Challenge based education: an approach to innovation through multidisciplinary teams of students using Design Thinking

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Abstract— **This work aims to describe and discuss the benefits and learning outcomes detected along four iterations of a learning experience carried out by three institutions: ESADE Business School, IED Istituto Europeo di Design and the Telecom Engineering School of UPC, Universitat Politècnica de Catalunya. Mixed teams of students from the three institutions face open innovation challenges with societal interest through Design Thinking. This study is focused on the learning outcomes of engineering students, compared to the ones obtained by Telecom engineering students that follow standard project-based courses. The students spend 3-4 weeks at IdeaSquare, a creative environment created at CERN Meyrin site in Switzerland, where they can consult and interact with scientists and knowledge transfer experts about possible applications and uses of CERN technologies in the student's proposed solutions. One example of a prototyped solution is a low-cost sensor-based system to detect malfunction in water wells in Africa, which uses SMS-based communication and cloud-based solutions to manage wells repairs. As a result, the ICT engineering students increase their awareness of user needs and the relevance of the problems to focus on when tackling a complex challenge. They also increase their ability to ideate more disruptive and high-impact solutions thanks to their understanding of the "big picture" based on their interactions with design and business students.**

Keywords— challenge based education; multidisciplinary teams; design thinking; innovation

I. Introduction

Innovation is not only about technology or technical solutions to problems, either business, market or industry based. Innovation is about solving complex challenges and developing solutions to these challenges tackling them from three perspectives: business, technology and people.

Every discipline involved in the innovation process is fundamental and a deep knowledge in engineering (technology), management (business) and design (people) is needed to develop solutions that have greater chances to succeed in the market.

As a society we are facing extremely complex challenges today and in the near future like water scarcity, climate change, over population, immigration and refugees, among others. To tackle this type of challenges, solutions must be holistic and the approach must be in multiple directions.

Training future professionals in the processes and methods to innovate and in understanding how to tackle this type of challenges from a multidisciplinary perspective could increase the chances to have solutions with greater chances to succeed.

For engineering students, getting to understand the innovation process, working in multidisciplinary teams with management and design students and approaching solutions beyond the purely technical or engineering perspective makes a great difference in their learning experience.

These types of complex challenges pose unforeseeable uncertainty [1] and require different approaches than "traditional" engineering projects. Design Thinking is a human centric innovation approach to innovation [2] suitable to deal with uncertainty in the early phases of projects through in depth user research, ideation and early prototyping and testing of solutions in an iterative process.

Based on Dym's research [3] using Design Thinking in project-based learning is the best pedagogical model for teaching design.

Challenge Based Innovation (CBI) is a program created by CERN to host educational projects where students from different disciplines working in multidisciplinary teams tackle innovation challenges through Design Thinking. The objective is to design solutions to complex social problems, considering the use of CERN technologies if suitable.

The objective of this paper is to describe the process, methodology and learning outcomes (focusing on engineering students) and examples of the technical solutions and prototypes as result of this new educational experience carried out by three higher education institutions: UPC (Telecom and Computer Science students), the business school ESADE and the Barcelona site of IED, Istituto Europeo di Design, after four editions of this course.

The methods and results are compared with the ones developed by a more classical approach: the capstone project that is carried out in the fourth year of the Telecom Engineering degree. In this case, challenges are also stated by external companies or institutions but are basically technical challenges, which have initial requirements and even specifications.

II. Design Thinking

According to Tim Brown, "Design thinking is a human-centered approach to innovation that draws from the designer's toolkit to integrate the needs of people, the possibilities of technology, and the requirements for business success" [2].

In the past decade, Design Thinking arisen as an innovation methodology to tackle complex problems, also beyond business or commercial environments. It is not a new phenomenon, as design professionals have been working with this processes and methods for many decades. What is rather new is using Design Thinking as a universal tool for problem solving and innovation in other fields than design, like management.

This approach brings together and balances what it is desirable (what people needs), viable (economically sustainable from the business point of view) and feasible (from the technology perspective).

The principles of Design Thinking are: Human-Centered, Collaborative, Iterative, Holistic and Experiential.

These principles emphasize the observation of people behaviors to detect needs and opportunities, collaboration in multidisciplinary teams, early visualization and rapid prototyping of ideas and solutions and testing in an iterative process. It does not replace professional design or engineering. It is a methodology for early stages of the innovation funnel [4].

Within the Design Thinking process we can clearly identify two different "spaces" to explore: the problem space and the solution space. Within the problem space, the focus is placed in understanding the challenge, the context, the user/s and stakeholders and detecting needs to be solved and opportunities. In the solution space, the aim is to generate multiple ideas and solutions to the specific needs and opportunities identified in the previous phase. These solutions are then prototyped and tested in an iterative process to learn and improve before developing the final solution.

From the cognitive perspective, it combines divergence and convergence processes to generate several choices and only then make choices between the alternative options [2].

According to [5] it is a process composed of 6 iterative phases where back and forth movements are involved between the different phases (Figure 1)

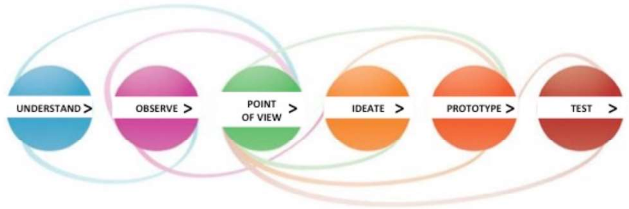

Fig. 1. Steps in a Design Thinking process . Adapted from [5].

The six phases are Understand, Observe, Point of View, Ideate, Prototype and Test. The first three phases belong to the problem space and the last three to the solution space. They will be developed through an example in section V.

III. Challenge Based Innovation (CBI) at CERN

A. *IdeaSquare @ CERN*

The European Organization for Nuclear Research, CERN, is dedicated to fundamental research in particle physics since 1954. According to CERN website "physicists and engineers are probing the fundamental structure of the universe. They use the world's largest and most complex scientific instruments to study the basic constituents of matter – the fundamental particles". In order to do this, they develop very specific and complex technologies. These technologies are purpose-built particle accelerators and detectors, which are instruments scientists use to observe and record the results of their experiments (collisions of particles).

More than 12.000 scientists from all over the world collaborate with CERN in these scientific experiments and developing new hardware and software. The technologies they develop for their experiments could have great potential applications and impact in the society. Some of them even can change our lives, like the case of the World Wide Web, invented by Tim Berners-Lee in 1989 at CERN. To find ways to allow, facilitate or accelerate the process of discovering societal applications for CERN technologies, a new experiment called IdeaSquare was created in 2013 in collaboration with Aalto Design Factory, which is a multidisciplinary teaching and development unit from Aalto University.

The objective of IdeaSquare is to prove or demonstrate that applying fundamental research concepts to tackle societal challenges is of value. For this purpose, IdeaSquare hosts different activities: long-term research projects on detector R&D, different innovation-related events and hackatons and multidisciplinary university projects like CBI (Challenge Based Innovation) [6]. Challenge Based Innovation is a human-centric experimental project hosted by IdeaSquare where multidisciplinary teams of students tackle societal challenges. Within these wide challenges, they identify end-user needs to be addressed. In collaboration with CERN mentors and coaches from their home Universities, they ideate and create tangible prototypes of the solutions inspired in relevant novel technologies from CERN.

To achieve better synergies and connections with CERN all student teams have a CERN mentor who helps them and guides them in everything related to technologies from this research institution. Also, the students have weekly working sessions with their coaches from their home institutions to progress in their projects.

B. CBI Course Structure

Similar to the four phases of the Double Diamond design process from the Design Council [7], which is based in the Design Thinking methodology, the basic structure of CBI is composed of three main blocks: Discover, Design and Deliver.

In the initial Discover phase, the teams focus on deep diving into their challenges, understanding the context, trends, benchmarking, needfinding, doing basic research and user research (observation, interviews, etc). At the end of this phase the teams define the specific need or problem they are going to tackle within the original challenge. In the Design phase the students generate multiple ideas and solutions to the problem that are prototyped in low resolution (cardboard, paper, etc) to quickly iterate and learn through user testing. After these iterations, one solution is chosen to be further developed and prototyped with higher resolution. In the Delivery phase, the selected idea is prototyped to a proof of concept level and the solution is developed from the technical, design and business model perspective. At the end of the project, all teams present their solutions and prototypes in a gala event at CERN in front of scientists and universities audience, with media coverage.

Ideally the societal challenges for the course are defined in collaboration with NGOs or companies, and with IdeaSquare team. The topics of the challenges are broad and allow multiple ways to approach them, aiming for educational and learning outcomes rather the technical solutions of the projects. In the two last editions, alignment with UN Sustainable Development Goals (SDG) has been taken into account when defining the challenges.

Teams are usually formed by six students (two from MBA, two from engineering and two from design). In a few cases, some teams had only one representative of one of the institutions. In several cases, they have been added to mixed student teams from other international universities also involved in the Aalto Global Design Factory Network.

The schedule and practical arrangements of the course has been adapted year by year. The course itself is a prototype. In the current setup, there is a kick-off period, with an initial intensive week in one of the local institutions followed by a 3-5 days at IdeaSquare@CERN. Then, there is a weekly full day (8 hours) devoted to the projects in one of the local institutions along 5 weeks, followed by an intensive week 3-5 days at IdeaSquare@CERN where the ideation phase is finished in most cases. Then another set of 5 weekly days at one of the local institutions, devoted to converging in one solution and designing it and a final intensive period of 10 days at IdeaSquare@CERN for solution integration and final presentation.

Each team at the end of the project must deliver the following items:

- Prototype of the solution (proof-of-concept)
- User testing feedback
- Demonstration of the impact of their solution
- Clear description of their link to CERN
- Final project presentation
- Well-documented project and process description
- Project video

According to the CBI Student Guidelines document, shared by the three institutions, the course learning outcomes are:

- Develop an Advanced Design project applying a methodology focused in product innovation.
- Study and guide the creation of future scenarios, based on a deep analysis of present and past, with the aim of creating new ideas applicable to the new context.
- Analyze the project considering market, society and technology, to define clear areas for new opportunities.
- Achieve the proper presentation tools to present and explain the design process, both orally and in digital format.
- Apply a strategy, making decisions for achieving innovation and quality.
- Fundament the concepts in a multidisciplinary project from a theoretical and practical perspective.

- Present and represent design ideas applying the proper techniques.
- Apply the proper digital technology for the communication and presentation of projects.
- Implement specific design research and experimentation techniques.
- Find out and study the productive processes for the fabrication of the designed projects.

The assessment of the individual students is based in the team performance (50%), the individual performance (35%) and the peer assessment (15%). The first two marks include several aspects specified in a rubric. Taking into account that the teams have, at least, a weekly coaching hour with several faculty members, we can use authentic assessment.

Feedback about the course is obtained through a specific feedback session with all students and faculty members, an individual reflection document and several questionnaires supplied by the different institutions.

IV. Capstone project at the Telecom Engineering School

For the sake of comparison with the CBI course, the capstone project, which is performed in the fourth year at the Telecom Engineering School, will be briefly described. When designing the engineering degree curricula according to the EHEA directives, the Telecom Engineering School adopted the CDIO Standards [8] and, as part of the implementation of the CDIO model, included a project courses path which currently includes a project-based course in the second, third and fourth year of the bachelor. The projects' complexity and degrees of freedom grow along the three iterations and also the team size increases. The capstone project, called Advanced Engineering Project (AEP), is located at the first term of the fourth year and has 12 ECTS credits. Teams of 7-12 students face a complex challenge by splitting in sub-teams, designing and implementing the different parts of the project and finally integrating ant testing the product, process or service, including the definition of a business plan. The teams usually have a mixed composition of students from the different minors of the Telecom Engineering degree (Electronics, Networks, Audiovisual Systems and Communication Systems). This subject has also evolved along the eleven iterations that already occurred. Currently, 8-10 different challenges are offered every semester. 7-8 out of 10 are proposed by companies or external institutions (hospitals, NGOs, …) and 2-3 are proposed by research groups. The projects follow a more classical structure: starting by requirements and even specifications to solve a technical need identified by the stakeholders, the teams build a Project Charter document and a Project Management Plan, following the PMBOK standard, and get them approved by the faculty members and the external advisors. Then they execute the different work packages they have defined until a Critical Design Review approximately located in the 8th week and then continue with the updated project plan until presenting the product or service and delivering the Final Report at the end of the semester (13-15 weeks).

The assessment of the individual performance is obtained by giving an overall mark to every project, which takes into account the different aspects and deliverables (technical performance and complexity, innovation, prototype, reports and presentation). This overall mark is modulated for every individual student with three factors: supervisors' individual assessment, team leader assessment and peer assessment performed by the team peers using a rubric, with a weight of 30% each. The feedback is collected through a reflection document included in the Final Report.

V. CBI and Capstone project examples

Along the 4 editions of the CBI course in which our three institutions have participated, 18 different projects have been carried out, four in the first two years and five the last two years. As examples of the stated challenges:

- How can we design a viable system that allows people to restore or enhance their ability to move?
- How might we improve public health by providing safe access to water?
- How might we deliver food to homes in a new way that maintains the food cold at a selected temperature, ensuring its safety?
- How might we improve the cognitive development and communication skills, and consequently the quality of life, of people with Intellectual and Developmental Disabilities through ICT?
- How could technology help to improve the living conditions of refugees, displaced and other people in need of emergency temporary sheltering?
- How to use new technologies to revamp radiation inspection methods?
- How might we use immersive technologies to design realistic, productive and memorable learning experiences for humanitarian missions in risky environments?

To give an overview of how the projects were developed according with the Design Thinking methodology, we give more details on two of them. About the challenge "How might we improve public health by providing safe access to water?", the six students team explored the needs in the sub-Saharan region through local and remote contacts at NGOs and international agencies. They focused in rural areas in Ghana and first explored the needs: locating water sources, sanitizing the water, improving the safety of the water use, … Then they explored the feasibility of using CERN-derived technologies:

high efficiency solar collectors for disinfecting water, using advanced sensors to perform remote sensing of water sources, advanced filtering devices … In all cases, they shared their findings with the stakeholders. At the end, and through the stakeholders' feedback, they realized that the main problem in this area was not the scarcity of water wells but the fact that more than 70% of wells were out of function. They also found pitfalls in the way the money provided by NGOs was used. The solution they designed (figure 2) and prototyped (figure 3) was a low-cost sensor arrangement that was attached to the well outlet pipe (no need of modifying it), detected if the well was operated through vibration pattern detection, if water was flowing through temperature change detection, and sent an SMS message to a cloud-server that displayed the well status in a synoptic map in the nearby villages and activated a Uber-like network of potential repairers, who would be paid through a NGO when the correct well status was automatically checked. The solution, at the end, only used the C2MON cloud solution from CERN technologies but potentially solved a relevant problem.

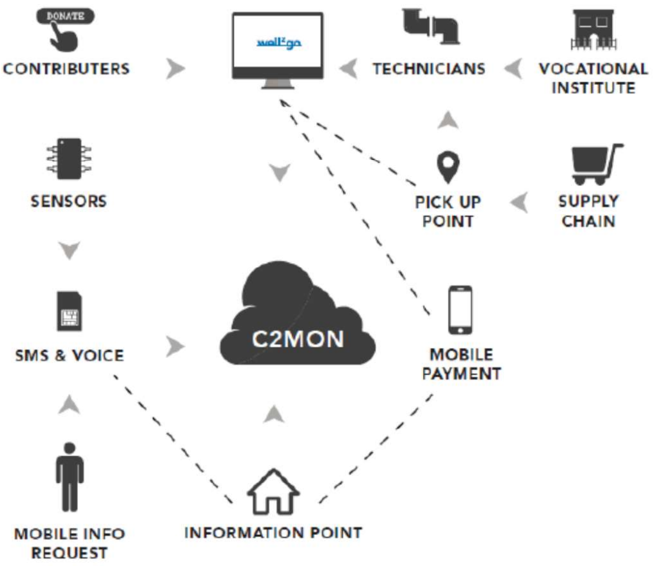

Fig. 2. Block diagram of Well2go, the system designed in the CBI course (2015) to improve the safe use of water in Ghana

Fig. 3. Prototype of the Well2go system

The second of the chosen examples is the challenge "How to use new technologies to revamp radiation inspection methods?". In that case, the students interviewed the CERN experts in radiation inspection, staff at a nuclear plant, managers of radiation therapy facilities in hospitals, public-health officers at the City-Hall, … The conclusion of the research phase was that the highly standardized radiation inspection procedures, although could benefit from an appealing revamp through the use of new technologies (e.g. augmented reality), were a field that affected few people, and that people had strong technical skills and did not really need more comfortable methods which, on the other hand, would find difficulties to be approved by the regulation agencies. In opposition, they found through CERN contacts that there was a radiation-induced problem with high impact in the population due to the accumulated exposition to radon gas in houses and workplaces with low ventilation, which results in a number of lung cancer cases. The students designed and partially prototyped a solution based on radon sensors developed at CERN which also included a service build on top of a database and a smartphone app which calculates and displays the accumulated exposure of an individual to radon gas using sensors and publicly available information and also takes into account the individual susceptibility based on family history of lung cancer and other environmental factors (smoking, …) and that could include genetic data in the future.

Almost all challenges and solutions have a similar story of choosing the relevant need and solution through intense user feedback although the solution was not so appealing from the technological point of view. The final reports and videos of the projects can be found at http://www.cbi-course.com/, under the "Projects" section.

While 10 students per year get their 12 ECTS credits of Advanced Engineering Project through the CBI course, only in the fall term, the remaining 160-200 students per year do it in the regular way through one of the 8-10 capstone projects (AEP) proposed every semester. Up to 78 projects have been carried out up to now. Most of them are new every semester and a few (one-two per semester) may be a continuation or second version of a previous one. A few examples of the kind of topics stated by the stakeholders are the following:

- Software application based on image and video processing to aid the rehabilitation of facial paralysis after facial nerve injury.
- Portable, non-destructive testing equipment to determine the health of "trencadís" tiles of Sagrada Familia temple.
- Improvement of several features in large-format printer sensors
- 3Cat-NXT and Distributed Satellite System projects: successive developments around a Cube-Sat platform
- Cost Effective communication payloads in Stratospheric Balloons

- Localization and monitoring of workers and assets in a Digital Factory indoor environment.
- Automatic analysis of infant sleep structure
- Chatbot for banking user-interface
- Low-cost, robust, autonomous blood-pressure measurement system for developing areas.
- Use of radar for non-contact measurement of ventilation and heart rate in newborns.
- Explore technologies for human-machine interface in vehicles.

In almost all cases, there is an initial statement which points directly to a technical solution, although the initial requirements are a bit open (we ask the stakeholders to do so), and it is a task of the students to explore the client needs around the product and define specifications that have to be agreed with the stakeholders. Nevertheless, in all cases, the need is already identified and in most cases there are clear clues about the technical solution. All projects should have complexity in order to allow splitting them in 3-4 parallel work packages (hardware, firmware, data processing, application and user-interface software, …) and solutions using advanced techniques and high level of abstraction are encouraged. At the end, the students develop a prototype able to perform a demonstration of the developed concept, including a business plan if the result is a product or service or at least the analysis of the engineering costs if it is an internal subsystem. For example, the challenge of detecting the adhesion state of "La Sagrada Familia" tiles (figure 4) resulted in a solution that involved:

- Image processing to identify the individual tiles from a picture taken with a tablet (image segmentation).
- A knocking device to test the tiles and a microphone and an acquisition system to record the resulting sound (based on a Raspberry Pi).
- A signal processing algorithm to distinguish the tiles that are well adhered from those that are not.
- A user interface that allows displaying the tiles which are not well adhered in a user-friendly way.
- A test campaign with reference samples.
- A business model about the possible commercialization of the product for additional uses.

Almost all projects involve a strong technical workload, with the design of several intermediate prototypes including the use of prototyping platforms (development boards, 3D printing, software development frameworks) and accurate treatment of measured data. In the last editions of the course, more than half of the projects proposed by external companies have solutions based only in software, with prevalence of data analytics, machine learning and BlockChain. Also the students' preferences are shifting to these fields.

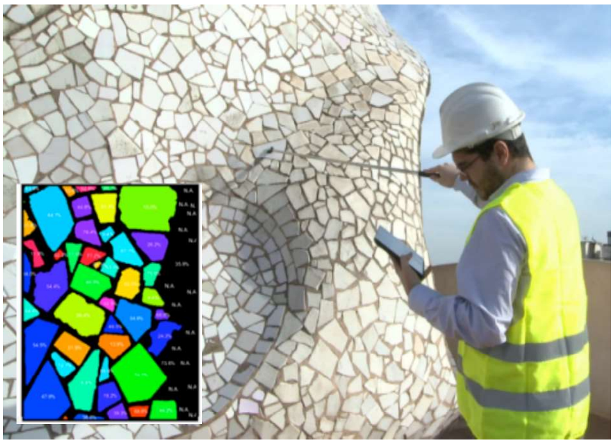

Fig. 4. System to detect adherence of tiles, developed in the AEP course.

VI. CBI and Capstone projects comparison

Both types of projects can be compared according to several criteria:

- About the context, in both cases the course provides a context close to a real-world activity and is therefore more suitable to obtain deep learning outcomes than regular theory-lab-problems-exam subjects. There are, however, some differences. In the capstone projects, the context is known and the multidisciplinarity is limited to the different minors into ICT engineering disciplines. On the other hand, in CBI, the context is unknown; all the students (mainly the engineers) are out of their comfort zone and have to learn to work with others.
- About the technical complexity and deepness, as it was said in the previous section, in capstone projects is high and there are strong learning outcomes on the science and technology involved in the solution, although this is not the main goal of the subject. In the CBI course, due to the lower workload devoted to the technical solution (less time, only 2 engineers per team), the complexity and deepness are lower, although relevant. The goal is to provide a final prototype able to provide a proof-of-concept of the critical parts of the solution.
- About the user-needs awareness, in the capstone course is usually low, with some exceptions. Although this aspect has improved since we have external stakeholders for almost all projects, the specifiers are usually engineers and not final customers, and the projects often are technology-driven. In the CBI course, the user awareness is extremely high, and so is the potential innovative impact of results, while the technology takes a secondary role. There is an issue that we have learnt that has to be controlled: Engineering students tend to apply technological solutions in the low-resolution prototyping phases during needfinding and ideation, where they are still

not needed and could distort the user-approach. Also the engineering students (and even the teachers) use to reveal the technology limitations in the ideation phase, where disruptive solutions that go beyond the currently possible solutions could appear.

- About the project planning and documentation, it follows a strict protocol in the capstone projects, using an adapted version of LIPS [9] and PMBOK [10] models. Although it is presented to the students as a way of ensuring the project success, it is often seen as bureaucracy and as an obligation. In creative processes, like the CBI course, however, documentation and planning are not so strict and are mostly based on presentations, videos and low-resolution prototypes, with a lot more iteration and interaction with users than the classic projects. The method can be considered close to the extreme-agile software development method.
- In capstone projects, the students feel stress on the need of completing the assigned sub-system on time and on dealing with incidences. In the CBI projects, the stress is put in the first two thirds of the course in the collaborative sense making (all students from all disciplines participating in all phases) and only in the last third, on the delivery of specialized outcomes.
- About the quality of the results, all these subjects are highly motivating and the project results are usually good or very good, often outstanding. In the capstone project, the students' commitment is medium to high and there are only a very few cases every year of individual students not getting good results and marks, even failing the subject. In the CBI course, the results are usually outstanding. There is a bias factor in the fact that the students compete to be part of this course and some of the best ones are chosen, but there is in any case a very high commitment and also the pressure of presenting at CERN. Also in the capstone projects proposed by external institutions the pressure and commitment are high, while in capstone projects proposed by faculty members, the students feel that are among peers and the context is closer to a regular subject.

VII. Conclusions

The true-multidisciplinary structure of teams has been identified as the highest value of CBI course, above the international experience and the singular environment of CERN and the possibility of contacting high-level scientists and technologies.

The inclusion of intensive periods in singular workspaces, out of the regular classrooms and labs has also been identified as a key factor for success.

The Design Thinking approach provides powerful tools to deal with uncertainty in open challenges, thanks to the systematic way to tackle it through iterative divergent-convergent phases and the test with users and other stakeholders.

This multidisciplinary experience has shown to be a successful tool to enhance the innovation and entrepreneurial skills in engineering students. Due to its cost, it cannot be scaled to all the students, but the methods developed and lessons learnt can be partially applied to capstone projects and even to standard courses.

Not all engineering students are prone to become entrepreneurs. The goal is to identify these who are through the exposition to CBI-like experiences and provide them experiences to enhance the innovation and entrepreneurial skills. The (not so) standard capstone projects would provide tools to get the learning outcomes of analytical design. There is a tradeoff: the direct contact with users improves the creative part (needfinding, ideation) but reduces the time for designing complex solutions and the associated learning outcomes. Then, with limited time and resources, engineering students should choose between acquiring more entrepreneurial skills or more technical skills.

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