two of the challenges faced by engineering undergraduate education for product development, as discussed earlier: the need to foster interdisciplinary work and to provide a complete view of the information flow that enables ideas to be developed into real products. Idea generation and customer need analysis at early development stages are structured to cover the entire integrated solution for the potential customer, not being restricted to a given engineering discipline. This has been resulting in product developments that embody multiple disciplines, including mechanics, electronics, and software. By following the process activities based on the selected reference model, students get an overall view of the whole effort to develop the product. The integration of several engineering disciplines, management, and industry practitioners, as well as the use of a defined stage-gate process from ideation through prototyping, exposes students to the way products are developed in the real world.

Besides demonstrating the improvements in the course itself, the contributions of this study to the current body of knowledge are twofold. Firstly, this paper makes a contribution to PBL empirical body of knowledge by demonstrating a successful PBL initiative, since there are still few studies that explore PBL approaches in EE in developing countries, especially in Latin America. Improvements in engineering education in emerging markets are extremely important due to the industrial development. Secondly, some aspects reported as important in the PBL literature such as the effectiveness of PBL and how to face the main difficulties for its implementation are explored in the paper.

The improvements' needs identified by the faculty and pointed out by students in a survey should be considered in further course improvement cycles based on the current business process approach. This is one of the next steps of this work, and it would enable to compare the surveys over the years. In addition, the course proposal only focuses on the first two macro-phases, and the consideration of the third macro-phase will be taken into account in further rounds of improvements. Finally, a more rigorous definition of the skills that the students learned through the interdisciplinary approach would be relevant to be investigated as a long-term impact of the proposed approach, and this will also be explored in future work.

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