Project-Based Learning in Industrial Engineering and Management: analysis of three curricular projects

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Abstract

In the 2nd semester of 2004/05 the Department of Production and Systems (DPS) of the Engineering School, University of Minho (UM), Portugal, deployed the first Project-Based Learning (PBL) approach, involving the freshman students of the Industrial Engineering and Management Integrated master's degree (MIEGI). Since then, in every year, without exception, new PBL editions have been held in different years of the programme, each with its own characteristics. The experience gained over time has allowed the change/refinement of conceptual and operational aspects of the projects, always bearing in mind a perspective of continuous improvement. In 2021/22 MIEGI underwent a major restructuring and gave rise to two programs: a 3-year bachelor's degree (LEGI) and a 2-year master's degree (MEGI). The curricular structures of these two programs include four integrated projects: three from LEGI (PIEGI1, 1st year; PIEGI2, 2nd year; and PIEGI3, 3rd year) and one from MEGI (PIEGI, 1st year). This paper aims to describe and compare three of these projects, more specifically PIEGI1, PIEGI3 and PIEGI, from a conceptual and operational point of view. One of the most important aspects in this description and comparison is the main objective of each project, which is defined considering the transversal and technical competences that make sense to develop in the respective curricular year. From the point of view of the development of technical competences, these derive mostly from the project supporting courses involved. Furthermore, several other aspects are considered, namely: problem characteristics, number and size of student teams, number and type of tutors, involvement of companies, milestones, deliverables, assessment model, coordination team composition, premises, etc. The findings show that these projects result from an integrated and complementary approach whose overall goal is to develop in students, throughout each year of the programme, key competences for their professional life.

Keywords: Engineering Education; Active Learning; Project-Based Learning; Curricular Projects.

1 Introduction

Projects are part of the identity of the engineering curriculum. Probably all engineering programs worldwide have at least a project course in one semester. Nevertheless, many changes have occurred in the last 50 years in engineering education (Kolmos & De Graaff, 2014). Research in engineering education has contributed with evidence about Project-Based Learning (PBL), helping instructors to understand its effectiveness in terms of students' learning (Guo et al., 2020). Thus, it is not surprising that PBL becomes a popular approach in engineering (Kolmos & De Graaff, 2014), particularly because it can be implemented in different ways, according to the educational context (Helle et al., 2006):

- Project exercise: students should apply knowledge in the context of a subject area. This is the most traditional PBL approach.
- Project component: the scope is larger, and the project becomes more interdisciplinary. It is connected to the real-world issues and students' learning focuses on working in teams to find out a solution for the problem. Often, project is supported by the courses studied in parallel.
- Project orientation: The curriculum is project oriented, thus PBL is the whole curriculum philosophy of the engineering program.

Considering the diversity of PBL models and practices, as well as its dissemination, the PBL concept cannot be reduced to a curriculum level or to a teaching methodology to be implemented. PBL definition must be a defined set of learning principles, namely: (i) the outcomes related to the learning objectives, (ii) type of problems and projects, (iii) progression, size, and duration, (iv) students' learning (by working in teams); (v) academic staff and facilitation, (vi) space and organization, (vii) assessment and evaluation (Kolmos & Graaff, 2015).

These principles can be identified in different PBL models and practices worldwide. Referring some examples, also cited in the MIT report 'The Global state of the art in engineering education' by Graham (2018); in United States, Olin College; in Latin America, Monterrey Tech in Mexico; in Australia, Charles Sturt University; in Asia, Singapore University of Technology and Design; in Europe, Aalborg University; University College of London.

In Portugal, the Department of Production and Systems (DPS) of the School of Engineering of the University of Minho (UM), has almost two decades of experience in the implementation of Project-Based Learning (PBL) in its main Industrial Engineering and Management (EGI) programs, with a core team of teachers and researchers that has undergone little changes over time. A large dissemination of the work developed was carried out, encompassing many different aspects such as: PBL management (A. Alves et al., 2016; Lima, Dinis-Carvalho, Sousa, Alves, et al., 2017) and operationalization (A. Alves et al., 2017; Lima et al., 2012), teachers workload (A. C. Alves et al., 2016; A. C. Alves, Moreira, Leão, et al., 2019), tutors role (A. C. Alves et al., 2017; Leão et al., 2022), assessment models (Fernandes et al., 2012a, 2012b, 2021; Moreira et al., 2009), students' feedback (A. C. Alves et al., 2020) production systems prototypes (Moreira & Sousa, 2008; Sousa, Moreira, et al., 2014), serious games (Sousa, Alves, et al., 2014) interaction with industry (Lima et al., 2018), connection between PBL and industry demand for competences (Lima, Dinis-Carvalho, Sousa, Arezes, et al., 2017; Lima et al., 2014; Mesquita et al., 2009).

The main objective of this paper is to describe and analyse the PBL approach adopted by DPS in its two main Industrial Engineering and Management programs (Bachelor's degree – LEGI, and, Master's degree - MEGI), by comparing three of the four integrated projects included in the curricular structure of these programs: (i) Integrated Project in Industrial Engineering and Management I (PIEGI1-LEGI), Bachelor's degree, 1st year, 1st semester; (ii) Integrated Project in Industrial Engineering and Management III (PIEGI3-LEGI) Bachelor's degree, 3rd year, 2nd semester; and Integrated Project in Industrial Engineering and Management (PIEGI-MEGI), Master's degree, 1st year, 1st semester. The comparison addresses both conceptual and operational aspects.

The paper is structured in five sections. After the current introduction, section 2 describes the methods inherent to this work. The third section is dedicated to the description and characterization of the three integrated projects. Section 4 presents and discusses the results, and, lastly, section 5 provides the concluding remarks.

2 Methods

For the development of this study, a document analysis was carried out based on the project guide (document containing the most relevant information about each project) and, although with less detail, the institutional assessment reports of the course unit (CU). In relation to these last reports, only the overall satisfaction level of the students was analysed in relation to the three PBL integrated projects under study.

The analysis of each project (sections 3.1, 3.2 and 3.3) was led by its project coordinator with the support of the remaining authors, also making use of feedback from other teaching staff, collected informally throughout the semester.

To characterize each integrated project, the following set of parameters was defined: (i) number of ECTS (European Credit Transfer and Accumulation System), (ii) duration, (iii) curricular year, (iv) number of project supporting courses, (v) number of project supporting courses of the industrial Engineering and management area, (vi) number of companies involved, (vii) numbers of students involved, (viii) number of teams (and teams' size), (ix) size of the coordination team, (x) number of tutors, (xi) role of the tutors, (xii) premises, (xiii) number of milestones, (xiv) number of deliverables, (xv) number of seminars, (xvi) assessment model, (xvii) peer assessment, and (xviii) students satisfaction level.

The comparison of the PBL projects was based on this set of characterisation parameters, and it should be noted that the information regarding the last parameter was gathered from the institutional CU report.

3 Analysis of the Projects

This section contains the characterization of the three integrated projects under study, according to the parameters defined in the previous section, but also adding other information, namely in terms of technical and transversal competences development.

3.1 PIEGI1 – LEGI

The Industrial Engineering and Management bachelor's degree (LEGI) has six CU in the 1st semester of the 1st year, each holding five ECTS (1 ECTS means 28 hours of student work). Five CU contribute as project supporting courses (PSC) for the Integrated Project PIEGI1 (Table 1). Two are taught by the UM Sciences School: Calculus for Engineering, and Linear Algebra for Engineering and the remaining four are from the UM Engineering School: Computer Programming I, Integrated Project on Industrial Engineering and Management 1 (PIEGI1), Introduction to Economics Engineering and Introduction to Industrial Engineering and Management. As with any engineering program, LEGI's 1st year includes Science, Technology, Engineering and Mathematics (STEM) courses that must be integrated in into an interdisciplinary project to solve a challenge provided to teams (A. C. Alves, Moreira, Carvalho, et al., 2019).

Table 1. Project Supporting Courses for PIEGI1 – LEGI (bachelor's degree, 1st year).

Course Unit	Scientific Area	ECTS (credits)
Calculus for Engineering	Mathematics	5
Linear Algebra for Engineering	Mathematics	5
Computer Programming I	Engineering Sciences	5
Introduction to Economics Engineering	Industrial and Systems Engineering	5
Introduction to Industrial Engineering and Management	Industrial and Systems Engineering	5

The challenge given to the students in the context of the PIEGI1 is focused, since the first edition, on sustainability issues (A. C. Alves et al., 2018; Colombo et al., 2015; Moreira et al., 2011). The 2022/23 PIEGI1 edition was no exception and addressed the "Separation, remanufacturing, revaluation, upcycling and/or recycling of end-of-life clothes" theme. Teams should design a product and the corresponding production system for the treatment of end-of-life clothes, reducing those that will be sent to landfills.

The PIEGI1 project involved teachers from different courses, voluntary tutors (department lecturers and third year LEGI students) and, sometimes, voluntary educational researchers in a total of 17 team members to manage in the edition of 2022/23. The project is regularly developed in the 1st semester, i.e. from September to January. The coordination team defines the project management (time, resources, theme and so on), before classes start (1st week of September). More details are provided in A. C. Alves et al. (2021). In the first week of classes, the project is presented to freshman students, which arrive at university one week before, in a session organized by the coordination team. In this session, the learning project guide is delivered to the teams, who are also formed in this session. This guide is a word document prepared by the coordination team for students to read and follow, explaining all details of PBL process organization, coordination team contacts, learning outcomes expected from each course, time schedules, tutors' role, among other important elements. In this edition, 68 freshman students were organized in eight teams of 7 to 9 members. Assessment included six milestones with deliverables during the semester. The team assessment counts for 90% and the remaining 10% comes from a challenge in student pairs, named IEM@ProjectNetworking (A. Alves et al., 2013; A. C. Alves et al., 2022).

3.2 PIEGI3 – LEGI

The CU of PIEGI3-LEGI, in 2021/22 , also follows a PBL approach, with an integrated project developed by seven teams of students (total of 61 students, teams with 8 to 9 members) in interaction with four companies (one from the metal-mechanics area, one from the furniture area and two from the textile area), and involving as Project Supporting Courses (PSC) all the five CU of the semester (Table 2). Three of the companies have two teams assigned and a fourth company has only one team.

Table 2. Project Supporting Courses for PIEGI3 – LEGI (bachelor's degree, 3rd year).

Course Unit	Scientific Area	ECTS (credits)
Data Analytics	Engineering Sciences	5
Decision Models	Industrial and Systems Engineering	5
Logistics and Supply Chain Management	Industrial and Systems Engineering	5
Manufacturing Planning and Control	Industrial and Systems Engineering	5
Project Analysis in Industrial and Engineering Management	Industrial and Systems Engineering	5

With PIEGI3-LEGI students must be able to develop a team project, using data provided by companies, consisting of two parts: (i) description and characterization of the company (including the production system), and, (ii) application of tools/techniques/methodologies (e.g. for production system diagnostics) using company data.

In terms of technical competences, with the CU of Data Analytics, teams will use data organization and pre-processing techniques on provided datasets, interacting with the other CU supporting the project. Based on the CU Logistics and Supply Chain Management, teams will characterize the supply chain and describe a chosen storage unit, in close articulation with the CU Manufacturing Planning and Control. In the context of this last CU, students should carry out some key production planning and control functions using data provided by the company. In terms of Decision Models, teams are expected to contribute to a medium-long term strategic analysis regarding the challenges facing the company, given current trends, namely digital and green. In addition to the technical competences inherent to each CU, it is intended that transversal competences are also developed (e.g. communication, teamwork, leadership).

The coordination team is composed by the 10 teachers, of which 4 are tutors, associated to the CU of the semester. The tutor supports the student teams in what concerns the project management, without, however, interfering in the technical contents. The teams have three specific project rooms during the project supporting weekly sessions and during the periods when they do not have classes.

Regarding the project planning, the coordination team started to meet about three months before the beginning of the semester, to define a whole set of conceptual and operational aspects, highlighting the definition of objectives and the contact/selection of companies, as well as the scheduling of the entire process (milestones, assessment moments, etc.). Ten milestones are defined, namely 9 seminars (4 from companies and one from each CU) and 2 presentation/discussion sessions (intermediate and final). Three deliverables are stipulated (intermediate presentation, final presentation, and final report).

Student assessment is based on: (i) intermediate presentation (deliverable and discussion) – 10%, (ii) final presentation (deliverable and discussion) – 15%, (iii) final report – 65%, and (iv) seminars' participation – 10%. Finally, each team can choose to conduct peer assessment sessions if they want to distinguish colleagues with different performances within the team.

3.3 PIEGI – MEGI

The 1st semester of the 1st year of the Industrial Engineering and Management Master program (MEGI) is a program designed as a continuation of the LEGI bachelor previously referred. During this semester, the students have 6 courses of 5 ECTS each. The first 4 courses of Table 3 support the Integrated Project in Industrial Engineering and Management (PIEGI) during a whole semester project developed in interaction with industrial companies. The sixth course of the list may use the project as a case for simulation.

In the academic year of 2022/2023, from mid-September 2022 to mid-January 2023, 54 students organized themselves in 7 teams of 7 to 8 students each, and one teacher was assigned as supervisor. Each team made almost weekly visits to a company (one for each team), analysing a part of the production system from the perspective of the project supporting courses. At the end of the semester, they present and defend a proposal of improvement and whenever possible implement and evaluate part of the proposal. As an example, students modelled and analysed a production cell and proposed an improvement of its performance. They must do this considering the best workplace conditions for the cell workers. Overall, it is expected, and supported by one of the courses, that each team applies agile project management approaches during the semester.

Table 3. Courses for the 1st semester of the 1st year of MEGI master's degree.

Course Unit	Scientific Area	ECTS (credits)
Process Modelling and Analysis	Industrial and Systems Engineering	5
Production Systems Advanced Organization	Industrial and Systems Engineering	5
Industrial Project Management	Industrial and Systems Engineering	5
Human Factors and Ergonomics	Industrial and Systems Engineering	5
Integrated Project in Industrial Engineering and Management	Industrial and Systems Engineering	5
Modelling and Simulation	Industrial and Systems Engineering	5

The project has three main phases and milestones (Figure 1), during which the students should tackle real industrial problems of a company and develop solutions to mitigate those problems. These are general guiding phases and milestones, as students may be in slightly different stages at the end of the milestones. Nevertheless, these phases will help all stakeholders to understand what is expected at a specific time. Students will have weekly classes of project, organized as team meetings, during which they will be supported by their supervisors. Additionally, project support courses instructors will refer and use the project as an object of learning during their classes whenever appropriate.

Figure 1. PIEGI-MEGI project phases.

The formative assessment process is based on the supervisor's weekly support and milestones feedback delivered by all project supporting courses. The summative assessment process is mainly based on the assessment of the deliverables at each milestone: Phase 1 – project plan (5%); Phase 2 – diagnosis presentation (20%); Phase 3 – proposals presentation (35%) and article (40%). If the article is published and presented, the team may apply for a bonus of 5% in the next formal evaluation phase. Additionally, there is the possibility for each team to make a peer assessment to distinguish individual performance.

One particularity of the assessment model in this project is the influence that it has in the project supporting courses grades, as each instructor agrees to use a component of 20% of their grade based on the team project grade. This mechanism creates a real interconnection between the project course and the project supporting courses, which is also supported by the integration of these teachers in the assessment process of the project.

4 Discussion

To support the comparison between the three PBL integrated projects, Table 4 summarizes the information gathered in the analysis of each of them (section 3). This information refers to the last edition of these projects, which for PIEGI1-LEGI and PIEGI-MEGI occurred in the 1st semester of 2022/23 and for PIEGI3-LEGI in the 2nd semester of 2021/22 (the 2022/23 edition is still ongoing). Although the three integrated projects presented here share some common aspects, they also have some significant differences. This discussion will focus mainly on the aspects that clearly distinguish them. A first noteworthy aspect is that the weight of CU in the scientific area of industrial and systems engineering increases as students progress through their study plan. This is quite common in most engineering programmes, and it influences what is expected from students in their projects. Unlike in the second and third projects (PIEGI3 - LEGI and PIEGI3 - MEGI), in the 1st year project (PIEGI1 - LEGI) there are no companies involved and, therefore, no actual real context in which the students carry out their projects.

Table 4. Comparison of the three PBL integrated projects in industrial engineering and management at UM-DPS.

	PIEGI1 – LEGI	PIEGI3 - LEGI	PIEGI - MEGI
General objective	Design of a production system and of a production process to produce a sustainable product	Company characterization and application of tools / techniques / methodologies (e.g. for production system diagnostics)	Analysis, diagnosis, and proposals for improvement of part of a production system from an industrial company, based on concepts and tools related to Lean, process modelling, ergonomic workstation, using agile project management approaches
# ECTS	5	5	5
# Duration	1 semester	1 semester	1 semester
Curricular year	1st	3rd	1st
# Project supp. courses	5	5	4
# Project supp. courses of industrial eng. and manag. area	40%	80%	100%
# Companies involved	-	4	7
# Students	68	61	54
# Teams (teams' size)	8 (7-9 elements)	7 (8 -9 elements)	7 (7-8 elements)
# Coordination team	17	10	7
# Tutors	8	4	6 (supervisors)
Tutors' role	Team monitoring and non-technical support	Team monitoring and non-technical support	Team monitoring and technical support
Premises	Specific project rooms (shared)	Specific project rooms (shared)	-
# Milestones	6	11	3
# Deliverables	6	3	4
# Seminars	-	8	-
Assessment model	55% Reports 20% Presentations 25% Prototypes and blog	10% Intermediate presentation 15% Final presentation 65% Final report 10% Seminars	5% Initial plan 20% Diagnosis presentation 35% Final presentation 40% Article
Peer assessment	Compulsory (3 sessions)	Optional	Optional
-	-	-	-
Students' satisfaction*	86%	74%	76%

* Information gathered from the institutional CU reports.

The whole project is carried out within the university. However, in the other projects, the students already have access to a real industrial context to develop some skills in applying concepts and tools, and other professional skills, as well as to identify the relevance and adequacy of the topics covered in the various CU.

Another noteworthy feature that distinguishes one of the projects is the role of the tutor. In the most advanced project (PIEGI-MEGI), the role of the tutor is no longer so focused on supporting the management of the project and the team but is more of a technical supervision role involving technical support. This difference stems from the greater demands of this type of project in terms of developing and implementing technical solutions in companies.

Students' satisfaction is an issue that clearly deserves some attention. As can be observed in Table 4, the project that generated the highest satisfaction was the first project while the second obtained the least positive result. These results contradict teachers' initial perceptions as they expected that real-life projects would result in greater student satisfaction. The possible reasons that can explain this difference might be related, according to teachers' intuition, to the fact that, in the first project, students have just entered university and this project allows them to experience a challenge as a team that they had probably never experienced before. In addition, this team project, due to its characteristics, creates favourable conditions for students getting to know each other and deepening bonds of friendship and companionship.

The main reason that can be pointed out for the low satisfaction shown by the students regarding the second project is that it was its first edition (following the major restructuring of the MIEGI programme) and therefore there were aspects that did not work as well, namely in terms of company interaction.

Regarding the last project (PIEGI - MEGI) the student satisfaction with the project was below teachers' expectations. This project takes place in companies where students' teams must perform analysis and diagnosis as well as proposing and implementing improvements. The project is quite challenging and for many students is the first experience as a near professional of industrial engineering. An important question to ask is why does such a project not provide at least the same level of satisfaction as the 1st year project (PIEGI1-LEGI)? Perhaps the fact that the 1st year project was an extraordinary personal experience for being the first experience of its kind is one of the reasons. Also, probably because the students, after other project experiences, became more demanding in terms of expectations. Another possible reason is related to the difficulties that students typically experience in dealing with real-life contextual challenges for which they are not prepared. Examples of these challenges are difficulties in setting up appropriate meetings, in dealing with different organisational behaviours and cultures, in communicating effectively, in clearly identifying the data they need and in dealing with incomplete (or even contradictory) data, among others. To better support and ground the results of this study, future work will focus on a qualitative study to collect evidence from students about the strengths and weaknesses of each of the three PBL approaches compared in this study, driving conclusions for the improvement of the conceptual and operational aspects of PBL approaches carried out in these two engineering programs.

In general, this study provides findings about a specific engineering program which has developed and improved its own model over time, creating its own identity, which does not necessarily mean implementing the exact same approach across the program. In other words, the three projects followed the same PBL principles but, in practice, they were quite different, based on the objectives and characteristics of each of the contexts (e.g., number of students, resources available, etc.).

5 Conclusion

The 1st year project (PIEGI1-LEGI), in addition to the development of the technical project itself, aims to provide students with a PBL approach that they have probably never experienced. Thus, besides the technical competences it develops in students, PIEGI1-LEGI plays a crucial role in the development of transversal competences (teamwork, communication, time management, conflict management, etc.), which will be crucial throughout the entire academic and professional path, of these students.

The 3rd year project (PIEGI3-LEGI) puts student teams in direct contact with the industrial reality, not in the sense of being mere visitors (these can already take place in previous years), but rather, and for the first time, with the objective of characterizing productive systems and applying tools / techniques / methodologies that they learn at the university, using real data, and that allow a diagnosis of these productive systems to be made. Thus, in comparison with PIEGI1-LEGI, the most distinctive feature of PIEGI3-LEGI is the fact that the work of the teams is carried out in direct interaction with companies, thus forcing students to face all the difficulties inherent to this type of work (identification and collection of information, interaction/communication with industry professionals, etc.).

MEGI's 1st year project (PIEGI-MEGI) is the one that goes further in terms of requirements, but which, for that very reason, also allows to students to go deeper in terms of competences development. In PIEGI-MEGI each team of students has its own company (in PIEGI3-LEGI each company received two teams) and the project starts with the diagnosis of the productive system, or part of it (like PIEGI3-LEGI, but more detailed), followed by the formal development of improvement proposals (not expected in PIEGI3-LEGI) and eventual implementation.

Thus, it can be seen that the three projects targeted by this study were designed and implemented in order to have complementary objectives. This approach resulted from the experience that the core team of teachers and researchers has acquired over nearly two decades of working with PBL. It is the authors' conviction that these projects represent an excellent preparation for the students' final challenge, which occurs in the 2nd year of MEGI, and that is the realization of the individual master thesis project. Perhaps this is why the overwhelming majority of MEGI students (often 100%) choose to carry out their dissertation in a company, when there is also the possibility of carrying out an academic dissertation.

Finally, to conclude, the PBL model presented in this paper has been considered sustainable over the time mainly due to the following three main factors: (i) level of collaboration, motivation and commitment of the faculty team engaged in the projects; (ii) ongoing research on PBL carried out by the faculty team, that helped reflecting about the practice and improving the model; (iii) institutional support in terms of considering PBL as an added-value for students' learning.

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