INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
12-13 SEPTEMBER 2019, DEPARTMENT OF DESIGN, MANUFACTURING AND ENGINEERING MANAGEMENT, UNIVERSITY OF STRATHCLYDE, UNITED KINGDOM

ENGINEERING PRODUCT DESIGN EDUCATION WITH A MIXED DESIGN-THINKING & LEAN START-UP APPROACH

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ABSTRACT
In the past 20 years, companies have successfully grown from start-ups to transnational companies are requiring new hard and soft skills from their employees, as they are using new methodologies in order to develop better products and services. Meanwhile, engineering students usually struggle to find projects in which they can apply their knowledge, solve a real market need, and remain financially self-sustainable. Thus, engineering education requires to constantly adapt its curricula. The article presents a project based learning strategy to develop technologically based products, using engineering, design and business tools, using principles from Design Thinking (DT) and Lean Start-up (LS) as a liaison between those domains. The approach was tested during 2 capstone courses for mechatronic engineers at Tecnológico de Monterrey Campus Estado de México for 4 years, where the students were required to develop a prototype along with a comprehensive business plan. Through a comparison with external evaluations, we validate the learning experience of merging engineering and Product Design (PD) education with topics from other domains to help leverage the students' skillset for their future jobs.

Keywords: Design thinking, lean start-up, educational innovation, higher education

1 INTRODUCTION

While some universities take care about developing a series of business oriented soft skills, most of them have industrial partners' requirements and others still neglect skills associated with entrepreneurship. Willing to prepare the latest generations of engineers in successful PD, a question arises: can these new requirements be successfully merged in engineering education? Several approaches point towards solving this question. For instance, a philosophical perception of entrepreneurship for engineering students is presented in [1]. A business programme for students in science, technology, education and mathematics has shown to help increase the confidence of students in entrepreneurship at a Junior High School [2] while a course on entrepreneurship and engineering design at Khalifa University had a higher students' approval rating than the average of their courses [3]. The University of Twente contributed to this effort by creating a course in *Creative Technology* using its own user centred method for products and applications [4]. The approach for the current paper was then developed after observing diverse interrelated phenomena happening around entrepreneurship, engineering and PD education.

1. The belief among students that soft skills are less important than demanding technical skills [5].
2. The lack of a deep understanding on the motivation fostered to technology entrepreneurs for the economic growth of their countries [6]. As instance, [7] indicates that entrepreneurship education was introduced in France 20 years ago in the *Grandes Ecole's* of Engineering, yet most students still prefer well paid, secure positions.
3. The very high failure rate of start-up companies where culture of entrepreneurship is not well developed. For example, 75% of Mexican start-ups close in the first 2 years, compared with the 70% still ongoing in United States after 3 years of operation [8].
4. Entrepreneurship has become an interesting career path for many people around the world during the past two decades [9] leading a growing number of incubators and accelerators following

methodologies of successful start-up companies like Google and Airbnb.
5. Long-established companies (e.g. Procter & Gamble) have recognised the importance of entrepreneurship techniques for PD by starting to implement them [10].

DT and LS are methodologies having earned an important prestige in the design of new products and/or services because of their user driven innovation strategies. DT was presented since the 1970's but it became profitable only in the 1990's. It requires constant feedback from the market, as users' demands are at the core for building and testing prototypes that will eventually define the final design [11]. LS, applies Toyota's lean principles in the context of technological start-ups [12]. It requires to develop prototypes with a minimum waste to validate the market needs. Both methodologies are currently well adapted to purely digital products (apps, social networks, etc.), often neglecting the requirements of traditional engineering and manufacturing, generating a poor traction on the market.

Moreover, "the two communities of LS and DT do not interact and cite each other very often" [13], but share common factors able to be merged into *Lean Design Thinking*. In education, both techniques have been reported to be used indepedently. For instance, a 12 week programme for university students included the basic concepts of LS, but without presenting any PD or manufacturing concepts [14]. However, DT has been included along with PD and business education programmes with positive feedback from students [15], nonetheless, lacking an integration with engineering. Engineering education also requires contents updated to the latest trends. For example, additive manufacturing and virtual environments have been reported as effective tools for PD for decreasing either design or production times, if taught along traditional manufacturing methods [16], [17].

The aim of this work is to propose and evaluate a user-centred PD methodology that provides an adequate skillset for engineering students. It is accomplished by choosing tools from different domains related to PD, including entrepreneurship ones. Section 2 states the objectives of the research approach, further explained in Section 3. Section 4 presents outcomes on the courses and a comparison with external evaluations to evaluate the method itself. Finally, some conclusions are given.

2 OBJECTIVES

The research approach is based on two complementary objectives, presented in Figure 1:

a) Evaluate the effectiveness of the present work to develop useful PD skills in engineering students.

b) Analyse the impact from the courses in developing entrepreneurship/intrapreneurship competencies.

To validate the first objective, we compare the course grades against two external evaluations: one given at the end of each semester by an external jury (professors of the mechatronics department and mechatronic engineers with 10+ years of industrial experience), and another given by industrial experts on a subset of the students within a contest associated to PD. Finally, as part of the metrics for both objectives, we surveyed former students already started working about the usefulness of the course topics in their current jobs. The quantitative comparison helps reinforce the standard of quality in the students' work from the perspectives of different experts.

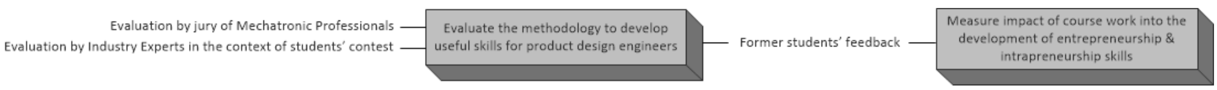


Figure 1. Objectives and metrics considered to evaluate the proposed approach

3 THE MIXED APPROACH

The approach was tested and iterated with students taking two interrelated capstone courses for the Bachelor of Science in Mechatronics Engineering: Mechatronic Design and Mechatronics Laboratory (MD&ML). The following describes the methodology to afford the research objectives quantitatively.

3.1 Mechatronic Design and Mechatronics Laboratory courses

Both courses are focused on senior level undergraduate students where advanced engineering courses are prerequisites. The syllabus requires to include innovation, creativity, entrepreneurship, ethics, and sustainability, as well to develop a functional prototype satisfying a real market need through the well-known Project-Oriented Learning Methodology (POL), reported as a successful learning strategy [18].

3.1.1 A Student Competition as the root for Project-Oriented Learning

The Partners for the Advancement of Collaborative Engineering Education (PACE) Forum was a yearly student competition organised by several engineering firms (including General Motors, Hewlett Packard, Autodesk, Oracle and Siemens), going from 1998 to 2018 [19]. Universities needed to work together in international teams to develop mobility products working as solutions to well stated problems identified by the PACE Partners. Starting at the 2014 Forum, Tecnológico de Monterrey at Estado de México contributed with manufacturing expertise through a course on Automation of Manufacturing Systems, which earned the team a first prize in that category. Afterwards, it was decided to include MD&ML students, with progressive changes implemented in the courses in order to align better to the workloads and students' skills required by the PACE competition. From August 2015 to July 2016, all students (around 22 per semester) taking the MD&ML courses, would work in generating solutions for the PACE competitions. Since August 2016, only 7 students would be working on the PACE competition each semester. A choice between different categories of urban topics (sustainability, education, healthcare, etc.) would be given to the remaining students, to identify and solve a real market need in 5 person teams. Despite PACE projects where the result of common effort from several universities in the teams, different recognitions were obtained every year, regardless of the universities forming them: 3rd place in Product Engineering (2016); Most Improvements in Prototype (2016); 3rd place in Manufacturing (2017); 3rd place in Customer Insight (2017); 1st place in Prototype Race (2018). In every case, the part of work done by the university had positive feedback from the jury.

3.2 Iterations on the Courses' Content

Depending on the discipline, there are different meanings of *design knowledge* term [20]. As oriented towards engineers, the focus of the courses was originally intended into conceiving a functional prototype, a manufacturing plan and a cost analysis, regardless of several other factors relevant for selling a product (*e.g.* aesthetics, needs analysis, etc.). Students entering the courses had good technical skills for prototyping and manufacturing mechatronic devices but lacked design and business skills. Furthermore, the knowledge they had in entrepreneurship was limited to one theoretical course during the major, where the projects were not necessarily technologically based.

3.2.1 Towards a more comprehensive and updated class material

Since 2015, iterations were done to fine tune the course content. Main topics gradually introduced are presented in Figure 2. Furthermore, notions on some of the latest trends in engineering were included: Artificial Intelligence AI, Virtual/Augmented Reality VR/AR, Internet of Things IoT, Data Analytics.

Figure 2. Main tools and topics gradually introduced in the courses

3.3 Mixed Approach: Activities

By surveying former students and professors, we learned DT methodology was previously presented as a tool used only by industrial designers, without much application for engineers, while the LS methodology was not mentioned at all. We decided then to use these methodologies as a linking pin of different activities (presented in Figure 3), related to the project, that were carried out through the semesters. These activities were carried out by the students following the big principles of DT:

- For the *desirability*, the students would identify a market opportunity by interviewing and surveying people. To boost their creativity, they were asked to build a *prototype* with recycled materials and an Arduino and present it to their target market for feedback.

- For the *feasibility*, the design criteria would be obtained from the market feedback with the help of a QFD matrix. The students would then need to build a Minimum Viable Product (MVP), and an optimised Computer-Aided Design by the end of the semester, as LS deliverables [8]. To incentive critical thinking, decisions should be justified either by engineering or financial considerations.
- For the *viability*, the students would need to define the manufacturing and assembly processes for a final version of their product, in order to stablish a down-to-earth business plan including financial factors. A virtual plant would be designed and simulated to validate their production plan.

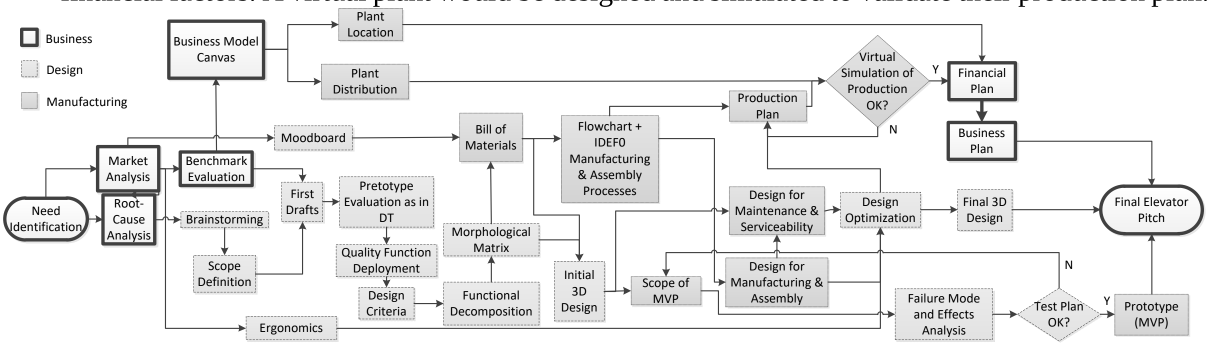
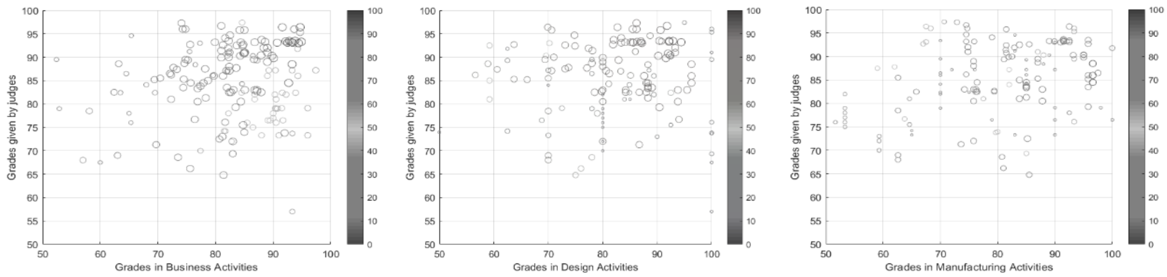


Figure 3. Flowchart of activities carried out as part of the classes

4 RESULTS

At the end of each semester, an external jury filled a scoring rubric considering the design of the product, manufacturability and feasibility of the business on a 100% scale. To analyse the influence of activities related to business, design and manufacturing (B/D/M), the individual grades on the activities associated to those dimensions were compared to the grade given by the jury (for the 173 students taking the courses between January 2015 to December 2018). Moreover, the averages per dimension were also calculated to measure the overall effort. Figure 4 summarises this information, in which the integral grade is normalised to its highest possible value and represented by a change in colour and size (*i.e.* the higher the grade, the bigger the circle, and closer to red). We observe that the effort put by the students in the design and business activities had a bigger influence in the grade given by the jury. However, the effort on the manufacturing activities did not seem to have such a straightforward correlation with the grade of the jury, possibly due they were aware of the manufacturing skills of the students.



a) b) c)

Figure 4. Scattering of grades for a) Business b) Design c) Manufacturing activities during the 8 semesters compared to the grade of the external jury

To validate the research objectives settled in section 2, we are considering several inputs: first one is the mean of the several grades (GC) through the course as they were obtained in the flowchart (Figure 3) but related with the B/D/M dimensions being studied. We also consider the evaluations given in the PACE contest, involving several specific abilities evaluated by experts on customer insight, industrial design, product engineering, and manufacture. With the feedback shared after the 2017 and 2018 Forums (including their scoring rubric), four outcomes could be gathered from such reports: i) the total score assigned (MS) for each specific skill dimensions, ii) the maximum score assigned (MSA) to some team in the contest, iii) the average score assigned (ASA) to teams, and iv) the score assigned to our team (TTS). Because the scales in the contest are high and the PACE jury normally assigns low scores, we normalised them with respect to the MSA for each year (2017, 2018) instead of the MS, to obtain their relative equivalents (*i.e.* TTRS, ARSA). The different grades reported in their scoring rubric were grouped into our study dimensions (B/D/M). While this index focuses on a subset of students, we consider the results to be generalisable as the approach used was consistent with the remaining students. Finally, a survey sent to the 173 students was carried out (21% of students from all semesters completed the closed questions section). There, we will include the appointment made for each participant regarding which of the tools presented in Figure 2 have been useful in their current professional life, to define their importance. Thus, such index could be interpreted as the percentage of participants fully declaring each dimension as critical in their professional life. Figure 5 relates all indexes, rescaled to 0-1 to make them comparable within each other:

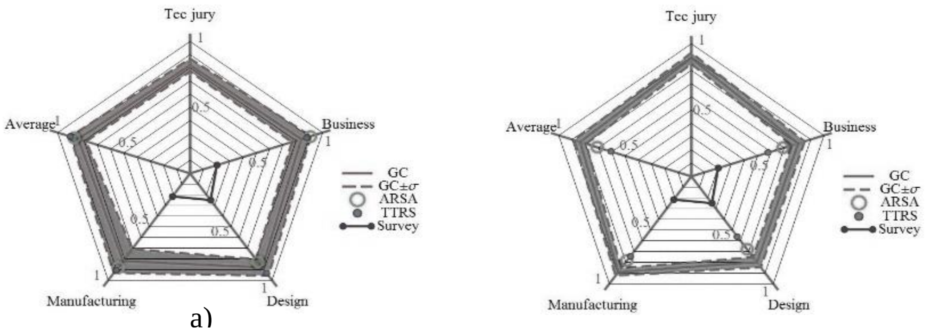


Figure 5. Comparison between GC (and dispersion σ), ARSA and TTRS for years a) 2017, and b) 2018, referred to the dimensions of study and their average and the local jury scores

Figure 5 shows a full match in the evaluation performance given in the course (GC) with that of the external jury at the end of the course. The performances demonstrated in the PACE contest shows a good performance as well: particularly the ARSA index is very close to TTRS given there to our students despite certain drop during 2018, due to harder rules and evaluations imposed in the contest. To further validate the context from the survey's results [21], some of their responses are presented next:

- 72% of the students reported they are currently working in international engineering companies (e.g. Ford, Tesla, General Electric, John Deere, Keyence, Procter & Gamble, Alstom). 21% were either working on their family's business, a small company, or starting up a company themselves.
- 59% of the students reported having design related positions in their short career.
- 23% thought as students that the material taught at the MD&ML courses would not be useful during their engineering careers, but only 8% still believe it after working. Two of the most meaningful comments were "You learn about innovation and entrepreneurship from a mechatronics engineering perspective" and "I've used in industry most of what I've learned in those courses". Along with the quantitative results, this helps validate the first objective fixed in Section 2.
- Every tool and subject were reported have been used by them except for the *mood board*.
- Teamwork, entrepreneurship, critical thinking, working under pressure, need identification, team management, creativity, and communication skills were soft skills that at least 50% reported as improved by the courses, complying with the second objective fixed in Section 2.

5 CONCLUSIONS & FUTURE WORK

The work hereby presented shows that there is a way in which PD can be taught by integrating DT and LS concepts, as part of capstone courses for engineers. The presented methodology for the courses boost effectively the several competencies expected in the design engineering area, validated by comparing their grades to an evaluation from an external jury of academic and industrial professionals, as well as an evaluation in the context of an international student competition. Having experts with adequate credentials judge the final project is essential to objectively validate the use of this methodology. The outcomes analysis from the surveys present a balance referring to the three dimensions of study (B/D/M), with a little 5% of predominance for design skills. Around 65% of students falls in one of such categories. The complementary 35% could be interpreted as participants denoting that diverse and combined balanced skills has become important in their professional life.

While not activities are suitable for product designers without an engineering background, the principles of the mixed methodology, as well as the presentation of the engineering considerations, could be introduced in non-engineering and start-up incubation courses for a holistic view of PD. Having this integrated view can help entrepreneurs and intrapreneurs to anticipate feasibility problems.

The upcoming work implies presenting a merging methodology for designing and engineering mechatronic products that can be used by start-ups anywhere, based on the learnings from this research. The methodology is yet to be tested in other contests such as the James Dyson Award.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial and the technical support of Writing Lab, TecLabs, Tecnologico de Monterrey, Mexico, in the production of this work.

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