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Developing innovation competences in engineering students: a comparison of two approaches

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ABSTRACT
The gap between industry needs and engineering graduates' competences is being tackled by project-based courses, which also help to develop key innovation competences to address current societal challenges. Nevertheless, there is limited understanding about what innovation competences are developed through the different types of project-based courses. This study discusses innovation competences development in these courses with the aim of understanding how to better design educational strategies to improve them. Through content analysis, we compare the outcomes of two groups of Telecom Engineering students undergoing a capstone course following a classical product development project approach and a challenge-based course using Design Thinking. Results show that both course types contribute to developing innovation competences. Nevertheless, depending on the chosen pedagogy some competences are developed further. The traditional project-based course demonstrates better results in Planning and Managing Projects. Creativity, Leadership, and Entrepreneurship are more developed through a challenge-based approach combined with Design Thinking.

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Project based learning; challenge-based education; innovation competences; Design Thinking; multidisciplinary education

Introduction

Over the past two decades, there has been a growing discussion about the gap between industry needs and the competences of engineering graduates (Dym et al. 2005). Engineering graduates are perceived to be 'too theoretical' by the industry and face difficulties when adapting to the practical working context. Traditionally, the education of an engineer has started by laying a solid foundation in science and mathematics, and specific engineering subjects are taught only after this theoretical foundation has been established (Dym et al. 2005). This approach for engineering pedagogy contributes to the gap between industry needs and engineering graduates' competences. Furthermore, the expected competences of future engineers go beyond the purely technical skills. Competences like creativity, innovativeness, business skills, sense of responsibility, problem-based thinking, collaboration, ability to communicate and effectively dealing with stress and uncertainty, among others, will be increasingly important in the future (Pippola et al. 2012). Also ABET (Accreditation Board for Engineering and Technology 2017) and NAE (National Academy of Engineering 2004) in the United States and ENAEE – EUR-ACE® (European Network for Accreditation of Engineering Education 2020) in Europe, emphasise these competences for future engineer graduates. An education that remains only in the scope of technical skills traditionally expected from engineers will eventually limit their capabilities to influence strategy and management decisions, as well as

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concept definition for new products and services (Leitch, Dittfurth, and Davis 2011). Ultimately, the more engineers master the innovation process beyond the technical aspects, the more impact they can have in shaping the society of the future, and the greater chances they have to position themselves as decision-makers.

Existing research shows that experiential learning approaches like project-based and challenge-based education are good educational strategies to develop innovation competences. Although, it is not found in literature and thus, a deeper analysis is needed to understand which approach is better to develop the aforementioned innovation competences in engineering education. Also, there is not a clear definition of what are the innovation competences required for engineering graduates. All this led us to define our research questions as: which are the innovation competences needed for future engineers and what are the best experiential learning strategies to develop them in engineering students?

To answer our research questions, we first developed a literature review to understand which innovation competences are required for engineering graduates. Then we selected two of the experiential learning courses taken by University of Catalonia (UPC) Telecom engineering students, a product development project (PDP) course and a challenge-based course and compared the results regarding these competences. In an initial hypothesis, it was expected that the challenge-based course would notably surpass the PDP course in almost all innovation competences development, especially in Creativity, Leadership & Entrepreneurship, Teamwork, and Impact, as it is a course focused on innovation, while the PDP course is focused more on engineering design and implementation.

In the following sections, we discuss existing innovation competences models and pedagogical approaches to develop those competences. We then define a combination of these existing innovation competences models into a framework used for analysing and comparing the results of the two experiential learning approaches and we discuss conclusions and recommendations for developing educational strategies to develop innovation competences in engineering education.

Theoretical framework

Innovative behaviours may be learnt, and this learning should be based on experience and experimentation incorporating real-world experiences into the engineering curriculum (Chell and Athayde 2009; Shuman, Besterfield-Sacre, and McGourty 2005). Thus, innovators may be developed with an appropriate education strategy, training, and experience. Innovation pedagogy is a learning approach that describes in a new way how students assimilate, produce, and use knowledge in a way that can create innovations (Kairisto-Mertanen, Penttilä, and Putkonen 2010). The main idea of applying an innovation pedagogy is to 'bridge the gap between the educational context and working life', which can be achieved through learning using active multidisciplinary methods. The core of this pedagogy lies in reinforcing an interactive dialogue between the educational institution, students, real working life, and society. Its learning outcomes are the knowledge, skills, and attitudes (competences) required for innovation projects to be successful (Kairisto-Mertanen et al. 2012).

To identify the innovation competences required for engineering graduates, the literature review focused on competences demanded by relevant engineering institutions (ABET, Conceive-Design-Implement-Operate [CDIO], and ENAEE – EUR-ACE®), with emphasis on innovation competences. In addition, the most exhaustive studies in Europe on innovation competences were reviewed: Innovation Competencies Development project (INCODE), Framework for Innovation Competencies Development and Assessment (FINCODA), and National Endowment for Science, Technology and the Arts of United Kingdom (NESTA). INCODE (Watts, García-Carbonell, and Andreu-Andrés 2013, 2014) focuses on higher education, while FINCODA (Marin-Garcia et al. 2016) is meant to be applied in companies or other organisations. FINCODA was created as a new innovation competence model that complements and extends the existing ones (previously analysing more than 12 innovation competence models). NESTA developed a set of innovation competences and a tool to measure them after a broad literature review and extensive testing in the UK (Chell and Athayde 2009).

Table 1 presents a summary of the identified innovation competences considered the most relevant ones for this research. Creativity, Critical Thinking, Network, Impact, and Leadership competences are consistently mentioned in the different innovation competences' studies. In the case of engineering competences literature, the most relevant ones identified related with innovation are Investigation and Knowledge Discovery, Experimentation, Engineering Entrepreneurship, Engineering Practice, Communication & Teamworking.

In general, it was found that competences listed by ABET, CDIO and ENAEE – EUR-ACE® do not explicitly talk about innovation competences, although there are many of them that are clearly related to innovation. In these cases, where competences are not specifically branded as innovation competences, the selection was made identifying the ones related to innovation within their definitions on a first or second level, by analogy, and/or similarity with the innovation competences explicitly defined by INCODE, FINCODA, and NESTA.

Table 1. Selection of innovation competences identified for the development of engineering education according to different standards.

Source	Proposed set of innovation competences	
INCODE The Innovation Competencies Development project (Watts, García-Carbonell, and Andreu-Andrés 2013, 2014)	• Individual: creativity and critical thinking • Network: networking and impact	• Interpersonal: teamwork and leadership
FINCODA Framework for Innovation Competencies Development and Assessment (Marin-Garcia et al. 2016)	• Creativity • Critical thinking	• Intrapreneurship: initiative, teamwork, and networking
ABET Accreditation Board for Engineering and Technology (ABET 2017; Shuman, Besterfield-Sacre, and McGourty 2005)	**Process skills:** • Communication • Teamwork • Ability to identify and solve ethical dilemmas	**Awareness skills:** • Social and global factors impact understanding • Contemporary issues knowledge • Ability for lifelong learning
CDIO Syllabus v2.0 Statement of Goals for Engineering Education (Crawley et al. 2011)	**Competences related with innovation:** • Analytical reasoning and problem-solving • Experimentation • Investigation and knowledge discovery • System thinking • Teamwork	• Communication • External societal and environmental contextEnterprise and business context • Leading engineering endeavours • Engineering entrepreneurship
ENAEE – EUR-ACE® European Network for Accreditation of Engineering Education	• Knowledge and Understanding • Investigations	• Engineering Practice • Making Judgements • Communication and Team-working
NESTA National Endowment for Science, Technology and the Arts of United Kingdom (Chell and Athayde 2009)	• Creativity (imagination, connecting ideas, tackling and solving problems, curiosity) • Self-efficacy (self-belief, self-assurance, self-awareness, feelings of empowerment, social confidence) • Energy (drive, enthusiasm, motivation, hard work, persistence and commitment)	• Risk-propensity (a combination of risk tolerance and the ability to take calculated risks) • Leadership (vision and the ability to mobilise commitment)

Current research stresses an experiential learning approach, where the participants go through the key stages of innovation, moving from the concrete and abstract worlds (Beckman and Barry 2007), in an environment with diverse teams. As Fixson (2009) states that

> If innovation is understood as a process of inventing and commercializing new products and services, as a process that incorporates activities from multiple disciplines, and as a process that follows more heuristic than algorithmic rules, then perhaps this process can be taught in an interdisciplinary setting with a strong experiential emphasis, such as product design and development.

Within these experiential learning approaches, the 5th standard of the CDIO initiative (www.cdio.org) (Crawley et al. 2014), states the convenience of including two or more design-implement experiences in the engineering curricula, including one at a basic level and one at an advanced level. Adhered institutions usually have even more than two, concluding in a capstone project in the last year of engineering bachelor. They have evolved from 'made up' projects created by faculty members, to product development projects with real industry challenges sponsored by companies or institutions (Dym et al. 2005). These types of projects contribute to developing competences like teamwork, problem-solving, or communication, among others (Bragós et al. 2010; Sayrol et al. 2015).

It could be said that product development projects have traditionally trained the engineers to develop technical solutions rather than to innovate. Following OECD's (2005) definition of innovation, engineering student projects tend to be more inventions than innovations, as in general they lack sufficient considerations regarding the implementation of the solution from a value generation and value capture perspective. This contributes to the gap perceived by the industry and highlights the need to create educational strategies to develop innovation competences in engineering students that meet industry needs, but also match those key innovation competences identified by institutions.

Challenge-based learning is offered as the model that takes the best of problem-based learning, project-based learning, and contextual teaching and learning while focusing on real problems faced in the real world (Johnson et al. 2009). Challenge-based learning, as defined by Malmqvist, Rådberg, and Lundqvist (2015) is

> a learning experience where the learning takes places through the identification, analysis and design of a solution to a sociotechnical problem. The learning experience is typically multidisciplinary, takes place in an international context and aims to find a collaboratively developed solution, which is environmentally, socially and economically sustainable.

Challenge-based learning can be seen as an evolution of project-based learning but with a few differences, such as for example starting with large open-ended problems, training of self-awareness and self-leadership, and entrepreneurial mind-set. The unique idea of challenge-based learning is that problems are relevant and with global importance, related to sustainability, water, energy, poverty, etc. Also, a differential aspect is the 'call to action' that goes beyond the classroom, inviting the students to have an impact on the society with their projects (Malmqvist, Rådberg, and Lundqvist 2015).

Working with open-ended problems in a more dynamic process (compared to design-build-test projects), shifting the focus from a technical problem to a societal problem, and requiring multidisciplinary knowledge pose challenges both for faculty and students involved in challenge-based learning. This approach raises the level of ambition of engineering education, going beyond the technical arena into the socio-technical domain developing competences like multidisciplinary teamwork, decision-making, communication, and leadership (Malmqvist, Rådberg, and Lundqvist 2015).

Design Thinking has been widely recognised for effectively dealing with the high levels of uncertainty involved in challenge-based projects. It is defined by Tim Brown (2008) as 'a human-centred 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'. This innovation approach emphasises people behaviours observation for detecting needs, multidisciplinary teamwork, quick and early visualisation, and prototyping of concepts to test them iteratively during the process. Design Thinking is for innovation early stages (Carr et al. 2010) and does not replace professional design or engineering (Charosky et al. 2018). It complements and reinforces the initial phases of innovation.

In summary, today's systems and problems are progressively larger and more complex, and problems cannot be solved by applying a technical solution alone, as societal, rather than technical issues play a bigger role Lehmann et al. (2008). This has shifted (or is shifting) educational strategies from the traditional paradigm with a discipline-oriented, lecture-centric, and technical knowledge-based to a new interdisciplinary, student-centric, and contextualised, with a complex understanding of technological knowledge. Engineers today need to have skills for interdisciplinary cooperation, communication skills, project management abilities, and life-long learning abilities (Lehmann et al. 2008). However, getting to this cross-disciplinary and contextual knowledge, integrating comprehension and skills from diverse disciplines is challenging and requires innovative ways to approach education.

Empirical setting

Once identified the innovation competences for engineering graduates and the two suitable and prevalent learning approaches for developing them, we aimed to analyse, identify, and compare the engineering students' innovation competences acquired in two different types of experiential learning courses: a project-based and challenge-based combined with Design Thinking. We analysed two courses developed at ICT engineering at Technical UPC: PDP course and the CBI course (Challenge-Based Innovation [CBI]).

PDP is a mandatory project-based course developed since 2012, within the CDIO (Conceive-Design-Implement-Operate) framework that follows the classical product development process described by Ulrich and Eppinger (2008) to solve a technical challenge posed by a company or institution. The ICT engineering degree curricula at UPC was re-designed according to the EHEA directives using the CDIO Standards (Bragós et al. 2010). Three project-based design-implement courses were inserted in the second, third, and fourth year of the Telecom engineering bachelor. The PDP capstone project (named Advanced Engineering Project [AEP]) is placed in the fourth year. Students from the different minors of the Telecom Engineering degree (Electronics, Networks, Audiovisual Systems, and Communication Systems) are arranged in mixed teams to tackle a complex technical problem defined by a company, NGO, hospital, or external institution. The students should design, build, and test the different blocks of the project and finally integrate and test a proof-of-concept functional prototype. They should also define a business model. The school asks the external institutions to present challenges with a complex solution, so the teams, which are intentionally big, are forced to split in parallel workpackages and have to manage the subprojects and the system integration, resulting in a functional prototype. This course can be assimilated to an NPD (New Product Development) course (Fixson 2009). Usually, the starting point is a solution proposal and a set of requirements stated by the external institution.

Also, since 2014 students can opt to take CBI (as an alternative to PDP), a course with a challenge-based learning approach (Malmqvist, Rådberg, and Lundqvist 2015) combined with Design Thinking methodology (Brown 2008, 2009; Ratcliffe 2009).

Challenge-Based Innovation is part of a CERN program that hosts innovative educational projects (Hassi et al. 2016). The course is developed collaboratively by three educational institutions from Barcelona: UPC Telecom (engineering), Istituto Europeo di Design (design), and ESADE Business School (management), in close collaboration with IdeaSquare at CERN, one of the nodes of the Aalto Design Factory Global Network. Its objective is to design disruptive solutions to complex societal problems following a challenge-based learning approach combined with Design Thinking, considering the use of CERN technologies if suitable. In multidisciplinary teams (engineering, business and design), the students develop a solution (after an in-depth user and market research) including product and/or service, a business model, and a proof-of-concept prototype, with three periods at CERN during the project and a final gala presentation in front of authorities, professors, and press (Charosky et al. 2018). In the first editions, the challenges were defined by collaborating companies, institutions, or NGOs, and since 2017 the challenges are defined within the United Nations – Sustainable Development Goals (2015).

As observed in Table 2, the main differential aspects of these courses are the pedagogical method (Project-based vs. Challenge-based), the innovation method (NPD vs. Design Thinking), the team composition (single disciplinary vs. multidisciplinary), and the learning outcomes. Regarding the latter, it is interesting to highlight that even both courses learning outcomes mention some innovation competences, PDP does mention innovation as a learning outcome, while CBI does not. Also, PDP focuses more on project management, engineering design and implementation, and CBI focuses more on ideation and validation through prototyping and testing with users.

Methodology

Out of the six different methodologies proposed by Prus and Johnson (1994) to assess professional skills in students, 'measures of attitudes and perceptions' was chosen for this research. More specifically, self-reports named reflection documents in these courses, produced by students as part of the final deliverables of both courses and portfolios (projects) were analysed and compared. Bandura

Table 2. Course comparison: PDP vs. CBI.

Course	Pedagogical method for innovation education	Innovation method	Team composition	Learning outcomes
PDP Product development project	Project-Based	NPD (New product development)	Single disciplinary (engineering students only)	• Project management and documentation • Specific disciplinary knowledge about the project topic • Practical design, implementation, and operation skills • Generic skills learning outcomes: Innovation and entrepreneurship, Societal and environmental context, Communication in a foreign language (English), Oral and written communication, Teamwork, Survey of information resources, Autonomous learning, Ability to identify, formulate and solve engineering problems (Bragós et al. 2010)
CBIChallenge-based innovation	Challenge-based	Design Thinking	Multidisciplinary (engineering, design and management)	• Develop highly futuristic, technologically feasible ideas that have the potential to challenge the status quo in socially and globally relevant human challenges • Develop skills applying design thinking tools and methods and product design in a practical, real world project • Develop skills in moving ideas into testable, tangible prototypes quickly • Develop skills in interdisciplinary teamwork and communication (Hassi et al. 2016)

(1982) found that reflective essays written by students can be a good predictor of design performance, as self-efficacy (belief in one's own abilities toward a given task) play a fundamental role in effectively executing innovation.

As the research aims to analyse whether an educational practice makes a difference (CBI course vs. PDP course) for developing innovation competences, we used an experimental design research approach. As described by Creswell (2012), experimental designs (also known as intervention studies or group comparison studies) are 'procedures in quantitative research in which the investigator determines whether an activity or materials make a difference in results for participants'. Our research assesses the impact by having one group going through a set of activities (an intervention, in this case CBI course) and with-holding these activities from another group (in this case the PDP group).

Strictly speaking, as we are not able to address some of the key characteristics of 'true experiments' as defined by Cohen, Manion, and Morrison (2007), we must refer to a quasi-experiment. One of the characteristics that we don't have and would be desirable is a pretest of the groups to ensure parity. We have run a post-test only and a comparison of the results of the two groups.

Research is based on a qualitative analysis of 'personal reflection documents' and project results produced by the students as part of their deliverables when finishing the courses (both CBI and PDP). In these documents, students were asked to reflect on their process, lessons learnt, project's results, and future/next steps of their projects through general and broad questions. In neither case (PDP nor CBI) students were asked specifically to reflect on innovation competences and/or their perception about them.

To analyse these materials, a content analysis was followed, described by Weber (1990) as a process 'by which the many words of texts are classified into much fewer categories' with 'strict and systematic set of procedures for the rigorous analysis, examination and verification of the contents of written data' (Flick 1998). In summary, a mixed-methods research design was followed for collecting, analysing, and 'mixing' both quantitative and qualitative methods in a single study to understand the research problem (Creswell and Plano Clark 2011).

Participants and sampling

The strategy followed to define the sample to study is a purposive sampling, defined by Cohen, Manion, and Morrison (2007) as selecting the cases based on their 'typicality or possession or characteristics being sought'. We aim to have homogeneous samples (Patton 1990), with the purpose to describe two particular subgroups in depth: students that follow PDP vs. students that follow CBI course.

The characteristics that we were looking for were students who went through a project-based course working on real projects for companies, external institutions, and/or social challenges aiming to develop a technical solution and a prototype.

In this case, as described previously we analysed results and compared two groups of students of Telecom Engineering from Technical UPC:

- Students that have taken the capstone project course PDP, called AEP from 2015 to 2019 following a classical project management approach.
- Engineering students that have taken the CBI course from 2015 to 2018 following a challenge-based education approach using Design Thinking.

The population of interest can be fairly determined as all Telecom students must take one course or the other.

PDP teams are composed of 9–12 engineering students only. In CBI there are 2 engineering students in each multidisciplinary group of 5–7 people. The proportion of female engineering students in PDP and CBI is 17%, slightly below Technical UPC 25% average (Farreras 2019). Age (20–22 years), cultural (almost all Catalan), and socio-economic background is pretty homogeneous in both courses, with the only possible bias being in CBI the need for affording the cost of three trips to Geneva for the CERN periods.

Both courses have a similar student's assessment: a team mark (50% is based on the process and 50% on the outcome: technical performance and complexity, solution innovativeness, prototype, final report, and presentation), plus an individual performance modulation given by the supervisors and by peer assessment. Also, both courses have at least a weekly coaching hour with several faculty members.

Sample size

Although there is not a fixed answer in what is the minimum number of participants or cases to define a sample for quantitative, qualitative study, or mixed methods, literature suggests a rough estimate for educational research of approximately 15 participants in each group in an experiment and 30 participants for a correlational study for a statistical procedure (Cohen, Manion, and Morrison 2007; Creswell 2012).

As the number of cases to be analysed are in both cases (PDP and CBI) more than 30 personal reflections and project results, we could say that it is enough to withdraw relevant conclusions.

Data collection

All personal reflection documents delivered and final project reports within the period researched were collected, being a total of 77 documents analysed with 38 from PDP and 39 from CBI (Table 3). The reason for having less reflection documents in the first years for PDP is that only projects with external stakeholders (companies or institutions) have been chosen for the analysis. These were gradually increased in the following years.

Data analysis

The analysed data are the 77 reflection documents produced by the students, with the aim of identifying mentions, insights, conclusions, keywords, and learning outcomes related to innovation competences through content analysis and data coding.

The sought data in the documents was evidence (direct or indirect) of innovation competences discussed in research and literature previously defined: CDIO, ABET, ENAEE – EUR-ACE®, NESTA, INCODE, and FINCODA projects. The competences identified in the literature review (Table 1) were merged and structured into a framework (Table 4) that synthetises and condenses all the competences into eight themes or categories composed of 26 innovation competences. The framework was developed through an iterative process of analysis and coding of the documents done separately by the authors, later discussing its validity and utility, evolving it into the final set of themes and codes innovation competences (derived from literature review) and used for the analysis of the documents (Table 4).

Table 3. Total number documents analysed per year and course.

Year	PDP No of reflection docs	CBI No of reflection docs
2015	3	9
2016	2	10
2017	15	10
2018	10	10
2019	8	-
TOTAL	**38**	**39**

Table 4. Innovation competences framework: themes and code system

1. Creativity • User awareness • Uncertainty management • Idea generation • Design Thinking	2. Planning and managing a project • Planning • Organisation • Time management
3. Leadership & entrepeneurship • Entrepreneurship • Leadership/Initiative • Energy • Risk-propensity	4. Teamwork • Communication • Coordination • Multidisciplinary
5. Impact • Business sense • Social impact • Sustainability	6. Personal & professional skills • Self-efficacy • Critical thinking • Self-awareness for professional life
7. Networking • Networking	8. Experimentation & knowledge discovery • Problem-solving • Technical solution/Technology • Investigation & Knowledge discovery • Experimentation

The process followed for the content analysis was the one described by Tesch (1990) and Creswell (2007). Using a convergent approach, the coded qualitative data were descriptively analysed and the frequency of occurrence of these codes was counted (Creswell 2012).

Finally, a total of 1665 segments were coded, 790 (47%) in 38 documents from PDP and 875 (53%) in 39 documents from CBI.

To analyse the data, the software for text analysis MAXQDA was used, as it enables to combine both qualitative and quantitative procedures. It allows identifying specific words and expressions as codes, organising the codes by themes, and counting and classifying them. The analysis consisted on reviewing all the texts imported in the software and manually marking all expressions that would have the same meaning than a given code under its category.

Results and discussion

This section has been split into two parts: in Results, there is first a neutral description of the numerical results of the code frequencies, commenting the content of the tables and the figures (in the online version) and the specific results within each group of innovation competences. Subsequently, in the Discussion subsection the authors' interpretation of the results are described.

Results

When analysing the groups of innovation competences or themes, it is observed that both courses CBI and PDP help to develop all innovation competences as shown in Table 5. Nevertheless, each course clearly emphasises some competences over others as observed in Figures 1 and 2. Planning and Managing a Project, Leadership & Entrepreneurship, and Creativity are the three groups of

Table 5. Innovation competences themes and total number of coded segments and row percentages.

	PDP		CBI		
	No of coded segments	%	No of coded segments	%	Total
Creativity	**73**	**22%**	**164**	**78%**	**237**
User awareness	21	36%	37	64%	58
Uncertainty management	47	42%	65	58%	112
Idea generation	5	9%	53	91%	58
Design Thinking	0	0%	9	100%	9
Planning and managing a project	**175**	**86%**	**30**	**14%**	**205**
Planning	36	97%	1	3%	37
Organisation	103	86%	17	14%	120
Time management	36	75%	12	25%	48
Leadership & entrepreneurship	**46**	**16%**	**117**	**84%**	**163**
Entrepreneurship	0	0%	21	100%	21
Leadership/Initiative	13	21%	50	79%	63
Energy	33	43%	44	57%	77
Risk-propensity	0	0%	2	100%	2
Teamwork	**127**	**41%**	**179**	**59%**	**306**
Communication	49	60%	33	40%	82
Coordination	77	64%	44	36%	121
Multidisciplinary	1	1%	102	99%	103
Impact	**27**	**35%**	**54**	**65%**	**81**
Business sense	17	44%	22	56%	39
Social impact	8	22%	29	78%	37
Sustainability	2	40%	3	60%	5
Personal & professional skills	**130**	**45%**	**144**	**55%**	**274**
Self-efficacy	80	53%	72	47%	152
Critical thinking	36	60%	24	40%	60
Self-awareness for professional life	14	23%	48	77%	62
Networking	**23**	**29%**	**56**	**71%**	**79**
Experimentation & knowledge discovery	**189**	**56%**	**131**	**44%**	**320**
Problem-solving	54	58%	39	42%	93
Technical/Technology development	95	64%	54	36%	149
Investigation & Knowledge discovery	20	50%	20	50%	40
Experimentation	20	53%	18	47%	38
SUM	790	47%	875	53%	1665
N = Documents	38	38 (49%)	39	39 (51%)	77

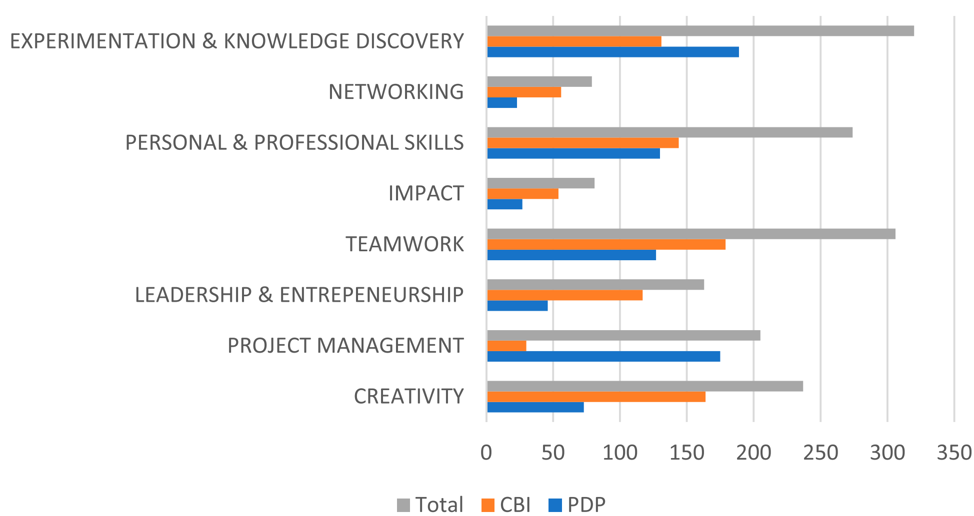

Figure 1. CBI and PDP total coded segments by innovation theme.

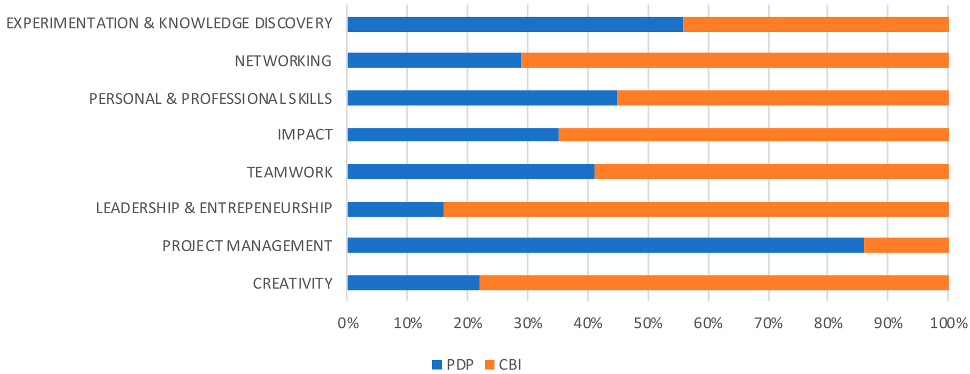

Figure 2. CBI and PDP total innovation themes coded percentages.

innovation competences with the biggest differences. On the other themes/groups of innovation competences the differences are not as big in a general view, but when looking at specific competences (codes) within the themes, great differences can be found as observed in Table 5. It is also observed that Experimentation & Knowledge Discovery, Teamwork, and Personal & Professional Skills are the competences with most coded segments in total. Table 6 shows where are the

Table 6. PDP and CBI Innovation competences percentages based on the total number of coded segments.

	PDP	CBI	Total
Creativity	**9.2%**	**18.7%**	**14.2%**
User awareness	2.7%	4.2%	3.5%
Uncertainty management	5.9%	7.4%	6.7%
Idea generation	0.6%	6.1%	3.5%
Design Thinking	0.0%	1.0%	0.5%
Planning and managing a project	**22.2%**	**3.4%**	**12.3%**
Planning	4.6%	0.1%	2.2%
Organisation	13.0%	1.9%	7.2%
Time management	4.6%	1.4%	2.9%
Leadership & entrepreneurship	**5.8%**	**13.4%**	**9.8%**
Entrepreneurship	0.0%	2.4%	1.3%
Leadership/Initiative	1.6%	5.7%	3.8%
Energy	4.2%	5.0%	4.6%
Risk-propensity	0.0%	0.2%	0.1%
Teamwork	**16.1%**	**20.5%**	**18.4%**
Communication	6.2%	3.8%	4.9%
Coordination	9.7%	5.0%	7.3%
Multidisciplinarity	0.1%	11.7%	6.2%
Impact	**3.4%**	**6.2%**	**4.9%**
Business sense	2.2%	2.5%	2.3%
Social impact	1.0%	3.3%	2.2%
Sustainability	0.3%	0.3%	0.3%
Personal & professional skills	**16.5%**	**16.5%**	**16.5%**
Self-efficacy	10.1%	8.2%	9.1%
Critical thinking	4.6%	2.7%	3.6%
Self-awareness for professional life	1.8%	5.5%	3.7%
Networking	**2.9%**	**6.4%**	**4.7%**
Experimentation & knowledge discovery	**23.9%**	**15.0%**	**19.2%**
Problem-solving	6.8%	4.5%	5.6%
Technical solution/Technology	12.0%	6.2%	8.9%
Investigation & Knowledge discovery	2.5%	2.3%	2.4%
Experimentation	2.5%	2.1%	2.3%
SUM	100%	100%	100%
N = Documents	38	39	77

bigger percentages of coded segments, to visualise which innovation competences are more present in students' reflection documents in each course.

On a deeper level of detail, as shown in Figure 3, analysing the percentages of specific innovation competences, we can observe big differences in PDP and CBI. While in PDP the bigger percentages of coded segments can be found in Organisation (13%), Technical solution/technology (12%), Self-efficacy (10.1%), Coordination (9.7%), Problem-Solving (6.8%) and Communication (6.2%); in CBI the bigger percentages are in Multidisciplinarity (11.7%), Self-efficacy (8.2%), Uncertainty management (7.4%), Networking (6.4%), Technical solution/Technology (6.2%), and Idea generation (6.1%).

In general, it could be said that CBI has a more balanced distribution of innovation competences development, while in PDP it is more concentrated towards some specific engineering-related competences. Also, as shown in Table 6, CBI shows better results in Creativity, Leadership & Entrepreneurship, while PDP demonstrates better results in Planning & Managing a Project and Experimentation &

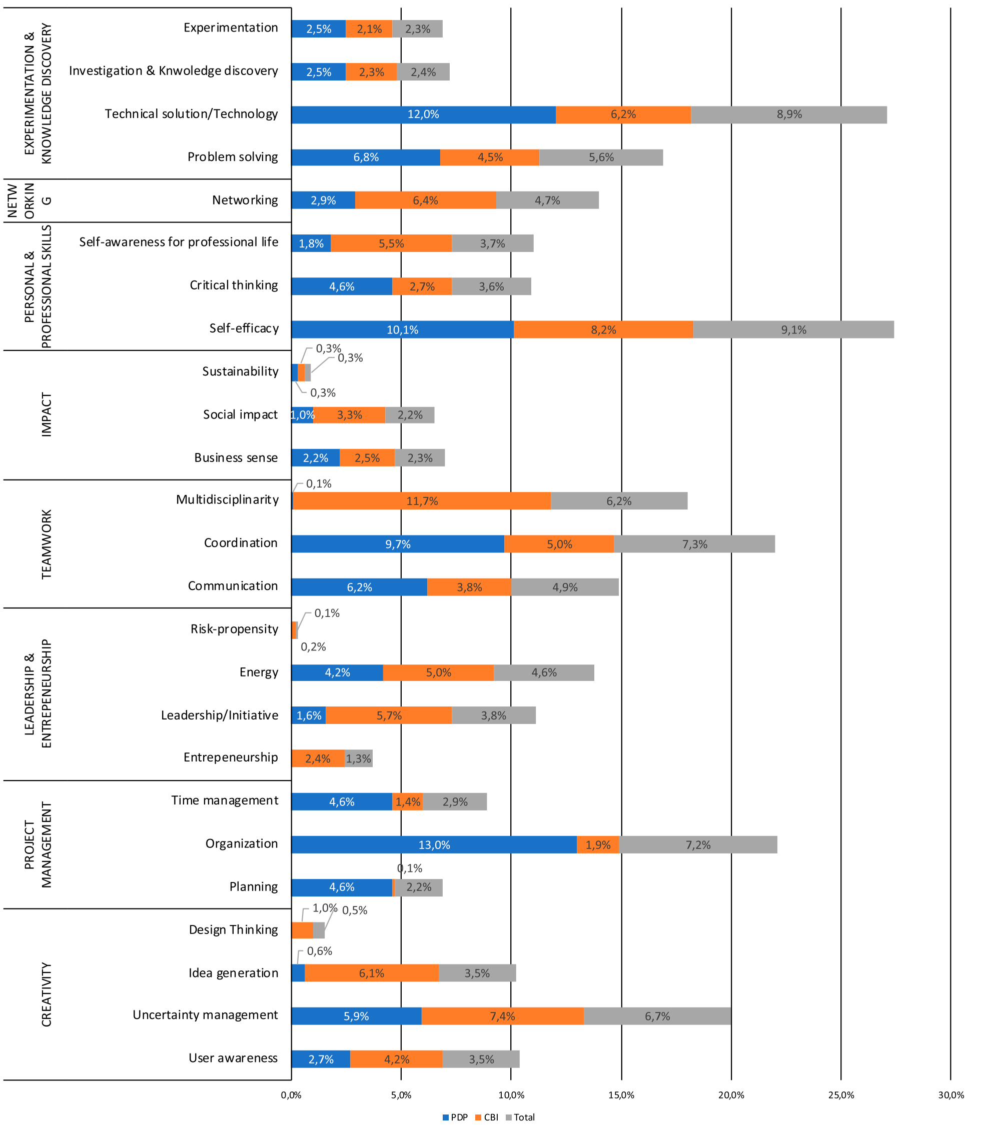

Figure 3. PDP and CBI Innovation competences percentages based on the total number of coded segments.

Knowledge discovery. Teamwork, Impact, and Networking have smaller differences, but with better results towards CBI and results in Personal & Professional skills are equal in both courses.

In the following paragraphs, the results within each of the eight innovation competences groups are presented in depth. Table 7 highlights some quotes related to each innovation competences group.

More specifically, the innovation competences related to Planning and Managing a Project (Planning, Organisation & Time Management) are which on average show the biggest difference between the two courses. Within the three competences related to Planning and Managing a Project, the biggest difference found is in Planning, with 36 (97%) mentions in PDP and only 1 (3%) mention in CBI. The differences are also big in Organisation, with 103 (86%) in PDP and 17 (14%) in CBI, and in Time Management, with 36 (75%) in PDP and 12 (25%) in CBI.

Leadership & Entrepreneurship, composed of the competences Entrepreneurship, Leadership/Initiative, Energy, and Risk-propensity, is the second set of innovation competences with the major difference observed, being 16% in PDP and 84% in CBI on average. The total number of coded segments is 163, with 117 for CBI and 46 for PDP (Table 5). No evidence or mentions of entrepreneurship are found in PDP and 21 coded segments are found in CBI. Regarding leadership, even though that PDP teams are required to define a project leader (while CBI teams don't), there are more findings in CBI related to this competence (50 coded segments in CBI vs. 13 in PDP). Regarding Energy, there is a small difference, with 44 coded segments for CBI (57%) and 33 for PDP (43%). Finally, there are only two mentions of Risk-propensity found in CBI.

Creativity, containing the competences of User awareness, Uncertainty management, Idea generation, and Design Thinking, is where is found the third biggest difference of the research (Table 5), with 22% in PDP and 78% in CBI, from a total number of coded segments of 237 (73 for PDP and 164 for CBI). Within this set of innovation competences, idea generation is where the more relevant difference is identified with only five mentions in PDP and 53 mentions in CBI. Design Thinking has nine mentions in CBI and no mentions in PDP (it was not explicitly included in this course during the analysed period). Even though that PDP is not taking a declared user-centered innovation approach, the difference in the level of user awareness is not as high as in other competences (21 mentions in PDP vs. 37 mentions in CBI).

Another big learning in this type of projects is uncertainty management, with little differences found between CBI (47 coded segments) and PDP (65 coded segments). Even though in PDP both requirements and outcomes are more defined, students struggle in both courses when they do not have an exact specifications of what to do, as observed in the quotes from Table 7.

Innovation competences' learning related to impact (Business sense, Social impact, and Sustainability) are also having a relevant difference between PDP (35%) vs. CBI (65%), out of a total number of mentions of 81, with 54 for CBI and 17 for PDP (Table 5). Even though the total number of mentions related to Impact is not so big (81). The main difference is in Social Impact with 29 mentions in CBI vs. 8 mentions in PDP. Regarding sustainability there are only 3 mentions in CBI and 2 mentions in PDP. And regarding business sense, there are 39 mentions, with a little difference in favour of CBI (22) vs. PDP (17).

The total number of evidence found in the analysed documents related to Networking is small (79) compared to other themes (Table 5). It has more weight in CBI (71%) than in PDP (29%). In most cases related to contacts with stakeholders and companies.

One thing to highlight is the relationship with CERN in CBI, which is mentioned a total of 17 times in the 39 CBI personal reflections & project conclusions.

Overall, there is a small difference between PDP (41%) and CBI (59%) students' competences development within Teamwork (Communication, Coordination, and Multidisciplinary) with a total number of coded segments of 306, 127 for PDP and 179 for CBI (Table 5). Specific mentions to coordination and communication are found with little more frequency in PDP students' analysed documents (49 vs. 33 for Communication and 77 vs. 44 for Coordination). Nevertheless, the big difference is in the multidisciplinary competence. In CBI students' documents there are found 102

Table 7. Innovation competences quote examples.

Innovation competence	Examples of quotes
Creativity • User awareness • Uncertainty management • Idea generation • Design Thinking	'was an interesting experience … to explore different ways of thinking and learning how an idea is created and developed' 'it is no bad for an engineer to be down to earth but he has to keep in mind his imagination is important too' 'we had plenty of interviews with doctors and victims and, for sure, we learnt a lot from them' 'a good engineer does not only have to know about the implementation, he also must think about the real demand of users' 'bigger efforts should be put in providing the project with clearer specifications and benchmarks' 'few things could be improved. The first of them is the excessive freedom we are given' 'I have the impression we were never told in clear terms what the course was about or what we were expected to do' and 'I started to like more and more this methodology although some phases were pushing me outside of my comfort zone'
Planning and managing a project • Planning • Organisation • Time management	'we did it thanks to good planning and coordination' 'there should be also a more important part in project management, which has proven itself to be the cornerstone of everything, and has been only given a quick look, and it could be an area of interest to some team members, more than the most technical part'
Leadership & entrepeneurship • Entrepreneurship • Leadership/Initiative • Energy • Risk-propensity	'I took the lead on organizing what tasks we had to do and who was the responsible for performing those assignments' 'One of the most interesting things I've learned during the course is how to make my voice heard and how to influence team decisions' 'Once we continue the research and try a prototype with the costumer we already have, the idea would be to create a startup.' 'The role that I would like to play if we create a startup is not only in the technology part, I would like to take part in all the decisions made within the process and also when the company grows'
Teamwork	'we could have done better as a team is to communicate more often and more accurately between the different subgroups' 'the team's weakness during the project was organization' 'the fact of working with people from other disciplines gave me an insight of the real world that I couldn't have received from any other place' 'before doing this project I thought that other disciplines were not as useful as my own. Now I can see that the part of engineering needs all the other disciplines as much as they need us in the process of building a company'
Impact	'Explaining how our engineering impacts over society and over the environment is something that always will be demanded by any entity' 'We had the opportunity to verify that our knowledge and our ideas can have a positive impact in the world'
Personal & professional skills	'I have learnt many things here that any theoretical course or lecture can't teach, and I feel much more prepared now for the real life, real projects and real work' 'this project has taught me a lot of key skills that are crucial for the professional life' 'we have learnt a lot from other branches which are in principle not taught in engineering and that surely they are essential in the professional world' 'I have learned a plethora of things that I am sure will be very valuable for my future professional career' 'the learning outcomes of the project are both very valuable and very sought in the professional world'
Networking	'regarding the companies we met during the course, we are analyzing which of them are the best so as to purpose a partnership' 'working with such a good institution as CERN has made us build a very powerful contact network'
Experimentation & knowledge discovery	'using Blockchain Technology we have successfully tackled the royalty distribution problem' 'a complete architecture for the radar has been built and a display for monitoring the vital signs has been designed, which also include the heartbeat frequency, breath rate and alarms in case of tachycardia, bradycardia and apnea' 'we have seen that one way to do an accurate design is to have a simple prototype that works and then to improve it'

mentions to this competence, being the most mentioned topic by these course students. In PDP there is only one mention, and even it refers to multidisciplinary it is actually considering different engineering specialties. The fact that in CBI the teams are composed by students of three different institutions and different profiles (engineering, business, and design) is highly appreciated by engineering students, as observed in the documents.

Within Experimentation & Knowledge discovery competences (Problem-solving, Technical/Technology development, Investigation & Knowledge discovery, and Experimentation), the difference found between PDP and CBI is 64% vs. 36% out of a total of 320 coded segments, with 189 for PDP and 131 for CBI (Table 5). Problem-solving (54 in PDP vs. 39 in CBI), Investigation & Knowledge discovery (20 in both PDP and CBI), and Experimentation (20 in PDP and 18 in CBI) are pretty well balanced in both courses as found in the analysis of projects' documentation and reports. The main difference is the fact that in PDP there is more evidence of mentions related to Technical/Technology development, being 64% (95) vs. 36% (54) in CBI of a total of 149.

Regarding Personal and professional skills (Self-efficacy, Critical Thinking, and Self-awareness for professional life), there is a very slight difference found on CBI (55%) with respect to PDP (45%), with a total of 274 coded segments, 130 for PDP and 144 for CBI (Table 5). Competences related to Critical thinking (36 for PDP vs. 24 for CBI) and Self-efficacy (80 for PDP vs. 72 for CBI) are almost equally found in both courses' students, with a little more emphasis on PDP students. What makes the difference in this group is the competence defined as Self-awareness for professional life, which is more mentioned in CBI (77%) than in PDP (23%).

Discussion

Our research demonstrates that both learning methods are good educational strategies for developing competences and, explicitly, innovation competences in engineering education, but each strategy emphasises some competences more than others. The big differences found in Planning and Managing a Project, Leadership & Entrepreneurship, and Creativity are aligned with the initial hypothesis. But our study also revealed that as well as CBI, PDP greatly contributes to develop all other innovation competences to a relevant extent, according to the reflections reported by the students. Although the two engineering education strategies were a priori known to be successful in innovation competences development, it was considered worthy to perform this study. This is due to the fact that, after more than one decade of experience developing both kind of courses, it was observed that the PDP model is easily accepted by the engineering school faculty members as a natural way of providing a context closer to the engineering practice, while the challenge-based model finds more reluctancy to be accepted. So the study was intended to highlight the diferential benefits, although being both of them highly beneficial.

The major emphasis on Planning and Managing Projects competences in PDP might be due to the fact that in this course the focus is more on achieving a technical solution to a clearly defined industry problem from a company. Thus, students focus more on a traditional project management approach and on problem-solving and technical/technology development. All emphasis is put into execution and not in exploration (Loch, De Meyer, and Pich 2006). Also, PDP has more demanding requirements for project planning and reporting, including bigger teams (9–12 people in PDP vs. 5–7 in CBI), which might influence this bias. This may be due to the fact that in PDP, the projects are technically complex and the teams are intentionally big, in order to force them to split in parallel workpackages and have to manage the subprojects and the system integration. Also, for the CBI course, the project plan is implicit in the Design Thinking methodology steps, and the students are asked to report the intermediate results with short presentations instead of formal reports.

The fact that Leadership & Entrepreneurship competences are more developed in CBI is probably due to that in most PDP projects the sponsors or clients pose very specific technical problems, with very concrete requirements of current business or industry needs. Thus, PDP students do not consider or need to employ entrepreneurship competences because they work on a technical solution within a very well-defined framework of an existing company. On the contrary, CBI students, even though they have project sponsors (yet not in all cases), are given challenges that are wide open and do not sit on short-term specific industry/company needs or requirements. This openness allows students a great freedom in the solution space (Ratcliffe 2009), making it possible to develop solutions integrated (or to integrate) in existing companies' processes or creating hypothetical startups that would develop and market the solution.

The fact of having an external institution, either a company, a startup, or any entity from outside the school proposing a challenge or project briefing provides a great sense of reality and develops a greater engagement and sense of responsibility in the students. It provides them a real practice in what could be typical projects they would face when graduating and start working at a company. On the other hand, if instead of having companies putting challenges, the framework is broader like the SDG-Sustainable Development Goals from UN (like in CBI), this brings another perspective and greater learnings and focus on the social impact of student's projects, as opposed to PDP where the focus is on a technical issue from the industry. Also, not having a 'client' with clear requirements, allows the entrepreneurial spirit to naturally raise in the students. As what they develop is not for an existing company, and the solution they create has not an existing channel for going to market, the idea of creating a hypothetical startup that would market that solution is more likely to appear. On the contrary, in PDP like projects, the idea of building a startup only makes sense when the institutions are not the ones developing the product/service (as in the case of NGOs or hospitals) while in the projects stated by industrial or services companies, the students' business model is more likely an engineering consultancy.

Another relevant fact is that in CBI, UPC (engineering) students are exposed to business and entrepreneurship sessions from ESADE (business) professors. Also, having MBA students and designers in the same teams with the engineers and interacting together with other stakeholders, as it is likely the case in a real startup, has a positive influence in developing leadership and entrepreneurship competences. On the other hand, PDP students in general have interlocutors, both from the company and from the supervisors' side, that are technical staff and engineers. Probably that is why there is no evidence or mention of entrepreneurship in PDP, whereas there are 21 coded segments found in CBI. This is in line with the results discussed by Palomäki (2019), which demonstrated that CBI has a positive impact on the entrepreneurial intentions of the students participating in this course. Regarding leadership, even though that PDP teams are required to define a project leader, there are more findings in CBI (where this leader figure is not formally chosen but naturally appears) related to this competence. As in this type of challenge-based course the level of uncertainty is higher (Malmqvist, Rådberg, and Lundqvist 2015) and tasks and deliverables are less defined, students' leadership is triggered as they need to find the answers and define what to do by themselves.

Factors like learning the Design Thinking process in CBI with its dedicated time slots for idea generation and iteration, as well as specific sessions with tools and methodologies for ideation definitely make a difference in developing Creativity competences in this course. Furthermore, Impact innovation competences are more developed in CBI possibly because of having more emphasis on social impact due to focus, especially since in the last years the challenges have been framed around the United Nations SDGs (2015) as mentioned above. The students, therefore, have to reflect more on the end-to-end implications of the solutions they are developing. Also, regarding to business sense, the fact of being in contact with MBA students and having specific classes on this from ESADE clearly make a difference. On the other hand, the PDP course students usually see the business model as a side topic of the project.

The multidisciplinary experience (engineering, design & business) has proven to be a successful tool to enhance the innovation and entrepreneurial skills in engineering students but due to its cost (teaching staff involved, dedicated spaces, …), it probably 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 in engineering education. Thus, it is highly recommended to introduce some degree of multidisciplinary in project-based courses. Students perceive this as a 'real life professional experience', as they are aware that in this type of team is how they will really work when they graduate, interacting with people from different disciplines.

It is important highlighting that one of the limitations of this research is that all the data analysed are post-test, without having a starting assessment. Although it was not possible in our study, for further research it would be recommended to have a pre-test and post-test, in order to compare student's innovation competences before and after the courses. This would give a more precise measurement of the impact on innovation competences of both type of courses. Also, it is important to mention that by default all students should initially take the PDP project course, but the CBI course is offered as an alternative way of doing it. For being accepted to CBI they need to proactively opt for it, and they have to present their grades and a motivation letter. This poses a potential risk for the study, as CBI students may already have a certain bias or motivation to better develop innovation competences vs. PDP students. This risk is also mitigated as PDP course runs twice a year (Fall and Spring terms) and CBI only runs once a year (Fall term), being that students taking the project-based course in the 2nd semester cannot opt to attend CBI. In addition, students enrolling in CBI acknowledge that their initial main motivation is the relationship with CERN.

Even though this research was focused on engineering education and only ICT engineering students' projects results were analysed, we could argue that the conclusions on experiential learning approaches for developing innovation competences could be applied to any field (not only in engineering). As discussed in the literature (Marí-Benlloch, Martínez-Gómez, and Marin-Garcia 2017), they are transversal competences that any future graduate and the society would benefit from. Being ICT an innovation driver in any field, due to the digitalisation trend, with most innovation projects in any field including an APP, AI, or IoT solutions, the fact of working with ICT engineering students gives an extra degree of value and reality to the projects.

Conclusions

Our study summarised the innovation competences needed for engineering students and confirms that experiential learning experiences like project-based and challenge-based education combined with Design Thinking are methods that successfully contribute to developing the aforementioned innovation competences, answering our initial research questions.

We can say that regardless of the effort and resources needed to develop these experiential learning experiences, it is worth to promote these types of courses (either project-based or challenge-based) to develop innovation competences on engineering students much needed by the industry and the society. We need people trained to innovate, to face the huge challenges ahead of us, like climate change, access to water, poverty, among others, that are well summarised in the SDG from UN. Following a traditional project-based course is better suited for developing Planning and Managing a Project related innovation competences and Experimentation & Knowledge Discovery. For developing Creativity and Leadership & Entrepreneurship competences, a challenge-based course combined with Design Thinking approach would be a better choice. Finally, both methods are similarly appropriate for developing all other innovation competences related to Teamwork, Impact, Personal & Professional Skills, and Networking.

Although a full immersion in Design Thinking like CBI probably cannot be extended to all engineering students due to the high number of resources required (trained teaching staff, dedicated coaches and spaces, time and calendar restrictions for the multidisciplinary projects), a basic knowledge of the basics of these user-centric innovation approaches would be very beneficial for engineering students. Nevertheless, there is a tradeoff that needs to be well balanced: the dedicated time for direct contact with users improves the creative part (needfinding, ideation) but reduces the time for designing, implementing, and testing complex solutions and the associated learning outcomes. Then, with limited time and resources, engineering educators should choose between focusing more on entrepreneurial skills or technical skills. The (not so) standard PDP courses would provide tools to get the learning outcomes of analytical design and more time for developing the technical solutions, but missing the value of empathising with users, deeply understanding needs, and penalising creativity.

A possible logical scenario could be to dedicate one semester to a CBI-like course and afterwards a PD-like course with the same challenge, in which the technical implementation of the idea generated and validated in the first one is performed. Nevertheless, the complexity and abstraction ability needed to perform CBL is higher than the one needed to follow a PDP course. Then, the reverse order would be more suitable, although having the same challenge would not be needed in that case. From our findings, the only evidence is that both kinds of courses provide learning outcomes on some innovation-related competences (as expected and known beforehand). But there is a clear advantage for developing Creativity and Leadership & Entrepreneurship competences using a challenge-based course model combined with Design Thinking approach, in which the multidisciplinarity and user approach are key factors. Therefore it is worth to provide this kind of experience to the engineering graduates.

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