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Towards Successful Project-Based Teaching-Learning Experiences in Engineering Education*

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Problem- or project-based teaching–learning experiences (typically 'PBL' or 'PjBL') have enormous benefits but also certain limitations and difficulties that have been analysed in this work with the purpose of setting some standard guidelines that may help to enhance the results of this kind of teaching experience. A systematic, prioritised analysis of forty factors that influence this type of experience and affect the planning, organisation, development and assessment stages, has enabled us to find and formulate nine problems that we deem to be major ones and that are usually repeated, particularly in machine and product development related experiences in the area of Mechanical Engineering. Having selected these most typical problems, we have then established causal relationships by taking account of: the methodology involved, the available resources, the teachers in charge of the experience and the students taking part in it. This has helped us to find and put forward different solutions and to discuss their effects, keeping in mind our team's experience and the information from the studies carried out by teaching staff from other universities.

Keywords: project-based learning; improving teaching–learning processes; active learning; European Higher Education Area

1. Introduction

1.1 Benefits and limitations of project-based learning

Problem- or project-based teaching-learning experiences (typically 'PBL' or 'PjBL') have enormous benefits but also certain limitations and difficulties. These are analysed in this work with the purpose of setting some standard guidelines that may help strengthen the results of this kind of teaching experiences. Problem- or project-based learning clearly tends to motivate students to participate and become involved in their own learning process. It is an excellent way of analysing whether students have acquired the basic concepts taught in the theory classes and if they are capable of applying them in real situations.

These PBL experiences have proven to be effective in primary, secondary and university education and in scientific–technological, bio-sanitary, humanistic and artistic contexts. In fact, most technical universities usually include the standard final degree project which, basically, is a PBL learning experience as part of the engineering degree studies. The doctoral programmes are also oriented towards being completed by a doctoral thesis where the Ph.D. students have to solve a problem or complete a complex project.

Although project-based learning goes back to the Middles Ages (apprentices who worked with their masters in the workshop), the term 'problem-based learning', which would later be adapted to 'project-based learning' for branches of Engineering, was coined in the field of Medicine. We can highlight the initial works of figures such as Dewey, Lewin, Piaget and Vigotsky on multiple issues related to cognitive development, social psychology and learning, of which some brief works included in the references are worth mentioning [1–4].

Some of these most active types of learning became institutionalised in 1966 when McMaster University's Faculty of Medicine was founded in Ontario, to pursue some of the marked principles of the preceding references but adopting a form of teaching based only on problems and case studies [5]. In the context of Engineering in Europe, the first institutions to become a point of reference were the University of Aalborg (Denmark, founded in 1974) and the University of Maastricht (Holland, founded in 1976). Systematic studies have enabled traditional and project-based approaches to be compared and reveal certain overall benefits for professionals who have undergone PBL training experiences [5], as well as considerable benefits in other scientific fields [6].

Therefore, PBL experiences are an excellent teaching–learning tool, especially in Engineering, for guiding students toward their future working life in industry, which will not only involve solving technical or financial problems on a daily basis, but also human problems. Regarding the human

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element of PBL experiences, work is done differently depending on the students for whom the experience is intended. In the case of final projects or doctoral theses, the relationship between the tutor and student encourages critical discussion of the results by strengthening the ability for analysis and the synthesis between them. In respect of PBL experiences, within the context of specific subjects, teamwork is usually preferred, so that students will learn to collaborate with their fellow students when finding solutions to complex problems.

Here we concentrate more on our team's experience in the field of Mechanical Engineering (although the analyses described and the ensuing conclusions can be extended to all areas of Engineering), and on the experiences linked to the development of new products and machines, where this kind of methodology has been of enormous use for encouraging students to use all kinds of advanced innovation, design, simulation and computer-aided manufacturing technologies (usually referred to as CAI, CAD, CAE, CAM and, in general, CA-x). It helps students to look closely at the conceptual aspects and to really get to grips with handling the tools that are increasingly required by industry.

Certain PBL experiences linked to complete product development and their related benefits and potentials are also detailed. These experiences are normally completed by manufacturing prototypes directly from CAD 3D files containing the parts geometry, thanks to the use of 'rapid manufacturing' technologies, as an aid to verifying the designs produced and as a way of boosting the students' motivation [8–10].

These kinds of teaching activities are also directly linked to many others that can be grouped together under the title of 'play-based learning experiences'. Among such experiences it is important to cite some competitions for students where the goal is to implement a new product or device, a series of laboratory experiments aimed at solving real problems, different problem-solving techniques based on the use of simulators and subjects in which students are assessed according to their involvement in enjoyable activities [11–13].

Apart from improving student motivation and their perception that what they learn at University 'is actually of some use', all these activities also help teachers to become more involved in their relationship with students, to be continually up to date with new developments and to renew or update subject content in line with the specific topic chosen for the PBL experience, although all this requires considerable time and a desire to interact with the students.

The benefits are thus evident, although these activities are usually more enriching in the final years of the degree, when students have already learnt sufficient concepts regarding basic science, materials science, applied mechanics, energy technology, mechanics, chemistry and electricity and the foundations of automation and electronics. These are just some of the many disciplines that students can summon to tackle problem-solving or complex projects.

However PBL experiences entail certain difficulties that can lead to educational gaps and imbalances when assessing students, if they are not borne in mind and their effects limited. The following section will present a brief description of the PBL learning experiences undergone by our team in the Machine Engineering Division of Universidad Politécnica de Madrid. It sets out a systematic and prioritised analysis of the most important issues that need to be addressed for these activities to be successful. The analysis lets us state the main difficulties of these experiences and put forward cause–effect relationships for these problems, so that solutions and action guidelines can be proposed to obtain a systematic improvement in the results.

Excellent previous studies have reviewed some of the main factors influencing the success of project-based learning experiences from primary to upper secondary level [14], as well as university experiences [15–18], including advice for managing this kind of initiative from its creation right up to assessment. In any case, we believe that the approach taken here contributes with new aspects, particularly regarding the implementation and continuous improvement of learning experiences linked to projects in Mechanical Engineering-related subjects, which is particularly the case if machine and product development is involved. In any case, the problems encountered and the proposals for solving them can be of interest and be valid in many areas of Engineering, such as Automation and Robotics, Industrial Design, Product Design or even Architecture and Civil Engineering.

A systematic analysis of forty factors that influence this type of experiences, and affect the planning, organisation, development and assessment stages enables us to find and formulate nine major and usually repeated problems. After selecting these most typical problems, we then establish causal relationships by taking account of: the methodology involved, the available resources, the teachers in charge of the experience and the students taking part in it. This helps us to find and put forward different solutions and discuss their effects, while bearing in mind our team's experience, together with the information from the studies carried out by numerous teaching staff from other universities.

2. Project-based learning in the Machine Engineering Division of the Universidad Politécnica de Madrid

The teaching work in the Machine Engineering Division of the Universidad Politécnica de Madrid (UPM) is devoted mainly to issues linked to the complete development process of machines, mechanical systems and industrial products, including aspects of design, manufacture, in-service performance analysis, maintenance and industrial safety. Most of our subjects are taught in the UPM's Industrial Engineering degree or in the UPM's Master's in Mechanical Engineering in which around 500 students take part each year. For over 30 years some of these subjects have included project-based teaching activities, especially Machine Design I and Machine Design II, which have gradually evolved throughout the different study plans in our School (1976, 2000, 2010) and in line with the available design and manufacturing technologies.

Recent methodological renewal, partly as a result of the European Higher Education Area being implemented (EHEA) and due to the continuous search for ways in which to get students more involved in their learning process, has motivated our team to extend this type of PBL experience to more subjects. Table 1 shows the different PBL experiences implemented that have been used as a main source of information when conducting this study for the different subjects taught by our team. The importance and impact of these experiences on the teaching of our group have encouraged us to make a close examination of the inherent difficulties in this type of teaching–learning methodology and to analyse the most appropriate solutions so that they can form the basis of a 'good practices' guide in the future.

Moreover, we are dealing with key actions that could benefit from continued improvement, since the results sought by this type of experience are key-points aimed at students' subsequent professional development, as can be seen from the information in Table 2. This table prioritises the teaching–learning results that are intended to be improved through project-based learning as a result of an assessment carried out by our work team. A survey of our team was carried out and the list of the teaching–learning results pursued was scored from 0 (minimum) to 10 (maximum).

It can be appreciated how these results are clearly linked to professional success skills for engineers. They range from technical aspects, such as the ability to apply knowledge to the solving of real problems or to critically analyse problems, to human aspects, such as the ability to solve personal conflicts or prepare work in international contexts. All of these are closely linked to the educational renewal sought by the implementation of the European Higher Education Area and, ultimately, to university quality.

3. Systematic detection of difficulties and their causes

To systematically detect the main difficulties related to this kind of teaching–learning experience, a

Table 1. Summary of project-based learning experiences carried out by the teaching team at the Machine Engineering Division of the Universidad Politécnica de Madrid

Subject	Degree	Course	Type of PBL experience	Average number of students	Group or individual	Weighting of the PBL experience
Machine Design I	Industrial Engineer	4th	Development of a machine	60–75	Groups of 3	50%
Machine Design II	Industrial Engineer	4th	Development of a machine	60–75	Groups of 3	50%
Machine Vibrations	Industrial Engineer	4th	Study of a machine's vibration behaviour	60–75	Groups of 3	30%
Engineering Design	Industrial Engineer	5th	Development of a machine or product	50–60	Groups of 5 or 6	70%
Safety and Regulations	Industrial Engineer	5th	Assessing the safety of a machine	30– 40	One individual and one in a group of 3	50% and 50%
Design and Manufacturing with Polymers	Industrial Engineer	5th	Development of a product (toys)	60–70	Groups of 3	70%
Mechanical Engineering by Computer	Master's in Mech. Eng.	1st	Development of a mechanism	15–20	Individual	80%
Bioengineering and Medical Devices	Master's in Mech. Eng.	1st	Development of a medical device	15–20	Individual	80%

Table 2. Comparative assessment of the main objectives pursued when implementing project-based teaching–learning experiences. (The most relevant are in italic.)

Assessment of results pursued when implementing PBL experiences	Average	Standard deviation
a. Application of knowledge to real problems	*9.8*	0.45
b. Critical analysis of problems	*9.6*	0.81
c. Systematic search for solutions	*9*	0.8
d. Conflict resolution through listening to opinions	*8.8*	1.30
e. Involvement in industrial-like practice	*8.6*	0.89
f. Teamwork	8.4	0.55
g. Conflict resolution through different motivating factors	8.4	2.07
h. Use of tools demanded by industry	8	1.58
i. Creativity in work and alternative solutions	7.6	1.67
j. Work in an international context	6.6	2.07

Table 3. Results of the analysis of the main factors that can limit project-based learning experiences (main issues in italic)

A) Planning and preparation	Average	Standard deviation
a. *Designing projects that properly reflect how the subject evolves*	*9.50*	0.55
b. Designing stages that will ensure progressive learning	7.50	0.55
c. Designing the assessment system to be used	8.17	0.75
d. Preparing a sufficient number of different questions	7.33	2.66
e. *Preparing questions of equivalent difficulty*	*8.50*	2.35
f. Choosing appropriate support tools	8.17	0.41
g. Implementing manuals and help examples	7.17	0.75
h. Implementing software support tools	7.17	1.17
i. *Planning projects to fit the time allocated to the subject*	*8.50*	0.55
j. *Searching for a realistic approach ('real' projects) but feasible for students*	*8.50*	1.05
B) Assignment and organisation	**Average**	**Standard deviation**
a. Explaining to students the 'PBL' methodology to be used	6.67	1.03
b. Students' acceptance of 'PBL' methodologies as something positive	7.50	1.52
c. Decision between group and individual projects	8.00	1.26
d. Choosing the number of students per group	7.33	0.52
e. Group training process	6.83	0.98
f. Assigning projects (should students be unable to propose them)	6.83	0.98
g. Choosing projects (should students be able to freely propose them)	7.83	0.75
h. Acceptance of projects by students / teachers	7.33	1.03
i. Consideration of alternatives to 'PBL' methodology, if appropriate	7.00	1.67
j. *Project coordination and timescales compared to other experiences in other subjects*	*8.67*	1.63
C) Development	**Average**	**Standard deviation**
a. *Setting milestones throughout the process*	*9.33*	0.52
b. *Taking action to adapt students' starting-out levels*	*8.33*	1.86
c. Tutorials throughout the process	8.00	1.26
d. *Coordinating the development with other experiences in other subjects*	*8.50*	1.38
e. *Motivation and follow-up to avoid deviations in the results*	*8.50*	1.87
f. *Motivation and follow-up to avoid deviations in the timescales*	*8.33*	1.86
g. Student access to learning resources	6.67	2.07
h. Student access to laboratories	7.83	2.32
i. Student access to software tools	8.00	0.89
j. Carrying out practice to back up the 'PBL'	8.00	1.55
D) Assessment	**Average**	**Standard deviation**
a. *Setting a diagnostic assessment system to find the starting-out level*	*8.33*	1.86
b. *Setting an adequate system to evaluate knowledge*	*9.33*	0.82
c. *Setting an adequate system to evaluate skills*	*8.33*	1.86
d. Setting an adequate system to evaluate generic competencies	7.00	2.19
e. *Setting an adequate system to individualise group experiences*	*8.50*	1.76
f. *Detecting and controlling unacceptable conduct (copied projects, 'parasite' students . . .)*	*9.17*	0.98
g. Public presentation of results as a supplement to assessment	8.00	1.10
h. Use of other conventional assessment methods to supplement (final exam, test . . .)	7.00	1.55
i. *Use of questionnaires to assess the progress of the experience and possible improvements*	*9.00*	1.26
j. Use of questionnaires to evaluate students' work load	7.50	3.21

questionnaire with forty issues grouped into four main blocks that affect PBL experiences ('planning and preparation', 'assignment and organisation', 'development' and 'assessment') was developed. The questionnaire was answered by the teachers from our department, a total of eight teachers, which we believe constitutes a representative sample, as the whole Mechanical Engineering specialisation from our University is taught by around forty teachers.

Table 3 contains the results of this analysis of the main factors that can limit the success of project-based learning experiences. They have been scored by our team according to relevance and complexity (from 0 or Very Easy / Irrelevant, up 10 or Very Difficult / Decisive). Mean values and standard deviations are included and the main issues are highlighted in italic.

Once the nine most dramatically limiting difficulties or issues had been selected, they were converted into the cause–effect diagrams illustrated in Figs 1–9, which group together the causes into main issues, upon which we can act and propose corrective actions. These are: 'methodology', 'resources', 'professors' and 'students'. For each target difficulty or problem analysed we have tried to find at least two

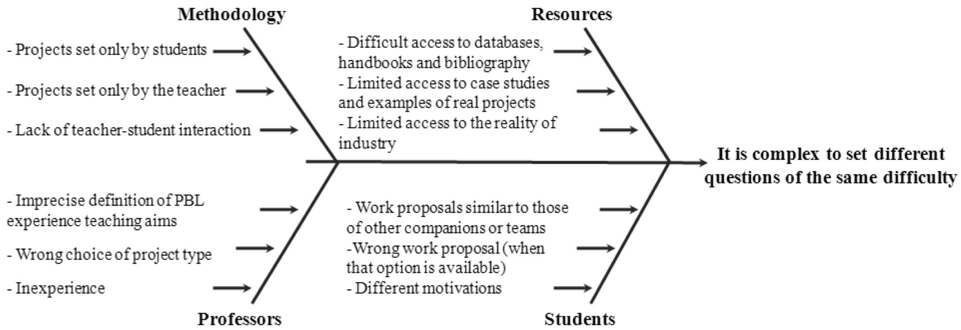

Fig. 1. Cause–effect diagram of the problem: 'It is complex to set questions of the same difficulty'.

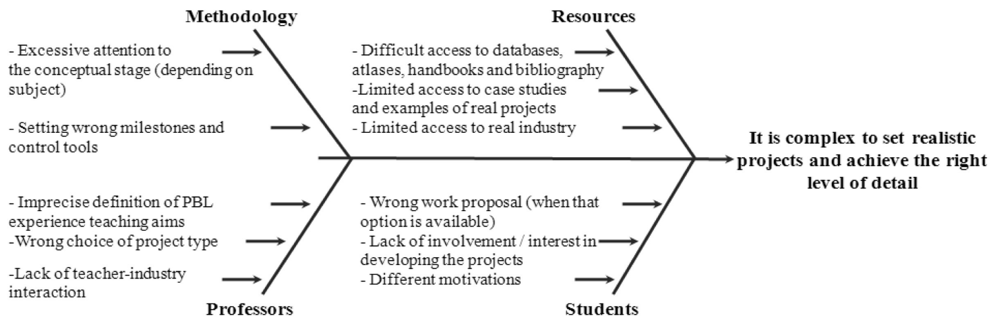

Fig. 2. Cause–effect diagram of the problem: 'It is complex to set realistic projects and achieve the right level of complexity'.

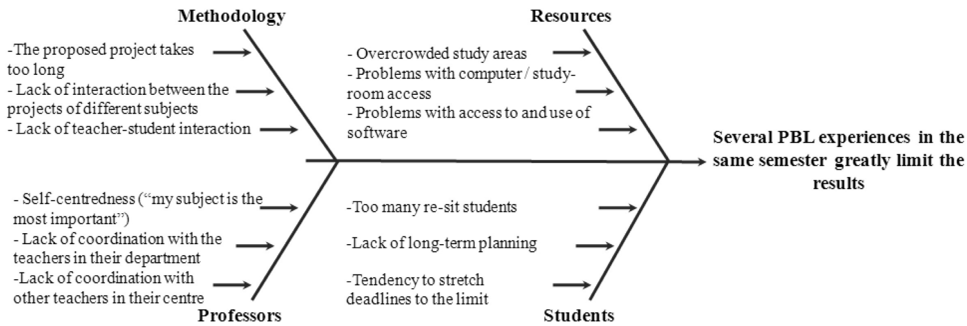

Fig. 3. Cause–effect diagram of the problem: 'Several PBL experiences in the same semester limit the results'.

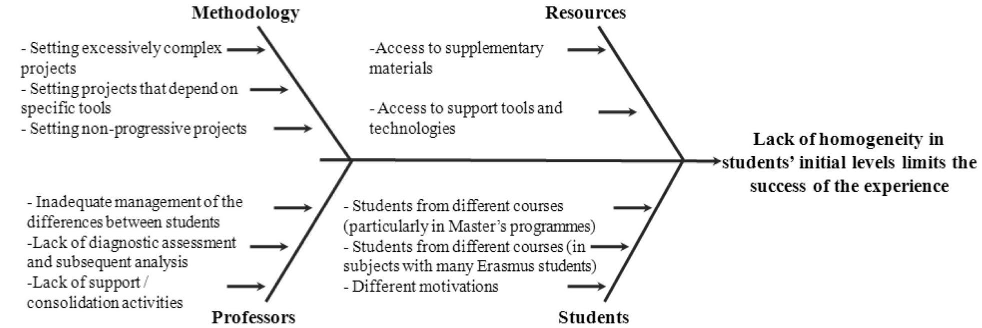

Fig. 4. Cause–effect diagram of the problem: 'The lack of homogeneity in students' initial levels limits the success of the PBL experience'.

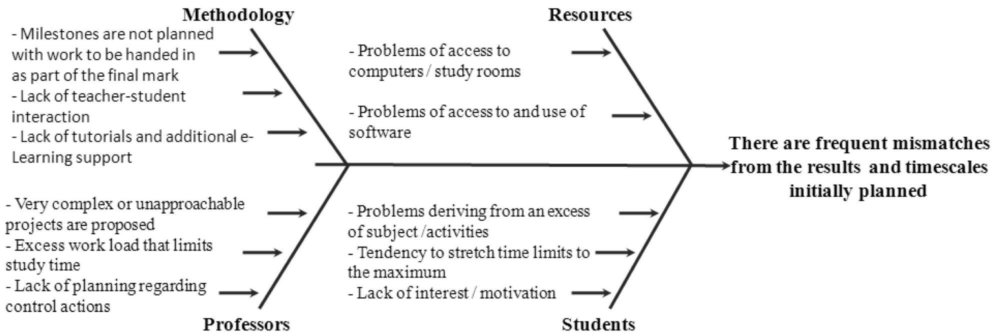

Fig. 5. Cause–effect diagram of the problem: 'There are frequent mismatches from the results and timescales initially planned'.

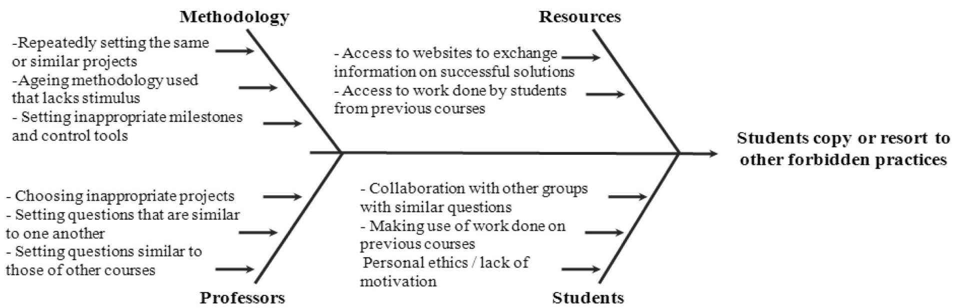

Fig. 6. Cause–effect diagram of the problem: 'Students copy or resort to other forbidden practices'.

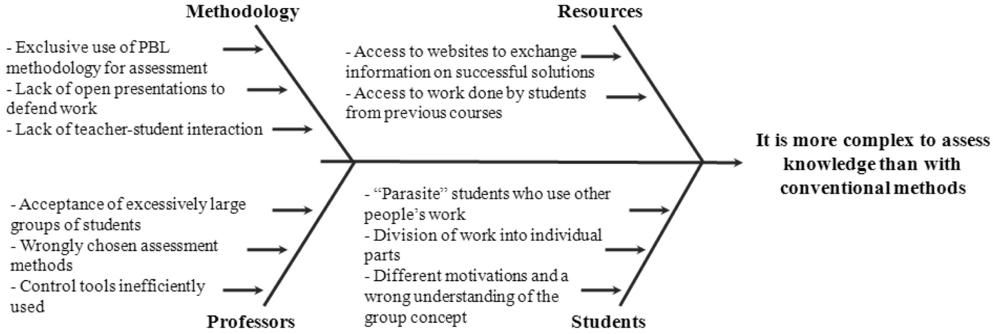

Fig. 7. Cause–effect diagram of the problem: 'It is more complex to assess knowledge than with conventional methods'.

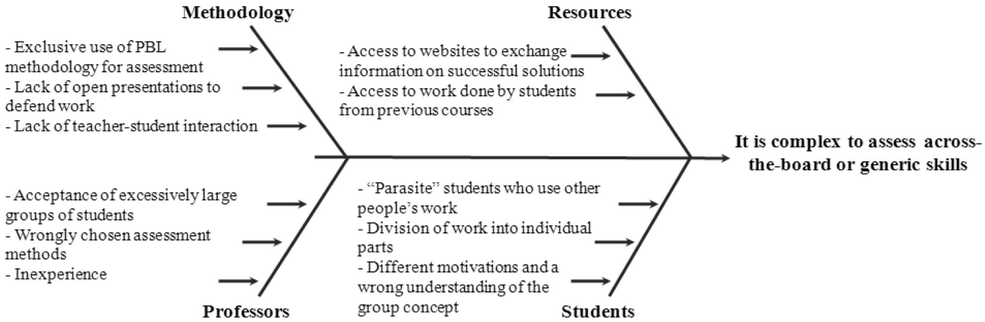

Fig. 8. Cause–effect diagram of the problem: 'It is complex to assess across-the-board or generic skills'.

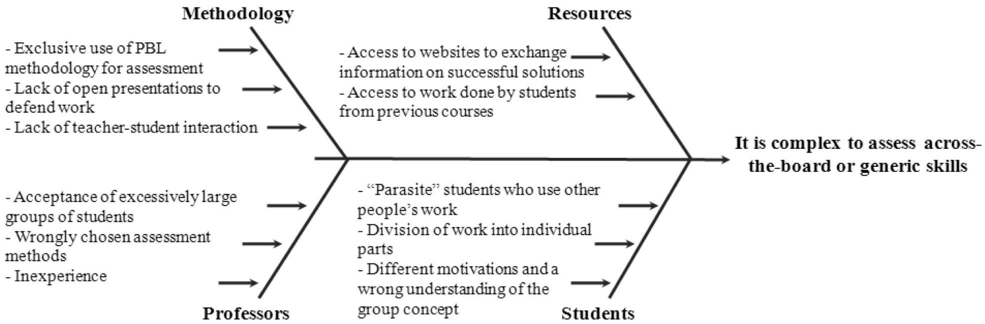

Fig. 9. Cause–effect diagram of the problem: 'It is complex to make individual assessments in group experiences'.

possible causes linked to each of the main issues to correct. In this way, we have attempted to facilitate the subsequent proposals for solutions, as well as to provide control or follow-up tools, as detailed further in Section 4 below. We have also attempted to organise the analysis and discussion arising from the different proposals for solution, which are included in Section 5, before summarising the main conclusions of the study.

4. Proposals for solving the main problems of project-based learning activities

The main problems or difficulties detected, grouped into the four main blocks that affect PBL experiences ('planning and preparation', 'assignment and organisation', 'development' and 'assessment'), are again summarised in Table 4. It should be pointed out that the difficulties or problems in the 'planning and preparation' and 'assigning and organising' blocks were scored (see Table 3) as less relevant than some of the problems and difficulties linked to the 'development' of the experiences and their 'assessment'. Therefore, on this occasion they have been grouped under the 'Planning/Organisation' of experiences heading, a decision that is justified by the close relationship between these two blocks. However, the following discussion will enable these aspects to be analysed more closely.

For each of the problems, Table 4 includes 3–4 proposals for solutions linked to the different main causes extracted from the causal diagrams included in Figs 1–9. A control tool is also included for each proposed solution, so as to help with checking the way the problem evolves after gradually applying the corrective measures. The solutions to the different conflict issues, as well as the tools proposed for checking how they evolve, are a result of our experience in PBL actions and our joint reflections upon them. However, they are also based on the decisions of many other teaching teams that have used them successfully in the various teaching–learning experiences described in the References below.

The next section includes a discussion on the proposed solutions included in Table 4. This discussion presents a critical analysis based on our team's experience in this kind of PBL activity and of similar experiences detailed in the references. Although the discussion basically deals with learning experiences based on projects linked to the area of Mechanical Engineering and actions to develop products, machines and mechanical systems (also linked to practically all the life-cycle aspects of these products and machines), we sincerely believe that many PBL experiences in other fields of Engineering

Table 4. Table summarising the main difficulties and problems of project-based learning and some proposed solutions for greater success.

Problems	Proposed solution	Tools to check progress
Planning/Organisation		
It is complicated to set questions of equivalent difficulty	Use a specific, limited single topic for projects	Project assessment (i.e. final mark)
	Use of handbook references, classic books, design, product or machine encyclopaedias	Comparative questionnaire
	Use of patent databases on the single topic	Project assessment (i.e. final mark)
It is complicated to set realistic questions and achieve the right level of detail	Use of a specific, limited single topic for projects	Project assessment (i.e. final mark)
	Use of handbook references, classic books, design, product or machine encyclopaedias	Comparative questionnaire
	Use of patent databases on the single topic	Comparative questionnaire
	Visits and support seminars	Evaluation questionnaires
Development		
Various PBL experiences in the same semester limit the results	Work to be handed in with specific objectives and dates	Progress of quality of work handed in
	Use of e-Learning as a support tool	Participation register
	Promoting tutorials	Attendance register
	Encouraging interaction with teachers of other subjects	Minutes of meetings
Lack of homogeneity in students' initial levels limits the success of the experience	Diagnostic assessment for analysis	Test results
	Setting progressively difficult projects	Progress of quality of work handed in
	Support actions	Participation register
	Progressively difficult inter-subject projects	Progress of project quality
Results and timescales frequently fail to meet the initial expectations	Work to be handed in with specific objectives and dates	Progress of quality and amount of work handed in
	Use e-Learning as a support tool	Participation register
	Promoting tutorials	Attendance register
	Extra 'homework' to be handed in to reinforce progress	Progress of quality and amount of work handed in
Students copy or cheat in other ways	Set different questions for the same course	Comparative questionnaire
	Different single topics for each course	Project assessment (i.e. final mark)
	Individualised monitoring of students by their defending their work in front of others	Evaluation questionnaires
Assessment and results		
Assessing knowledge is more difficult than with conventional methodologies	Students defend their work in front of others and all take part	Evaluation questionnaire
	Conduct personalised interviews	Evaluation questionnaire
	Implement supplementary tasks (exam, progress tests . . .)	Exam result
It is complicated to assess across-the-board or generic competencies	Students defend their work in front of others and all take part	Evaluation questionnaire
	Conducting personalised interviews	Evaluation questionnaire
	Compiling questionnaires on personal opinions	Survey result
	Using questions developed ad hoc	The rubric itself
It is complicated to make individual assessments in group experiences	Students defend their work in front of others and all take part	Evaluation questionnaire
	Conducting personalised interviews	Evaluation questionnaire
	Implement supplementary tasks (personalised exercises to be handed in, co-assessment . . .)	Progress of quality and amount of work handed in

can benefit from such a critical analysis of the various problems and proposed solutions. Our intention is to compile a summary of the problems and actions to take in order to form a 'good practices guide' for PBL experiences in Engineering to help apply this kind of teaching strategy to a wide range of qualifications.

5. Analysis of the proposed solutions

5.1 Regarding the planning and organisation of the experiences

When considering sufficiently complete PBL experiences that cover all the aspects involved in a subject, it is a good idea to use projects linked to complete product or machine developments (from the market research and product planning stage, up to the pre-production stage, passing through issues connected with conceptual design, basic design and detailed design, that is, working from the general to the particular). Occasionally it is difficult to cover all the development stages in just one subject, but anyway assigning groups of students complex complete projects does strengthen their positive interdependence and increases the percentage of students who seriously devote themselves to the proposed project-based learning experiences [19].

It is sometimes especially complicated to prepare enough project ideas for the number of students (or groups of students) involved, so that the different PBL experiences arising may be equally complex and may require similar efforts on the part of the students. To ensure this, single topics can be chosen (e.g. toy development), so that all the projects may be similar but with certain differences to avoid students copying. It is also important to change the single topics for the projects frequently, from one course to another, in order to avoid repeating projects and limit students making use of previous course work.

Another key point for PBL success is the scope of the project. This must be carefully thought out according to the subject's teaching aims. The most complex stage and that which decides the success of a novel product or process is conceptual design. For this reason, recent years have seen the introduction of numerous subjects, such as 'Product Specification', 'Computer-aided Innovation', 'Creativity and Intellectual Property', to name but a few, in a wide range of Engineering qualifications that look to methods for systematically proposing and evaluating alternative solutions.

In the fifth year 'Engineering Design' course of the Industrial Engineering degree at the UPM, we have carried out various PBL experiences linked to innovative designs of machines and mechanical systems. The complexity of the 10–12 projects developed in the subject, usually chosen by a ballot from the 50–60 proposals and the limits to the amount of hours that can be put in means that it is impossible to experience the complete development process. Therefore, we have usually focused the projects on the conceptual design and basic engineering stages, as detailed in the previous references [20].

However, quite often, particularly in the final semester subjects, the Master's and the Doctorate, a much higher level of detail is required in order to consider PBL experiences to be successful. This is so that the knowledge and more specific tools taught in this kind of advanced subjects can be applied, consolidated and strengthened, as this will be vital when students join the industrial practice in their different jobs. As a rule, students will start in industry working on the most technical tasks of the projects that they are involved in to gradually evolve towards more conceptual and supervisory tasks. This means that their taking part in PBL experiences oriented to the interim stage between the basic design and the detailed design is particularly appropriate.

In order to achieve sufficient level of detail in 'teaching–learning' PBL experiences that normally fall within one subject in just one semester, it is useful to begin the project by starting out from an already existing conceptual design, on which students can work progressively to precisely define geometries, joints, materials, commercial elements, manufacturing and assembly processes, useful life and maintenance, among others. We can mention, as an example, our experience in the subject 'Computer-aided Mechanical Engineering', in the first semester of the Master's in Mechanical Engineering at the UPM, where students receive the conceptual design of a mechanism taken from the *Mechanisms in Modern Technology* by I. I. Artobolevski (a seven-volume encyclopaedia containing all types of mechanisms for different purposes) [21]. Starting out from the outline of the mechanism, students design the different parts with the aid of CAD software, perform assembly and movement simulations and verify the in-service performance using finite-element calculation in order to optimise the design and reach a final proposal. Since this encyclopaedia of machines and mechanisms contains over 20 000 conceptual designs, it is an excellent source of very varied project ideas of equivalent difficulty, since the mechanisms are grouped according to similar mechanical principles and functions.

One possibility worth underlining is linked to what we have been calling 'patent-based project-based learning' or 'P^2B^2L' experiences, where students are given the patent document defining a product or conceptual process as the project idea, on which they then work until they produce a detailed pre-production design. In this respect, we can mention our experience in the subject of 'Bioengineering' [22–23], in the second semester in the Master's in Mechanical Engineering at the UPM. At the beginning, each student is given a patent on a medical device that they must then design in detail with the aid of CAD–CAE tools, applying the knowledge and skills acquired in the preceding subject on 'Computer-aided Mechanical Engineering'. This experience also enables them to acquire important notions about intellectual property issues, as well as consolidating previous learning by applying it to more complex experiences. In addition, patents are an unending source of varied questions, which limits the chance of students copying or using work from previous courses.

Another excellent option for students to experience a complete project, while going into sufficient detail in the different stages, from conceptual design to detailed design, consists in programming PBL experiences that are developed across various subjects with increasing complexity and detail, so that students can devote more time to the projects. In this regard, we can refer to the EDIMPO (Computer-aided Machine Design) experience led by Prof. Pilar Lafont [24]. This has been the longest-running Engineering project-based learning experience in

Spain (apart from being the first to include CAD–CAE as support tools). It has been running continuously since the beginning of the 1980s, in parallel with the subjects, 'Machine Design I' and 'Machine Design II', in the first and second semester of the fourth year of the Industrial Engineering degree at the UPM. In this experience, students, in groups of three, experience the complete development process of a two-stage reduction gearbox, for different applications, from the conceptual stage up to the detailed design stage and the generation of pre-production plans. In parallel with the first subject, students approach the problem and predimension of the various main parts, basically the shafts, the casing and the relative positions between the pairs of gear wheels forming the transmission. In parallel with the second subject, the design of the gear transmission is approached in great detail as well as the final choice of commercial parts, with results similar to those in real projects in industry.

Organising and planning PBL experiences should ideally be done with the mutual consensus of the teaching staff on the degree or specialisation programme, so that students are not overloaded with project-based activities at only certain times of the year and can gain the maximum benefit from their participation in the different subjects and projects. In addition, if a PBL experience is divided into several subjects, is dependent on the results of preceding subjects or affects later subjects, the communication between teaching staff must be strengthened and the scope and teaching aims of the different activities must be clearly defined.

5.2 Regarding the development of the experiences

An interesting question when applying PBL strategies, which connects organisational aspects with development aspects, consists in deciding whether to conduct individual or group experiences, a decision that depends very much on the number of students. It is usually difficult for a teacher to monitor more than 15–20 projects per semester. Therefore, in subjects with a small number of students (i.e. fewer than 20), individual projects can be resorted to, while in subjects with a lot of students (i.e. more than 60), groups of three or four students can be formed to adjust the number of projects to a manageable number. Larger groups may encourage the appearance of 'parasite' members and make it harder to individualise marks. The implementation of the groups is therefore a determining factor on the progress of the experiences.

So that things go well from the start, particularly in the first years of the degree, which has students from many disciplines and with different levels, it is important to use a diagnostic assessment method. This diagnostic assessment helps to check that students are starting at the right level or to suggest reinforcement measures, in case general gaps in major areas are detected. If there continue to be large differences of preparation within the group, even after the reinforcement measures, a minimum scope can then be defined for the projects and the most proactive students or groups can be motivated by more ambitious approaches that will be reflected in their marks. To this end, projects can be set as a design competition, with a final stage for the teams that achieve a pre-set level of detail. The prize may be a typical financial incentive or extra points towards the final mark, or even the chance to take part in more important competitions with their designs. Students can also be encouraged to continue working on their project with a view to it becoming their final degree project.

On the other hand, for a development free of unforeseen events, the interim milestones need to be clearly defined so that any possible departure from the results and timescales can be corrected and the educational aims achieved. These interim milestones can also help to check that there is a positive interdependence between students of the same group and encourage individuals to give their best. It is therefore vital for the teacher to systematically check the group relationships. Personalised interviews can also be conducted together with the use of other continuous assessment tools. For an experience that lasts around 3–4 months, it would seem reasonable (in addition to the diagnostic assessment) to set some test at the end of the first month, another half-way through and one at the end.

To prevent students copying the work of other groups or students from previous courses, the best way to eliminate the problem is to ensure that projects do not coincide or do not have similar or repeated components. It is fine for students to have access to example projects from other courses as a way of showing the stages to be followed and what is expected of them provided it stimulates them to work, rather than foster plagiarism or other undesirable conduct. So the main line of action is to methodically plan different questions with similar levels of difficulty and variations that are systematically introduced from one course to another.

We should again mention the importance of a proper coordination between subjects of the same semester to lead to better results and avoid any overlapping of critical tasks. These coordination measures can be really simple and effective. It is sufficient for teachers to hold meetings (at least one at the beginning to coordinate actions and one at the end to analyse any deviations and make proposals for the future) and decide different dates for handing in the final work.

Regarding the infrastructures and the usual supplementary resources for PBL experiences, especially those linked to product and machine development, we must mention the benefits of: using computer-aided design and manufacturing technologies, using 3D printing tools for the manufacture of prototypes, using universal platforms for automation and robotics with flexible software–hardware ('Arduino', 'Lego Mindstorms', among others) and having access to university laboratories and their qualified support staff. It is also becoming increasingly popular to invest in specific environments to promote collaborative and project-based learning, although these environments are sometimes designed more as important elements of many universities' marketing strategies rather than spaces to promote learning.

What is clear is that the right infrastructures can improve the final results of the experiences and extend their scope (e.g. going from design to prototypes), as well as motivate the students involved. However, it is also true that most PBL experiences can be conducted by simply having groups of students sitting around a computer connected to the Internet. Maybe for this reason none of the infrastructure-related issues was rated as especially relevant in Table 2.

5.3 Assessment methods

In group experiences it is always advisable to supplement the PBL group assessment with something that lets the individual members of the group be differentiated. The idea is to get each individual to give their best and encourage all those in the group to really take part in the project and avoid any personal conflicts arising from any members trying to take advantage of their harder-working companions. To this end, final exams that carry a percentage of the final mark may be appropriate as well as knowledge assessment tests throughout the course, handing in compulsory or voluntary exercises, presentations to the group, interviews and the use of portfolios, among other things [25].

According to our experience in the Design and Manufacture with Polymers course, in the fifth year of the Industrial Engineering degree at the UPM, where we have developed toys over the last 4 years [26], a certain number of hours need to be devoted throughout to the subject for students to do exercises to be handed in on the analysis of products and components similar to those that they will meet in the PBL experience. These analysis problems will help them to approach the synthesis problems that are part of their projects. They are an excellent tool for supplementing and individualising assessments, apart from checking class attendance and the effects of the improvements introduced course by course.

In special cases when it is found that some students might have worked less than their companions (normally through observation and questions), it may be sufficient to implement co-assessment activities where the student's final mark also depends on the score given by their companions. It is generally reasonable to allocate from 5% to 15% of the final mark to co-assessment except for special cases where a student has made no contribution whatsoever to the experience.

Leaving aside the problem of discriminating between students in the same group, collaborative- and project-based learning experiences have many teaching aims linked to generic skills that are difficult to assess through a final report or exam but which are essential to these teaching strategies. Aspects such as reflecting on the work done, a critical presentation of the results, improving interpersonal skills and group work, learning from one's own and other people's successes and mistakes and understanding different points of view must be assessed face to face. An open presentation of results is an excellent tool if there is enough time. The presentation itself encourages people to give their best. The student to represent the team should be chosen at random or the presentation divided up between several members. Specific rubrics can also be used to assess generic skills, which can be designed following proposals described elsewhere [27], sometimes more efficiently than by group presentations and individual interviews as these latter usually take up a lot of class time or cannot be fitted into the tutorial timetable. However, at least one final presentation per project is recommended as an aid to assessment and to boost global learning as it lets each group see and evaluate the results of their companions and leads to self-criticism and group discussion.

5.4 Prioritising actions

A comparative analysis of the different proposals for improvement or specific solutions has also been performed for the relevant aspects previously discussed. When actions for improvement are suggested in any kind of process, such as teaching strategies, they should be placed in order of priority before being implemented. Process re-engineering methodologies can be used with a prioritised process analysis [28] or the now classic 'quality function deployment' tools to analyse client expectations (e.g. students) and other processes that might be interesting, and also responsibilities [29–32]. Here we have compared the proposed actions bearing in mind their effectiveness regarding certain determining factors, including the time and the cost of implementation. Thus it is hoped to prioritise actions so that the most cost-effective in terms of

Table 5. Implementation time, cost and effectiveness rating for important actions detected for improving PBL strategies with regard to product and machine development

Proposed actions for improving PBL strategies	Effectiveness score	Implementation time rating	Implementation cost rating
1. Use of single topics for questions that change every year	7.5	2.5	1.5
2. Use of complex product or machine related development projects	7.5	3	1.5
3. Clear definition of aims, scope and interim control milestones	9.5	1.5	0.5
4. Use of classes and analysis problems in parallel with the PBL activity	9.5	4.5	2
5. Correct choice of the number of students per project	7.5	1	0.5
6. Dividing increasingly complex projects between several subjects	8.5	3	1.5
7. Meetings to coordinate PBL projects between subjects	7	2	1
8. Use of e-Learning tools as an aid to PBL experiences	6.5	5.5	2.5
9. Use of specific software as part of PBL experiences	8.5	4.5	5.5
10. Use of laboratories as an aid to prototype manufacture	8	4.5	6.5
11. Creating specific areas as an aid to collaborative learning	4	8.5	9.5
12. Involvement of laboratory support staff	9	3	3
13. Preparation and use of tools for diagnostic assessment	8	3.5	0.5
14. Preparation and use of tools for diagnostic assessment	8.5	4	0.5
15. Open presentations for joint assessment and learning	9	4.5	0.5
16. Implementation of co-assessment	3	3.5	0.5
17. Personalised interviews with students	3.5	6	2

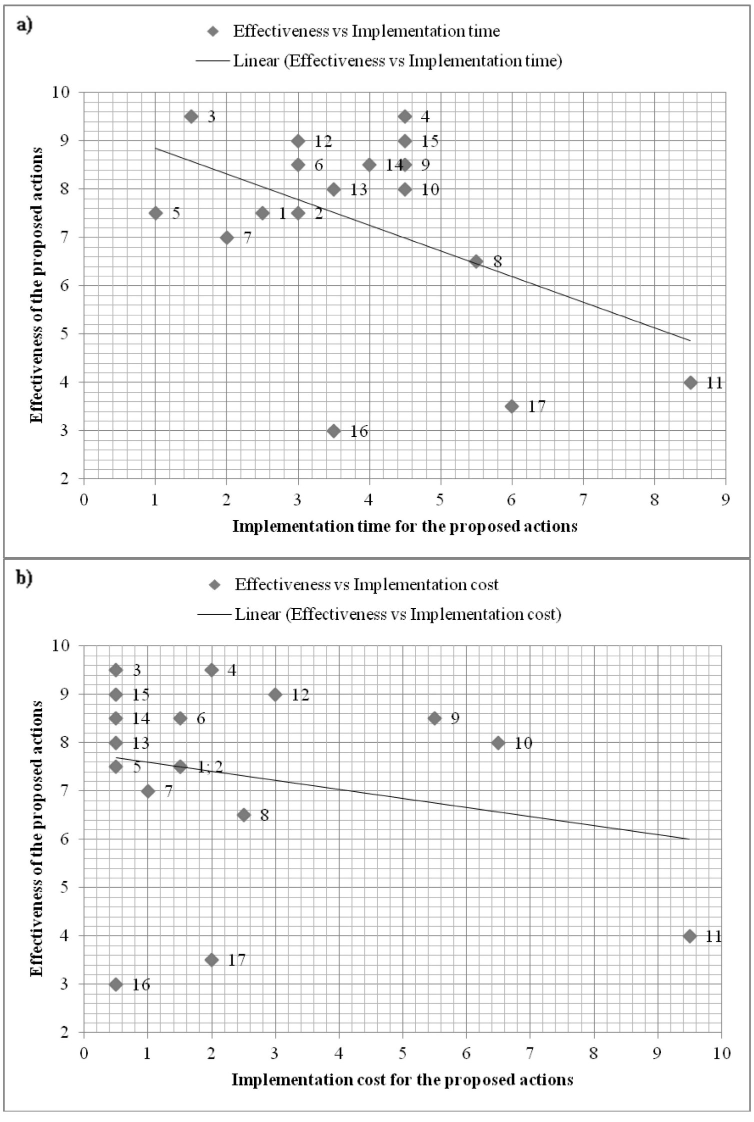

Fig. 10. (a) Comparison of effectiveness and implementation time for improvement actions. (b) Comparison of effectiveness and implementation cost for improvement actions. (Actions are coded according to the numbers that correspond to them in Table 5.)

time and implementation (considered as priority) can be undertaken first, followed by those that are most effective in spite of their greater cost in time and implementation (considered as actions for continuous improvement).

The results of the evaluation are included in Table 5 and in graphic form in Fig. 10. It is especially important to point out that many of the most effective actions to implement or improve successful PBL strategies involve very low implementation times and costs. For example, invoking strategies such as clearly defining the aims and scope and carefully setting milestones, improving coordination and communication among teachers, using methodical assessment tools (diagnostic assessment, tests throughout the project, systematic observation, a final training assessment, as is the case for open presentations), among others.

Other particularly costly actions in terms of time or money are not as effective, in spite of their often being used or promoted, and should be given second priority. Some examples are: individual interviews with students as a way of getting each one to give their best, co-assessment (even though there is a benefit in specific cases) or large investments in infrastructure as an aid to collaborative learning (in the way of games rooms and multi-purpose rooms, rooms for promoting 'creative thinking' and rest areas). Some of the results have already been made clear in the previous sub-sections, but the weighting is important to set the priorities more methodically. Priorities obviously depend on the personal opinions of our team, but we believe they may be of interest to other teachers involved in similar activities.

6. Conclusions

Project-based teaching–learning experiences have enormous benefits but also have certain limitations and difficulties, which we have attempted to analyse in this work so that some standard action guidelines can be set to help strengthen the results of this kind of teaching strategy, particularly for strategies linked to product and machine development in Mechanical Engineering.

From the analysis it can be seen that experiences that are methodically planned and assessed, from different perspectives and with a view to continuous improvement, run more smoothly and enhance students' final results and overall learning. Clearly defined milestones and control measures also help enormously to correct any mismatches from the initially estimated timescales and results. Coordination among the teachers of different subjects is essential to avoid any overlapping of critical tasks and to encourage students to concentrate on their learning and to enjoy their PBL experiences. It also avoids their being focused only on the work and summaries to be handed in or their aiming only at the test milestones they will have to confront at certain times.

In fact enormous benefits can be gained from project-based teaching–learning strategies where students face realistic situations or problems and, as well as acquiring knowledge, take an in-depth look at issues including: the integration of knowledge and job skills from various areas or the development of high-level intellectual skills like forming judgments, decision-making and an ability for analysis and synthesis. We hope that the reflections in this work may be of use to teachers in many fields of Engineering who wish to apply this kind of teaching strategy and design specific actions for their subjects.

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