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Study and Research Paths: A New tool for Design and Management of Project Based Learning in Engineering*

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An open issue in Project and Problem Based Learning (PjBL and PBL) research is how the project topic or the "problem" can be selected or constructed systematically. This issue has been investigated in the field of didactics of mathematics and one of the proposed teaching formats is "study and research paths" (SRPs) based on the principles of the Anthropological Theory of the Didactic (ATD). We hypothesize that the methodology for problem design and analysis associated to SRPs can enrich the application of Project and Problem Based Learning in engineering education. We conducted a case study on the design and experimentation of an SRP, implemented in a course of General Linear Elasticity of a degree program in Mechanical Engineering. The results show the potential of the SRP and its associated devices such as the Question-Answer maps to support the a priori design of a proposed project topic or problem. Q-A maps show to be useful both for teachers and students to describe and manage the knowledge involved. The SRP is compatible with the principles of PBL and enriches it with tools to explicitly deal with the design and preliminary analysis of project topics, as well as with the analysis of observed project work.

Keywords: project based learning; course design; study and research path; general linear elasticity

1. Introduction

Problem Based Learning (PBL) and Project Based Learning (PjBL) are teaching formats that have been widely encouraged in school institutions (from primary to tertiary education) for the last forty years. Moreover, these formats have been promoted by governmental policies such as funding large-scale research projects, curricular changes and specific actions in teacher education (see for example the PRIMAS Project of the European Union and the Next Generation Science Standards of the United States).

The field of engineering education is not an exception in this methodological shift, and many experiences have been described, ranging from occasional interventions to entire institutions whose pedagogical foundations have become based on these approaches. Examples of such institutions are Aalborg University (Denmark), Delft University of Technology (The Netherlands) and, more recently, the Universidade de Aveiro (Portugal) [1–3]. Even if these approaches spread in many institutions, research on their implementation still faces many challenges, such as how to assess their capacity to cover basic sciences [4], the character, design and choice of "projects" [5], and the project management and team communication involved in actual practice [6].

In parallel, in the research field of Mathematics Education, a similar development is taking place: mathematical modelling activities in open inquiry settings are becoming central, and many examples of this new approach exist, based on different theoretical frameworks [7–11]. One of them is the Anthropological Theory of the Didactic (ATD), belonging to the *epistemological approach* within the field of didactics of mathematics [12]. The ATD argues for a paradigm shift in education: from the paradigm of "visiting monuments" (or "monumentalism") to the paradigm of "questioning the world" [13]. Both paradigms differ in the role they assign to knowledge. In the "monumentalism" paradigm, works of knowledge are put at the centre of the study programmes and curriculum design, as content to be taught and learnt because of their intrinsic importance. In the paradigm of "questioning the world", works of knowledge are introduced because of their utility to raise and answer questions or to solve relevant problems. This paradigm shift is in line with some of the main principles of PBL and PjBL, such as the "learning organisation around problems" [14].

The specific instructional proposal of the ATD to

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promote this shift in school institutions is the use of Study and Research Paths (SRPs), an inquiry-based teaching format with an associated methodology regarding its design and analysis. An SRP is initiated by the consideration of an open *generating question* (Q_0), leading to moments of *study* of available information in different sources, along with moments of *research* and creation of new solutions, including the adaptation of the information obtained to the specific question. This dialectic between study and research is a crucial characteristic of SRPs and allows them to be easily incorporated into more traditional settings including lectures, tutorials and laboratory sessions, acting as a connecting and motivating device between the different types of sessions.

Given the shared principles between PBL and PjBL in engineering and the ATD approach in mathematics education, we consider that the methodology and the management tools associated to SRPs can enhance the field of engineering education. This paper presents a first evaluation of this hypothesis, through empirical research using a case study methodology [15] based on the design, experimentation and analysis of an SRP in a 3rd year course of General Elasticity in a Mechanical Engineering degree.

2. Background: Mathematical and engineering education

2.1 Issues in PBL in engineering education: selection of the problem and managing the study process

The first explicit application of the PBL instructional approach at tertiary level is said to have occurred at the time of a major reform of Medicine Studies at the McMaster University in Canada in the 1960s [16]. In Europe, in the early 1970s, the creation of new universities, for instance Maastricht (The Netherlands), Roskilde and Aalborg (Denmark), facilitated the incorporation of both PBL and PjBL as a major educational paradigm, which was also seen as a ‘‘possible factor contributing to change in society’’ [2]. This transition has been spreading with more recent reforms, e.g., at the Universidade de Aveiro in Portugal, where this change was initiated in 2001, explicitly following the Aalborg model [3]. Despite this dissemination process, research in PBL still faces some challenging questions.

One of the open issues is the selection of the problem or project: according to Servant [18], this question is the elephant in the room of PBL and PjBL. The application of these approaches in engineering has traditionally been based on general principles emerging from constructivist theories of learning [17] but it lacks a widely accepted model to guide the design and a priori validation of the problems the project sets out to solve, the corresponding study processes and the knowledge involved. The selection process and the nature of the problem depend heavily on the tradition in the teaching institution, as highlighted by Servant [18, p. 228]:

> ‘‘[. . .] problems in the McMaster and Maastricht model differed quite markedly from those at Roskilde and Aalborg—in their purpose, their form and their formulation. Problems at Roskilde also differed to a smaller degree from those at Aalborg.’’ [18, p. 228]

The way in which a project theme is defined and chosen for its study is also of crucial importance to evaluate to what extent the project achieves the learning goals and competencies, and how it furthers students’ motivation [19]. Moreira et al [20] describe this challenge as follows:

> ‘‘[. . .] the project theme is crucial for the students’ and teachers’ motivation, because it has an impact on the learning and teaching process. Additionally, it is the theme that allows an interdisciplinary approach in the project, relating competencies that students are to develop in each individual course to achieve the objectives of the project.’’ [20, p. 66]

A second challenging aspect faced by researchers in engineering education is the need to manage the project, to describe and institutionalize the knowledge involved and to communicate with different teams [5, 21]. One important aspect of these new needs experimented by lecturers is stated by Lima et al [6]:

> ‘‘Project management of these types of projects faces challenges that overcome the traditional role of the teacher. Thus, teachers that want to embrace this type of approach have to be prepared for this.’’ [6, p. 74]

Certainly, these managing, and communication tasks involve paying attention not only to interpersonal aspects but also to the content of the project itself: this generates a need of tools to empower tutors and students to explicitly describe, modify and manage the knowledge in development.

2.2 Inquiry-based mathematics: a proposal from the ATD

In parallel to the PBL and PjBL spread in Engineering, research in mathematics education has also experienced a major revolution. Artigue and Blomhøj [11] conceptualize the notion of Inquiry-Based Mathematics Education (IBME) and relate it with six well established theoretical frameworks. One of these frameworks is the ATD, which is presented as a ‘‘coherent framework that seems able to support the conceptualization of different forms of inquiry processes’’.

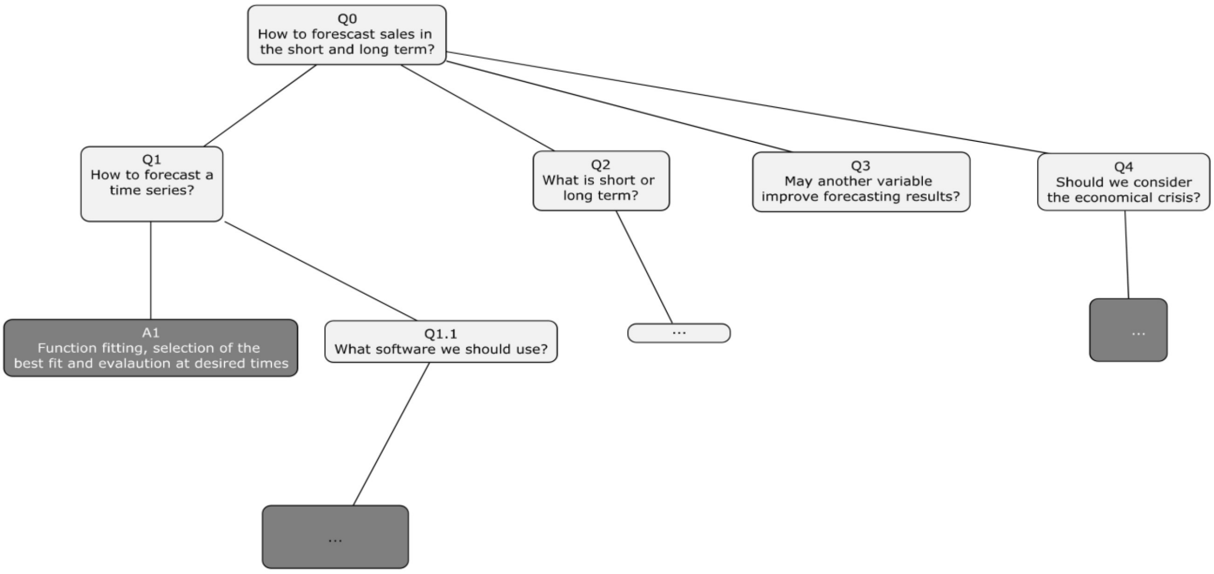

Fig. 1. Initial part of a Q-A map. Questions in soft grey, answers deep grey [25].

As stated before, the ATD approach claims for a shift from the paradigm of "visiting monuments" to the paradigm of "questioning the world" [13]. This change has to modify not only the practices in school institutions but also the conception of the knowledge to be taught: its components and its raisons d'être. The conception of knowledge in the ATD is broad: not only does it include concepts, theorems or techniques, but also the mathematical activities themselves and the competencies that are assigned to them. Researchers within this framework use specific methodologies and tools to manage and describe knowledge and to design study processes. Two of these devices are *Didactic Engineering*[1] (DE) methodology and the *Question-Answer maps* (Q-A maps).

DE is a central methodology in the ATD approach. It has its origins in the works of Guy Brousseau [22] as a research methodology to design study processes with specific target knowledge, in order to observe, study and analyse phenomena related to the knowledge involved [23]. The methodology is expected to change specific aspects of the teaching proposal to—partially—overcome unsatisfactory results observed in common forms of teaching. This initial use of DE has become a methodology enabling researchers to systematically design, experiment and analyse study processes and, more specifically, SRPs [24].

As a central tool to manage and describe the different phases of the DE methodology, the ATD proposes to use the so-called Q-A maps. Q-A maps are a representation of an inquiry process as a rooted tree showing the questions derived and addressed by both the students and the teacher, as well as the answers obtained. The use of such rooted trees has also been proposed as a model to be employed by teachers to communicate and describe study processes [9]. In more recent studies, both teachers and researchers have used them in the design phase and in the management and assessment of SRPs [25, 26]. The initial part of a Q-A map describing an SRP experimented by Barquero et al [25] is presented in Fig. 1.

3. Research questions

We hypothesize that the ATD framework, and specifically the DE methodology and the Q-A maps, may enhance the open issues in engineering education regarding the selection of the initial project in PjBL and the need of tools to communicate and manage these kind of study processes.

In the rest of this paper, we want to investigate two main research questions:

- RQ1. To what extent can the DE methodology be applied in engineering education and enrich the answer to the previously described open issues? Specifically:
  - RQ1.1 Would the DE methodology help to systematize the choice of the initial question of a PjBL study process in engineering education?
  - RQ1.2 What conditions enable and what constraints hinder the implementation of SRPs using the DE methodology?
- RQ2. Would the use of Q-A maps help lecturers and students to explicitly describe and commu-

[1] Didactic Engineering comes from the French term *Ingénierie didactique*. Even if didactic in English means a "teacher instructed process", it does not have this connotation in French.

nicate aspects that traditionally remain implicit during a PjBL study process? Specifically:

- RQ2.1 Would the use of Q-A maps help make the raison d'être of the knowledge developed explicit?
- RQ2.2 Would the use of Q-A maps help manage and communicate aspects from professional practice (such as estimation, testing and fruitless work) in a university setting?
- RQ2.3 Would the use of Q-A maps help manage the collective work, and the new share of responsibilities assumed by both teachers and students during the development of an SRP?

In order to answer these questions, we have designed an exploratory case study [15, 28] based on a whole DE methodology process (preliminary, a priori, in vivo and a posteriori analyses) in an Elasticity course. The data gathered during the DE process and its analysis (including the use of Q-A maps) will generate a first answer to the research questions.

4. Methodology

4.1 DE methodology for the design, experience and analysis of study processes

The methodology used to design, experience and analyse the SRP is the DE methodology. DE is described as based on a four-phase process [29]. The first phase includes the *preliminary analysis:* it takes into account an explicit characterisation of how knowledge is conceived in the considered teaching institution and what (undesirable) consequences this conception has for teaching processes. This characterisation will include an analysis of teaching materials—such as textbooks, guidelines, syllabi, curricula, etc.—and a description of the structural raison d'être of the target knowledge within the curriculum. This description is a crucial step: unquestioned target knowledge may be at the basis of undesired facts such as a perceived absence of motivation of the target knowledge, or disconnections between notions or concepts and techniques. In consequence, researchers designing new study processes should explicitly consider an alternative conception and structure of the target knowledge and eventually connect it with other domains of the curriculum.

The second phase concerns the *a priori* analysis of the designed process. In the case of an SRP, students are presented with a generating question, which is expected to initiate a study process. In this phase, researchers have to evaluate the generating power of the chosen initial question, considering new derived questions (Qj) students can raise and the kind of partial answers (A_i) they can provide. Researchers also have to check that this production is coherent with the learning resources available and the target knowledge established in the first phase.

The third phase concerns the implementation and observation of the study process as well as the data collection; all this work is the called the *in-vivo* analysis. In this phase, not only do researchers need to generate, manage and store data to be analysed. Teachers and students also need to organise the information collected and treat it conveniently in order to provide answers to the questions raised. Data collection is both necessary for the research and the teaching and learning process.

The fourth phase of the DE process is the *a posteriori* analysis. For researchers, the main work in this phase is to analyse the collected data, to compare the *a priori* analysis to the actual activity carried out, to describe the roles assumed by teachers and students, and to highlight the conditions and constraints affecting the viability of the study process. For the teachers, this phase is essential to assess the instructional process and make decisions for future designs and implementations.

4.2 Course context and description

Here we present an SRP designed for a 6 ECTS General Elasticity Course in the third year of a four-year Degree in Mechanical Engineering at an Engineering School in Barcelona, Spain. The course is mandatory for all the students pursuing this degree. The course lasted for the whole fall semester of 2015 (14 weeks) and consisted of two 2-hour sessions per week. Teaching was structured as follows: the first 9 weeks included traditional instruction (lectures and classical Elasticity exercise solving sessions) while the sessions during the last 5 weeks focused on the implementation of the SRP. The participants were fifty students divided into two groups (of thirty and twenty participants respectively). The students conducted the SRP in self-organised teams of 3 or 4 students.

While the lecturing sessions took place in a traditional classroom (blackboard and projector available), all the SRP sessions took place at the Materials Lab. The Lab is used exclusively by students (and not by researchers in materials who work in other settings). It is equipped with a universal testing machine, a Charpy testing machine, a hardness testing machine, an oven the temperature of which ranges from 100° to 1.100°C and 12 workstations using CAD and FEM software. Students also had access to 3d-printers, an educational milling machine and traditional lab tools.

4.3 Data collection and planned analysis

In order to provide an answer to the research questions, we planned to collect four kinds of data. Firstly, we collected researchers' and lecturers' productions. This material included the notes produced during the preliminary and the a priori analyses, the project assignment as well as the presentation slides used by the lecturers to introduce the project to the students. We also collected the simplified operation manuals of the laboratory equipment distributed to the students in order to enable them to use any testing machine autonomously.

Secondly, we collected all the students' productions: weekly reports (4 for every small group) and a final report at the end of the project. The analysis of these reports allowed us to find out to what extent the generated Q-A maps helped students and lecturers to address important tasks which are usually absent in more traditional teaching (such as estimation, iterative design, etc.) and to see how the maps were used to describe and talk about the steps followed during the SRP.

Thirdly, we conducted a final on-line survey to evaluate the students' perceptions of the SRP, including both general aspects (such as duration, organisation, balance between practical and theoretical sessions and group and individual work) and knowledge-specific aspects (students' opinions on the use of Q-A maps, and their conceptions of the raison d'être of the main general elasticity topics). The survey included twenty-four statements to be evaluated on a four-level Likert scale ranging from strongly agree to strongly disagree; it was answered voluntarily by 46 out of 50 students. This survey had already been piloted and validated in previous research [25, 30, 31]. The survey and its answers can be found in the supplementary material [32].

Finally, we conducted semi-structured interviews with three groups of students and with the non-researcher lecturer. The structure of the interviews was based on the survey: the interviewer showed the results of the survey and asked about the reasons justifying the interviewees' personal position regarding the collective answer. The semi-structured interviews were conducted by the second author, external to the institution: she carried out four interviews, one with the non-researcher lecturer managing the SRP, and three interviews with three working groups, each consisting of three students. The interviewed groups were randomly drawn from all the participants and nobody refused to participate. We will refer to each student using two-digit numbers (e.g., the second student from the third group will be Student 3.2). The structure of the students' and lecturer's interview is outlined in Appendix 1.

5. DE methodology applied in an Elasticity course

5.1 DE first phase: preliminary analysis

General Elasticity can be considered as the study of models describing the deformation of solids under certain load configurations. The specific case of General Linear Elasticity is a simplified model of the non-linear case, a branch of Continuum Mechanics. Cauchy, Navier and Lamé developed the theoretical bases of this model during the second half of the nineteenth century. The theoretical model of the behaviour of solids under loads developed to describe the level of stress and strain in any point of the balanced solid studied was, at the time of the formulation of that model, only analytically solvable in very special cases. These boundary cases include prismatic geometries under certain load conditions. For example, the assumptions of the beam theory approach (small deformations and prismatic geometries), simplified the model in order to make most of the equations solvable. General problems covered by the general model remained analytically unsolvable until the emergence of numerical methods (the finite element method (FEM), the finite difference method or the boundary method).

This historical specificity led to the standard teaching organisation of General Elasticity: a theoretical part where the foundations of the method are introduced; and the presentation of the boundary cases where an analytical solution can be calculated. A closer analysis of the structure of chapters, the list of contents and the exercises proposed in General Elasticity courses in various Engineering schools, reveals that this organisation is widely used around the world [33–39]. A paradigmatic statement about this approach was found in Reddy[40].

> "Many problems of even linearized elasticity involve geometries that are complicated, and analytical solutions to such problems cannot be obtained. Therefore, the objective is to familiarize the reader with certain solution methods as applied to simple boundary value problems. Boundary value problems discussed in most elasticity books are about the same (. . .) Methods discussed here may not be directly useful in solving practical engineering problems, but the discussion provides certain insights into the formulation and solution of boundary value problems" [40, p. 265]

This approach highlights the theoretical aspects and foundations of Cauchy, Navier and Lame's model at the expense of the solution of real problems that are the objectives of the model itself: choosing an adequate shape and material (limiting stresses and strains) for a part with a generic shape under a specific set of loads. In general, the above-mentioned teaching organisations include some introduction to the numerical approach, but it remains something secondary. In fact, many Engineering programmes propose a specific course for Numerical Methods that is usually detached from other courses.

The structure of the course taught at the institution under study, before the implementation of the SRP, followed this approach, which was also identified in the analysed textbooks. Each week included a 2-hour lecture and a 2-hour session for solving exercises using pen and paper. Three laboratory sessions were proposed during the last two weeks: (1) An introduction to FEM (including the simulation of tensile test following a tutorial), (2) a standard tensile test in order to determine Young's Modulus and Yield Strength in three materials (AISI 304, S275 and Al6061) and (3) a Charpy test in order to determine toughness in the same materials.

The main raison d'être of the course was to enable students to solve boundary problems, mainly using paper and pen. This conception of the field is very *monumentalistic*: the model is taught and learnt (or "visited") because of its assumed intrinsic importance. Meanwhile, the capacity of the model to solve real problems (which provoked its historical emergence) remains in the shadows.

A second problem identified concerns the practical sessions of the course. Although lab sessions were included to demonstrate the capacity of the theoretical model introduced in the lectures, a problematic phenomenon appeared: the use of computers was totally detached from lectures and exercise sessions, the computers outputs were blindly accepted by the students, and the implementation of the model in the software and its limitations remained unquestioned. In addition, the three proposed practical sessions appeared as totally disconnected to the students. In fact, they were presented and experienced by the students as isolated activities, even if the mechanical tests (tensile and Charpy tests) provided the necessary results to feed into the FEM simulations.

Taking into account these phenomena and in order to overcome them, at least partially, researchers and lecturers agreed on the need to break with the monumentalistic conception of the domain. A change in the way Elasticity was taught would not be enough: its raison d'être and its content organisation had to change. We consider that the type of tasks that Cauchy's model deals with is: "Describing the level of stresses and strains of any solid part in order to be able to design the studied part (shape and material) avoiding elastic failure and excessive deformations". With this conception of the knowledge to be taught, a central question of mechanical engineering becomes the core of the course and leaves the model and its theoretical foundation as a crucial tool to solve the question, but not as a learning goal in itself.

5.2 A priori analysis: didactic and engineering design

The second phase of the DE methodology includes two main steps. Firstly, selecting a *generating question* for the SRP: this is the central question that students and lecturers will address and to which they will provide answers. This question has to be consistent with the new raison d'être and organisation of the knowledge to be taught. An evaluation of its generating power has to be performed in terms of the potential questions and answers derived from the initial one. In addition, the selection of the generating question must meet the constraints of the syllabus (see Table 1). Secondly, the structure of the whole course will be established: duration of the SRP, ensuring its compatibility with lectures and exercise sessions, and deciding how the course will be assessed and which kind of deliverables the students will generate.

According to the first phase of the DE methodology, we considered that the *generating question* should include the design of a part (shape, material) but also that the question should lead the students to use the equipment as stated by the official learning goals.

The generating question of the SRP was stated as follows: "A bike company ask you to design a bike

Table 1. Competence and learning goals assigned to the General Elasticity course at the Escola Universitària Salesiana de Sarrià—Univ. Autònoma de Barcelona [41]

Competences and learning goals of the General Elasticity Course
General competence • Be able to use knowledge and capacity to apply the Foundations of elasticity and strength of materials at the study of the behaviour of real solids.
Learning goals – Be able to list and use the basic laws of Continuum Mechanics. – Analyse and interpret the results of the mechanical tests obtained at the Continuum Mechanics laboratory. – Solve problems of Continuum Mechanics. – Use the techniques and instruments from the Continuum Mechanic laboratory tests properly.

part using one of three given materials. You will have to provide an answer in a final report. The report will include the dimensions and shape of the proposed design, the considered loads and their justification, the factor of safety, the deformations, as well as the time planning of the project and the cost of the project"

We considered that the question fulfilled the requirements: it involved a bike part (thus, a familiar object for students) and it allowed having small groups (3–4 students) working with different parts (such as parts of gears, the frame, etc.) while, at the same time, contributing to a bigger project (the bike itself). The selection of the three specific materials took into account materials available at the laboratory that were possibly suitable to be applied in a bike (the selection was AISI 304 steel, SR275 steel and Aluminium 6061). In fact, the available materials were mainly provided to the students for tensile, hardness and Charpy testing, but without telling them the name of the materials.

As a tool to validate the potential of the chosen question, lecturers and researchers developed an a priori Q-A map (Fig. 2) to see how the content of the practical sessions of the previous teaching organisation now appears connected. Another aspect revealed by the Q-A map was the central role of the FEM solution to the Cauchy, Navier and Lamé theoretical model, presented in the lectures and exercise sessions. At the same time, this solution was not detached from an in-depth analysis of the results based on the more theoretical aspects of the model.

A more detailed analysis of the Q-A map reveals that the design of a bike part may generate further work regarding new topics, ranging from the cost of the part, the time required to develop the particular design and to produce the required part, to more mechanical aspects such as the loads and the material properties. In Fig. 2, we highlighted the tasks that were expected to appear in the practical sessions of the previous teaching organisation in yellow. This a priori analysis shows how previously isolated content elements now appear connected, as a result of the SRP. The a priori Q-A map also reveals that questions which are usually absent from General Elasticity courses, such as the estimation of loads (traditionally a given data in pen and paper exercises), time consumption and costs, also become central tasks in the SRP.

The second aspect to be considered in the a priori analysis is to plan how the SRP will be assessed and what deliverables students will generate. These aspects are crucial in the lecturers' management of the study process. Lecturers and researchers decided to ask students to generate two kinds of documents: a weekly report to be used as a monitoring tool of the study process, and a final report summarising the final answer of the group. Students were asked to deliver the reports using specific content (see Table 2).

Lecturers generated weekly feedback to the stu-

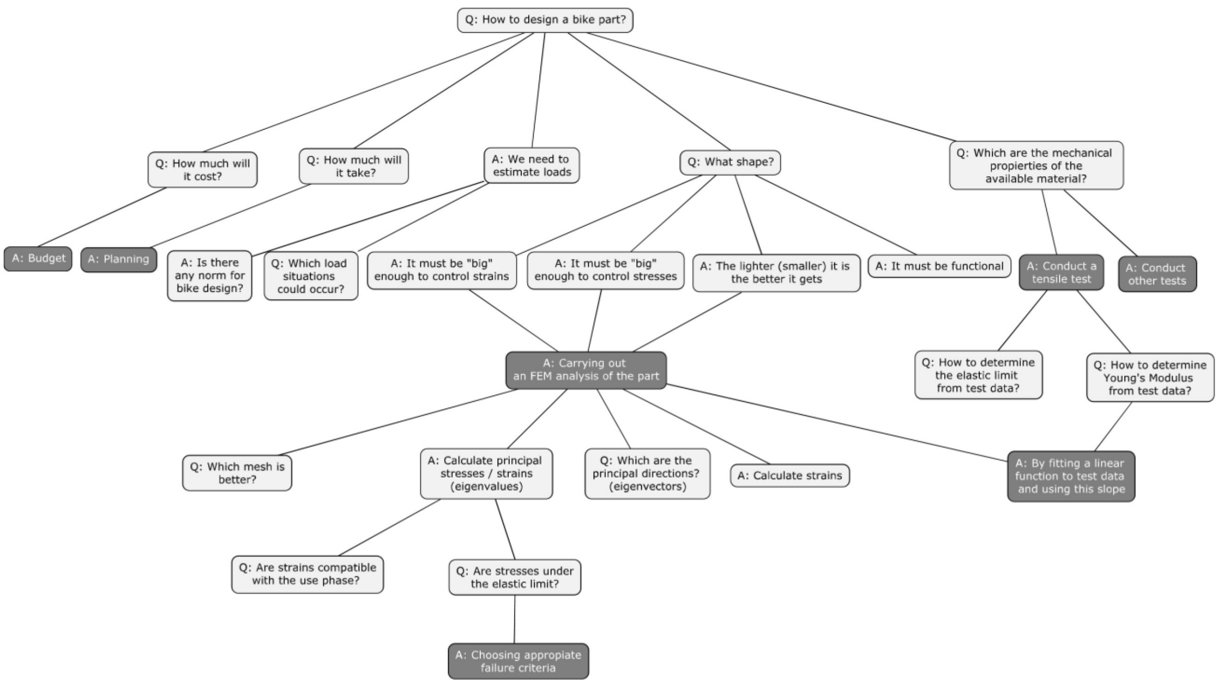

Fig. 2. A priori Q-A map. In deep grey, content explicitly present in the previous configuration of the practical sessions. It can be observed how these yellow boxes become now related and result from a justified and functional previous path of questions and answers.

Table 2. Content checklist provided to students for the weekly reports

Content requirement for weekly reports
1. Updated task plan.
2. Role assignment for the following week for each member of the team.
3. Questions addressed the previous week.
4. Answers obtained and validated from the previous week's work.
5. Questions to be addressed the following week.
6. Budget use and plan.

dents based on a rubric (see Appendix 2) assessing both the completeness of the report and what was called "accepted answers". Assessment was communicated to the students through a Moodle based platform. Regarding the evaluation of the SRP, the final mark of the project combined the marks given for the weekly reports with the mark of the final report. The latter graded the completeness, the technical quality and the economic suitability of the final solution proposed by the students (see Appendix 2).

5.3 Implementation and in vivo analysis

The SRP was presented to the students during the first session of the course in week 1 (and not just before starting the SRP, in week 10). This presentation included assigning a bike part to each of the groups and presenting them with the initial question Q_0. The main goal of presenting the project in the first session was to connect the problem with the whole course (lectures, exercise sessions and the SRP) from the beginning.

The delivery of the first weekly report and its analysis by lecturers using the evaluation rubrics showed that all groups faced important problems with formulating explicit questions and answers. The main problem both lecturers and researchers identified was that the students were reluctant to record non-productive questions or wrong results. Even though these Q-A maps were a point of the assessment rubric, in only two of the 18 groups included it in the first weekly report.

As expected in the a priori analysis, all groups conducted laboratory tests to obtain the basic mechanical properties of the three available materials. All groups conducted tensile tests to obtain the materials' Young Modulus, Yield Strength and Maximum Stress. During the laboratory work, collaboration emerged between groups. Some of the groups shared the results of tensile tests in order to save time and to increase the amount of data obtained from the tests. Three of the groups also conducted hardness and Charpy tests. However, two of these groups never used the results in any weekly or final report, while the others used them appropriately as supplementary justification of their final solution. A remarkable phenomenon was observed: groups sometimes decided to perform a specific test merely because they could do it in the laboratory, and because they were able to use the testing machines (acquired in previous courses), but not because they saw a need for it to solve the generating question. These unjustified tests are a good example of the previously described suppression of dead ends in the weekly reports. However, in some cases, the need to describe the activity during the week in terms of Q-A maps did in fact make the groups aware of the arbitrariness of their decisions as to what tests to perform.

The work regarding the iterative simulation of different shapes and sets of loads using FEM software generated important difficulties. This work is intended to validate the design in terms of stresses, strains and level of safety. This is an iterative process trying to optimise the use of materials but ensuring an appropriate level of safety.

5.4 A posteriori analysis of the SRP

As said before, the last phase of the DE methodology considers the data collected during the SRP and analyses it in order to validate (or not) the hypotheses established in the a priori analysis and to highlight the conditions and constraints affecting the study process implemented. The implementation of the SRP intended to partially overcome two undesired phenomena existing in the previous organisation. On the one hand, the SRP intended to change the raison d'être of the course putting the design of a part at the centre. On the other hand, the implementation of the SRP intended to make the knowledge appearing in the previous practical sessions as functional (not because of its intrinsic importance) and connected.

A change in the conception and structure of General Elasticity. The analysis of the SRP through weekly (Q-A maps) and final reports (final answer to Q_0) shows, in general, that students addressed new questions of relevance to the course, in a more connected way than in the previous structure of the course. These new questions are closely related to the laboratory and professional activity: determining mechanical properties of the materials, FEM simulation, study of costs of laboratory tests and materials, as well as the need to estimate a set of loads that their part should be able to resist. Moreover, these new questions, together with questions already studied in the previous course (concerning the principal stresses, maximal strains, their relation and the need for a failure criterion) appeared naturally to solve the generating question. As seen in the a priori analysis, many of these derived questions were supposed to appear. However, after analysing the weekly reports, we detected other Q-A duplets that had not been predicted. One of these non-predicted questions was about the theoretical base for FEM simulations: the a priori analysis took for granted that students could manage this Q-A duplet.

The production of Q-A maps by both teachers and students showed that all the groups faced questions similar to those considered in the a priori analysis, but not necessarily in the same chronological order. At the same time, depending on the group, other Q-A duplets appeared, some of them regarding the manufacturing process of the part, fatigue-related aspects, possible surface treatments, and durability issues such as corrosion and surface resistance to abrasion. These are important topics in mechanical engineering, but they are often addressed in other courses. This highlights the capacity of the generating question to connect the content of the course with the knowledge to be taught in other parts of the programme and to promote a new conception of what General Elasticity is. The survey revealed that about 70% of the students agreed on one of the statements from the survey, asking them if the SRP had changed their mind about what General Elasticity'' is, and what it is for. This trend is confirmed in the interviews, for example, Student 1.3 stated: ''I liked doing real engineering activities with open questions: the theoretical lectures become useful and it is important for me to know why they are taught''. Student 3.3 commented: ''I was very surprised at how FEM analysis could solve any shape. . .it helped me see that General Elasticity goes beyond very specific examples''.

Viability and constraints of the SRP. In relation to the viability of the SRP and the conditions enabling or hindering this kind of study process, we wish to highlight two main points. First, the Q-A rooted tree of the groups involved all the curricular content of the General Elasticity course, which is formulated in terms of competence and learning goals (see Table 3). In fact, the knowledge described in terms of Q-A maps covers them and many other aspects that are not considered in the learning goals.

Some of the constraints hindering the implementation of the SRP were related to the *didactic contract* [22], which prevails in the teaching institution, that is, the implicit rules that regulate the share of responsibilities between the teacher and the students in relation to the content in question. In fact, all the other courses of first and second year in the teaching institution follow a traditional structure with lectures, tutorials, and laboratory sessions. The role of lecturers and students appears to be quite different than in the SRP, with teachers retaining all responsibility for providing information and validating students' solutions of relatively simple tasks. The change in the SRP represents a considerable challenge: lecturers have to refrain from validating students' answers and students have to assume a lot of new responsibilities, like raising questions the teachers is not answering, searching for new information to address the questions raised—and validating them—, sharing answers with their classmates without the teacher's interference, deciding when and how to test their results in the lab, etc. It is normal that the evolution of the didactic contract takes some time and needs some specific devices, like the weekly reports, that play an essential role in this respect.

Finally, another constraint that appeared is related to the integration of the SRP into traditional lectures: First 9 weeks of lecture-problems and then 5 weeks of SRP. This structure limited the teachers' possibilities, during the SRP, to focus on those notions and methods that turned out to be necessary (although one supplementary lecture was given with this aim, as mentioned). This constraint might be avoided using a modified time organisation of the SRP in relation to other elements of the course.

Table 3. Content checklist provided to students for the final report

Content requirement for the final report
1. Final solution.
2. Technical justification including:
a. Considered loads.
b. Levels of stress in the designed part.
c. Levels of strain in the designed part.
d. Factor of safety.
3. Time planning of the project.
4. Final budget based on the provided prices.
5. Drawings.

6. Results and Discussion

The results obtained in the information collected from the interviews and the survey provide evidence about the use and functionalities of the Q-A maps by both the lecturers and the students. During the a priori analysis phase, the Q-A map generated by the researchers and lecturers (see Fig 1) appeared as an essential tool. This map showed the potentiality of the generating question but also helped lecturers to forecast the Q-A duplets that students might face during the project. This aspect enabled the lecturers to partially prevent possible problematic knowledge from appearing. However, each implementation of the SRP can be seen as a way of experimentally testing the Q-A map to enhance it—and consequently make the SRP evolve. In this case, although the central task ''Carrying out a FEM analysis'' was identified in the a priori Q-A map, the lecturers did not consider this fact as problematic, while the students did. For instance, in the interview phase, Student 1.2 stated: "obtaining the results of the simulation is quite easy, what is difficult is to know is whether your simplifications are good or bad, and if the mesh is fine enough [. . .] we needed some training". This issue, which was identified by the lecturers' analysis of the weekly reports, led them to intervene in the study process, by giving a lecture-session on FEM analysis.

In addition, the analysis conducted by lecturers during the preliminary and a priori analysis of the DE methodology to elaborate the a priori Q-A map, made lecturers become aware of the raison d'être of the course, an aspect usually taken for granted and left implicit. The interview with the non-researcher lecturer highlights this fact: "Implementing the SRP and the first phases have changed how I teach the first part of the course, including lectures and exercise sessions. Although they are very similar to the previous year's sessions, I have changed the way I teach. Enabling students to answer the SRP generating question has become the raison d'être of the taught knowledge. Now I feel that my teaching task has a rationale, the Navier, Cauchy, Lamé model has changed somehow, and it changed my idea of what I teach. And this fact, makes sense when training engineers to face real problems . . ." The results of the survey seem to confirm this fact when more than 65% of the students consider that the project has changed their mind about what Elasticity is (see Fig. 3). This aspect also emerged in the students' interviews. Especially interesting is the statement of a repeat student (Student 1.3, that experienced the previous organisation of the course): ". . . the project has been very interesting, last year practical sessions were totally algorithmic and unjustified. This year has been better [. . .] we have done almost the same tasks, but it was very useful to design a bike frame!"

Another aspect that emerged in the data analysis is the fact that the elaboration of the a priori Q-A map enabled lecturers to validate the project and analyse the knowledge involved. In the interview, the non-researcher lecturer stated: "Compared to the practical sessions of last year, many new issues have emerged: budgetary restrictions, manufacturing viability, levels of the factor of safety, estimation of loads. This is central in the engineer's activity and did not appear before. And we wanted it to appear!"

The study of collected data regarding the use of Q-A maps by both lecturers and students reveal significant facts. Firstly, the analysis of the weekly reports showed that the reports handed in the first week did not include the maps. In fact, in this first delivery not a single group explicitly stated aspects regarding the modelling of their study in terms of Q-A, even though it was a content requirement in the evaluation rubric (see Appendix 2). The difficulties that students faced when elaborating the first weekly report were due to the fact that the process of study (including hypothesis, doubts and wrong tasks) is usually not considered to be an aspect to be explicitly communicated during an academic project. Some authors have stated that this absence is mainly due to the lack of focus on the dynamic and evolving nature of knowledge in the traditional didactical contract at the university (Barquero, Bosch, and Gascon 2008). This hindered them from presenting partial or non-validated answers. Two illustrating examples can be found in the students' statements: Student 3.2 said: "My first report did not include the Q-A. Although they asked for it I was sure the lecturers were not interested in the Q-A (. . .) then I started to see that making Q-A explicit was central and that it actually was what we were doing: Which material should we choose? What shape? How do I obtain Poisson's ratio? In the end it turned out to be very helpful: we knew what we already knew and what we wanted to know." Student 2.2 explained in the interview: ". . . I failed the first weekly report: I did not understand what teachers meant about questions and answers. . . I was only worried about designing a gear for the bike and in just one week we did not have any concluding result . . ."

In contrast, the results of the survey highlight that most of the students considered that writing the weekly reports (that included the Q-A explicitly) was difficult, but very useful (see Fig. 4). Student 1.2

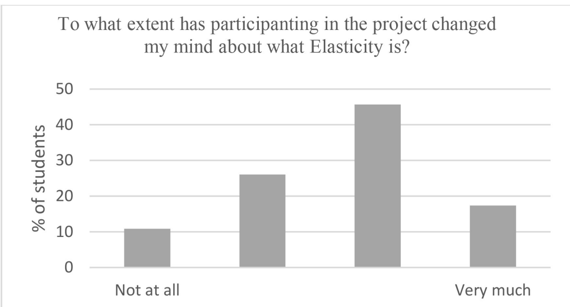

Fig. 3. Results of question 21 of the survey.

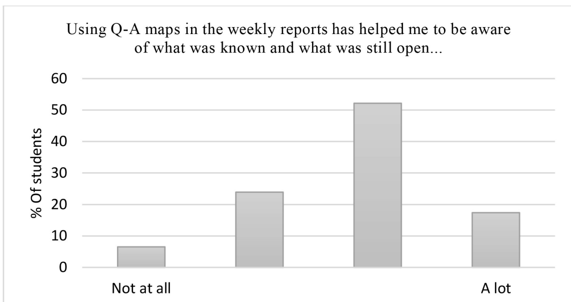

Fig. 4. Results of question 22 of the survey.

made this point: "The Q-A section in the weekly reports was useful: iterations appeared there, we saw where we were progressing. We just took the final answer of the session as our answer. In fact, the final report was just to gather up all the correct answers of the weekly reports and to combine them" and Student 1.1 stated "Q-A maps became very useful when managing the work load: we assigned questions to everyone". The non-researcher lecturer highlighted this point in the following terms: ". . . writing the weekly report and receiving our feedback helped the students very much: they knew where they were, who was in charge to do things . . .". It is also very illustrative, and seems to confirm the role played by the didactic contract. More than 80 % of the students considered that writing the final report, a report only including the final solution to the initial question, seemed easier.

Another aspect that data seem to confirm is the fact that Q-A maps played an important role as a management and communication tool. This communication aspect is explicitly stated by two students during the interviews: Student 1.1 described this phenomenon in these terms: "Q-A maps became very useful when managing the work load: we assigned questions to everyone". Student (2.1) described the role played by Q-A maps as follows: "Q-A maps helped us to inform the teacher where we were in the project . . ."

7. Conclusions

Regarding RQ1.1, the collected evidence shows how the use of the DE engineering methodology provides an explicit strategy to select and justify the generating question for the study process. This choice is not merely based on intuition or on more or less implicit general principles, but emerges from an explicit epistemological work about the raison d'être of the domain, its connection with other fields as well as the questions that the students will be able to derive and answer. This epistemological work provokes changes in the teachers' and students' conceptions of General Elasticity. This is an important finding helping to systematize the selection of the project in PjBL that is an open issue in research.

With respect to RQ1.2, data shows that the DE methodology, and in general the SRP implementation, demonstrated its viability within the curricular constraints and conditions of the considered university institution, and it was possible to maintain, and complement, part of the previous organisation. The explicit epistemological work to analyse the potentials of the generating question enables a systematic analysis of whether specific learning goals are met by the implemented SRP. Further research must be conducted to validate these facts and to test the SRP viability in different institutional environments.

Regarding RQ2 and its derived questions about the role played by Q-A maps, we consider that the analysis of data, especially the students' reports and interviews, shows that the use of Q-A maps helped both lecturers and students to make central aspects of their study process explicit. With respect to RQ2.1 findings show that the Q-A maps have been used in engineering education as a crucial communication tool, and this helped them manage the study process (assign tasks and responsibilities, detect stuck working groups, etc.). In addition, and regarding RQ2.2, the use of Q-A maps is compatible with commonly cited principles of PBL and PjBL, and help to make explicit knowledge appearing during the project. Moreover, they serve as a specific tool to supply the design and implementation of study processes in engineering education with an explicit epistemological reflection.

The maps have also been used as a design tool: the a priori Q-A map shows that the potential study process not only meets all the curricular requirements, but also connects them and makes them contribute to answer a meaningful question. In relation with RQ2.3, the maps have been used as a central item in the collected data (students' weekly reports and final reports), which reveal an important change in terms of the knowledge constructed by the students. Especially remarkable is the fact that the map makes the need to compare and contrast the students' designs with the real available solutions existing in the market explicit. The in vivo analysis also confirmed the potential of Q-A maps to become a relevant tool for communicating and sharing the work done by the students. The need of this kind of tools, allowing students and lectures to communicate, has been emphasised by researchers in both mathematics education and engineering education. Finally, we would like to highlight that this is a first exploratory case study, intending to set the basis for further research in order to validate the conclusions in other institutional settings.

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Appendix 1: Interviews Guide for Students

Personal data

As a starting point, we need some personal data in order to improve the data analysis:

Student 1

Gender:
Retaking the subject:
Final mark:

Student 2

Gender:
Retaking the subject:
Final mark:

Student 3

Gender:
Retaking the subject:
Final mark:

General aspects

The first phase pretends to collect your general opinion, after your participation in the project of Continuum Mechanics. If you had to explain the Continuum Mechanics project to a student that did not take the subject: what would you say?

Which aspect would you highlight?
Which aspects were surprising or shocking?

The second phase of the interview will consist in asking you about your personal opinion and position on the answers we have collected from the general online survey.

Length of the project

About 80% of the students agree on the fact that the project has been long or too long.

Why do you think they consider it too long or long? What do you think?

Difficulty

About 80 % of the students consider the project "difficult" but only 4% consider it "too difficult".

What do you think about the difficulty? Which aspects were the most difficult ones? And the easiest ones?

Team work

60 % of the students think that sharing tasks and responsibilities with other group members was "difficult" or "too difficult".

What do you think? Was it difficult in your group?
Which was the most difficult part? And the easiest one?
How did you manage to overcome these difficulties? Were the roles made explicit in the reports actually real?
Which tools did you use in order to arrange meetings, exchange information. . .?

Level of lecturers' guidance

Around 70% of the students consider that the level of guidance was "high" or "too high".

What do you think? Which is the main reason leading to this result in your opinion? In which aspects have you felt too guided or not guided enough?

Difficulties in writing reports

The results of the survey show that in general it has been much more difficult to write the weekly reports (where Q-A should be made explicit, useful and useless tasks. . .) than the final report.

Why do you think that we obtain this result? Why are weekly reports considered more difficult to write than the final one? Do you think it is useful to consider the study process as a rooted tree sequence of questions and answers?

Utility of Elasticity

Most of the students consider that the project has changed their idea of "what elasticity is for and why is it useful?

What do you think? In which aspects your initial conception changed?
Thank you.

Appendix 2: Evaluation rubrics for weekly and final reports

Table 4. Evaluation rubric for weekly reports

Time-planning (format)	No time-planning	Non-updated time-planning or not detailed enough	Time-planning partially updated	Updated and detailed time planning
	0 points	1 points	2 points	4 points
Time-planning (contents)	Time-planning does not follow a coherent path	Time-planning is partially coherent with the real needs of the team	Time-planning is coherent with content-related needs	
	0 points	2 points	4 points	
Role definition	Not defined	Partially defined	Totally defined	
	0 points	1 points	2 points	
Questions and answers	No questions and answers stated	Partially stated questions and answers but not updated	Detailed and updated questions and answers	
	0 points	2 points	4 points	
Completed tasks (format)	No detail of the completed tasks	Partial presentation of completed tasks	Total presentation of completed tasks	
	0 points	1 points	2 points	
Completed tasks (content)	Results from completed tasks are wrong	Most of the results are wrong	Only some of the results could be improved	All the results are right
	0 points	2 points	4 points	6 points

Table 5. Evaluation rubric for final report

Final budget	No final budget presented	Unjustified final budget	Justified final budget	
	0 points	1 points	3 points	
Orthography (core competence)	Many spelling mistakes	Some spelling mistakes	No important spelling mistakes	
	0 points	1 points	2 points	
Text (core competence)	Text is not understandable: important writing defects	Some problems appear when reading the text	Text is understandable, well written using short and correct sentences	
	0 points	2 points	4 points	
Figures, graphs, tables (core competence)	Figures and graphs are not readable, a title is missing and variables are not defined	Some aspect is missing: titles, definition of variables, units	Figures, graphs and tables are readable, have a title and variables are defined	
	0 points	2 points	4 points	
Mathematical formulas	No formula is presented, or with important format mistakes	Formulas are partially presented and not numerated	Formulas are numerated and well written (using an equation editor)	
	0 points	1 points	2 points	
Choice of the material	No material is chosen	The choice of the material is based on wrong notions	The choice of the material is not fully justified	The choice of the material is well founded in solid notions
	0 points	1 points	2 points	3 points
Loads and constraints	Presented and estimated loads and constraints are wrong and not justified	Many of the estimated loads or constraints are wrong and partially justified	Some of the estimated loads or constraints are wrong and partially justified	The estimated loads and constraints are appropriate and justified
	0 points	1 points	2 points	3 points
Stresses and strains	The presented stresses and strains do not correspond to the problem	The presented stresses and strains are not fully correct or they are misinterpreted	Even if stresses and strains are correct, presented data is irrelevant	Stresses and strains are correct and they are well presented without redundant data
	0 points	1 points	3 points	4 points
Safety factor	The safety factor is not correct or its value is not appropriate	The use / choice of the safety factor is only partially appropriate	The adopted and calculated safety factor is correct	
	0 points	2 points	4 points	
Dimensions and drawings	Dimensions do not correspond to the use of the part	Dimensions could be improved and drawings are not enough to describe the designed part	Dimensions are correct but drawings could be improved	Dimensions and drawings are correct
	0 points	1 points	3 points	4 points
Final solution	The presented solution does not solve the initial problem	The presented solution partially overcomes the initial problem	The presented solution solves the initial problem	
	0 points	3 points	6 points	
Research path (evaluated also in the weekly reports)	The "path" followed during the project is not coherent. Decisions are not justified	Decisions during the project could be optimised and better justified	Decisions during the project are justified and respond to coherent decisions	
	0 points	3 points	6 points	