Problem- and Project-Based Learning in Engineering: A Focus on Electrical Vehicles

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***Abstract*—An innovative learning approach, qualified as Problem- and Project-Based Learning (PPBL), has been developed in the department of Electrical and Computer Engineering of the *Université de Sherbrooke*. PPBL is applied totally from the first term of our programs, instead of being applied gradually. Basically, the students are involved in two types of activities in each term. The first one consists of several (typically, six) consecutive Problem-Based Learning (PBL)-units, where each PBL-unit lasts generally two weeks and is focused around the resolution of an engineering problem. The second type of activities is to realize a project throughout the term, which requires the resolution of a more complex technical problem and the use of project management methods. The experience and learning obtained in solving the small consecutive engineering problems should be used in the resolution of the project.**

After a presentation of how PPBL is implemented in our department, its benefits are highlighted in an area that is becoming increasingly important: Electrical vehicles. We present in particular several capstone projects realized by our students that have led to the production of prototypes of electrical vehicles. Several prototypes have obtained prices in international competitions or will participate in competitions in a near future.

***Index Terms*—Problem- and Project-Based Learning (PPBL), competence development, knowledge acquisition, electrical vehicles, capstone projects.**

I. Introduction

Throughout the 1990s, the department of Electrical and Computer Engineering of the *Université de Sherbrooke* has been working for the development of a new learning approach called Problem- and Project-Based Learning (PPBL, in French: *Apprentissage par problèmes et par projets en ingénierie, APPI*) [1]. A fundamental principle of PPBL is that it aims to develop competencies, where knowledge acquisition is just a means to develop targeted competencies. The students are involved in two essential types of activities in each term[1]. The first type of activities consists of several (typically, six) consecutive Problem-Based Learning (PBL)-units, where each PBL-unit lasts two weeks and is centered in the resolution of an engineering or scientific problem. In each PBL-unit, the students have several activities for acquiring knowledge and developing competencies for the resolution of the corresponding problem. Some activities are supervised, while others consist of personal studies. The second type of activities in a term consists in realizing a project throughout the term, which requires the resolution of a more complex problem and the use of project management methods. The experience and learning obtained in the PBL-units should help the students in realizing the project.

PPBL was used for the first time with students who were starting their engineering studies in the term of Autumn 2001. Our department has opted to apply PPBL to the whole program of electrical and computer engineering, instead of applying it gradually. That was a great challenge that we believe we have succeeded, as evidenced by our reception of the 2015 Innovative Program Award from the Electrical and Computer Engineering Department Heads Association (ECEDHA) [2].

We highlight the results obtained by our students in an area that is becoming increasingly important: Electrical vehicles (EV). More precisely, we present several capstone projects realized by teams of students that have led to the production of prototypes of EVs. A team consists of 6 to 9 students, but some large-scale projects may regroup 2 teams. In such a case, the respective mandates of both teams must be well distinguished. The students specialties are in software, computer, electrical and mechanical engineering. To have an idea of the amount of work, a capstone project lasts about 30 weeks where each member of a team works about 20 hours weekly for the project. As an evidence of the quality and efficiency of PPBL, several prototypes have obtained prices in international competitions (see Section V for more detail).

The remainder of the paper is structured as follows. In Section II, we present the pedagogical principles of PPBL and the organization of a term. Section III explains the structure of a typical PBL-unit. Section IV describes the project organization in the first six terms, while Section V describes the project organization in the last two terms. Finally, we conclude and propose some future studies in Section VI.

II. Principles of PPBL and Organization of a Term

To make this paper self-contained, this section gives a summary of the principles of PPBL and its organization in one term. A detailed presentation illustrated by an example of PBL-unit is given for example in [1].

A. Competencies and knowledge

Competencies development is the priority objective of PPBL. To be brief, a competency is an ability to act on resources for realizing nontrivial tasks. Note that a competency must not be reduced to the ability of executing a given procedure, a competency requires rather the ability to adapt to various situations to solve a category of problems. In our

[1] A term denotes a period of 4 months.

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Weeks	1- 2	3-4	5-6	7-8	9-10	11-12	13	14-15
	PBL-unit 1	PBL-unit 2	PBL-unit 3	PBL-unit 4	PBL-unit 5	PBL-unit 6		Final Assessment
Project	Meeting 1-2	Meeting 3-4	Meeting 5-6	Meeting 7-8	Meeting 9-10	Meeting 11-12		Presentations

Fig. 1: Organization of T1 to T6.

Weeks	1- 2	3-4	5-6	7-8	9-10	11-12	13	14-15
	PBL-unit 1	PBL-unit 2		PBL-unit 3		PBL-unit 4		Final Assessment
Project	Meeting 1-2	Meeting 3-4	Meeting 5-6	Meeting 7-8	Meeting 9-10	Meeting 11-12		Presentations

Fig. 2: Organization of T7 and T8.

programs, we classify competencies in four categories: 1) engineering and scientific, 2) design, 3) interpersonal, and 4) intrapersonal competencies. The distinction between competencies and knowledge is that knowledge acquisition is just a means for reaching the objective of developing competencies. We classify knowledge in the following three categories.

- *Declarative* knowledge is the fact to know factual information, such as a definition, a hypothesis, or an algorithm.
- *Procedural* knowledge is to know how to use factual information, for example the ability to execute repetitive tasks.
- *Conditional* knowledge is to know when and where to use factual information, for example the ability of selecting appropriate resolution methods.

B. Organization of a term

Our programs are structured in eight academic terms (denoted T1,. . . T8) which alternate with 5 industrial training terms (denoted W1. . . W5). Here is an example of sequence of terms: T1-T2-W1-T3-W2-T4-W3-T5-T6-W4-T7-W5-T8. Each academic term is based on a theme (e.g., architecture of computer systems, electrical and electronic systems, embedded systems, control and automation, digital systems and circuits, etc.) and contains two types of activities: several consecutive two-week PBL-units, and a design project which is spread over the whole term. In each T1 to T6 there are 6 PBL-units (Fig. 1), while in each T7 and T8 there are only 4 PBL-units but with a more substantial and complex project (Fig. 2).

III. PBL-UNITS

The objective in a 2-week PBL-unit is to develop one or several given competencies. An essential means to achieve this objective is the resolution of a problem. The latter must be sufficiently complex so that its resolution leads to the development of the targeted competencies, but it must also be sufficiently simple so that its resolution can be done in less than 2 weeks. The problem must correspond to a real (possibly simplified) engineering situation, but also be formulated so that the students can do the exercise of identifying the necessary skills and knowledge that are necessary for solving the problem.

The PBL approach makes the students more responsible and autonomous in the learning process. Professors are resources that help the students to find solutions (by providing opinions or indications, validating or invalidating solutions, etc), but they should never provide directly a solution.

Typically, before the beginning of a PBL-unit , the students have access to a Student Guide that regroups the relevant contents related to the PBL-unit; the most important of them are introduced in the following subsections.

A. Targeted competencies

Since the main objective of a PBL-unit is that the students develop given competencies, it is natural to start by specifying to the students each of the targeted competencies. Since a competency corresponds to an ability to realize a category of tasks, its formulation must start by a verb that implies an action, like describe, specify, analyze, design, realize, implement, etc. Here is an example of the competencies of a PBL-unit on modeling and controlling electrical vehicles given in T8:

- model and simulate different traction chains for vehicular applications using the macroscopic energy representation;
- design control laws for different types of chains traction;
- develop energy management strategies for vehicular applications.

B. Examples of problems to be solved

The problem that the students have to solve must be carefully written in order to promote the learning process. Let us for example consider the PBL-units we have developed in the area of electrical vehicles (EV).

Two PBL-units are given in T3:

- The first one is targeted to transformers topics learning and the selected topic is related to residential EV recharger spot with isolation transformer. The focus of the problem is to carry out some experimental tests on a real transformer in the electrical laboratory to determine the characteristics (B(H) and equivalent electrical circuit). The efficiency of the studied transformer, regarding the charge application and the energy analysis, is also performed.

	Mo	Tu	We	Th	Fr
Morning	1h30 Opening tutorial	3h Study	3h Problem Solving Procedures	3h Project	3h Collaboration
Afternoon	6h Study	3h Study	3h Laboratory	3h Project	3h Study

Fig. 3: Activities in the first week of a PBL unit

	Mo	Tu	We	Th	Fr
Morning	3h Problem Solving Procedures	3h Laboratory Validation	1h30 Closing tutorial	3h Project	1h30 Consultation
Afternoon	3h Study	3h Study	3h Assessment	3h Project	3h Assessment

Fig. 4: Activities in the second week of a PBL unit

- The other PBL-unit of T3 is related to electric rotational machines, where the target is the comparison between a traditional DC motor and an asynchronous motor for EV application. A complete analysis is demanded regarding the different powertrain performances using data come from two sessions in electrical laboratory tests (equivalent circuits) in order to evaluate the behaviour of a specific vehicle.

Two other PBL-units which are given in T7:

- The first one targets the design of a complete powertrain based on a permanent magnet synchronous machine (PMSM), a three-phase inverter and Li-ion battery pack. Given different characteristics of a road vehicle, the student should design a devoted PMSM, inverter and battery pack under several constraints at the lowest price.
- The other PBL-unit of T7 is related to the electronics for high power devices and the aim of the problem is related with electric trains. Within this scope the students study and design several parts of the powertrain focused on the power electronics parts (rectifiers, inverters and LC filters) and the control of the converters.

A PBL-unit given in T8 is devoted to modelling and control of EVs. The modelling approach is based on energetic macroscopic representation (EMR) [3]. EMR is a graphical description that highlights the energy proprieties of the components in order to develop control schemes in an automatic way. Only the physical causality (i.e. integral causality) is considered. Moreover, all elements are connected according to the interaction principle: the product of the action and the reaction variables yields the power exchanged. The case study is a multi-sources hybrid electric bus, including three different sources, two energy storage elements and an internal combustion engine-generator. A goal is the definition of a comprehensive energy management strategy for a specified driving cycle.

C. *Necessary knowledge and readings*

It is important to give indications to the students about the knowledge acquisition targeted in the PBL-unit. This information is useful for selecting the relevant readings and exercises for their preparation to the assessed activities.

In T1, the students are given precise directives of the readings that are relevant and necessary for their learning. Then, gradually at each following term, the directives are less precise so that the students acquire progressively the ability to determine by themselves the relevant readings.

D. *Main activities*

Figs. 3 and 4 show when the main activities of a PBL-unit take place. The term “Study” denotes personal studies without supervision. The other activities, which we discuss in the following subsections, are under the guidance of the tutor who, recall it, should never present ready-made solutions.

1) Opening tutorial: For each group of about 12 students, a PBL-unit starts by a 90-minute tutorial meeting. In a collaborative way, the students:

- read the terms of the problem to solve, keep only the relevant terms, and formulate succinctly the problem;
- identify tasks to do and knowledge to acquire to solve the problem;
- organize and prioritize the identified tasks; and
- review the list of knowledge to be acquired.

The tutors role in the opening tutorial is to ask relevant questions, validate students prior knowledge, ensure that learning needs and tasks to do are well identified.

2) Problem solving procedures-session 1: Students apply knowledge acquired in personal study, by doing problem-solving exercises in a 3-hour session. In some cases, acquired knowledge cannot be applied directly as such, it must be adapted to the exercises to solve.

3) Laboratory work: Students have a 3-hour laboratory session where they make experiences leading to a better understanding of the problem. Ideally (but not necessarily), they should implement or realize a solution developed theoretically in the previous session of problem solving procedures.

4) Collaboration for solving the problem: Through a 3-hour session, students use knowledge acquired so far and collaborate to elaborate solutions to the problem. After the previous activities of problem solving procedures and laboratory, the students should be able to realize a part of the tasks identified in the opening tutorial.

5) Problem solving procedures-session 2: Students make exercises in a second 3-hour session of problem-solving procedures. After this activity, the student should have acquired the necessary knowledge and competencies to solve the problem entirely.

6) Problem solving validation: For each task identified in the opening tutorial, the students explain to the tutor the method used to realize it and the obtained results. The latter can take the form of a running program, an electrical circuit, measurements, curves, etc. This session is in general formative (instead of summative), in the sense that if the tutor detects some incorrectness, the students can continue working in the problem resolution to correct their errors.

7) Closing tutorial: Each group of students has a second 90-minute tutorial meeting, just after they have submitted a written report presenting their resolution of the problem. In a first part of the meeting, the students reflect on what they have learned and try to determine if anything is missing in their understanding of the problem. In a second part, the tutor helps the students to verify if they can apply the learned concepts in other contexts than the solved problem. This can be seen as a preparation to the summative assessment given at the end of the PBL-unit (usually Friday).

E. Assessment

Assessment must be carefully elaborated in order to permit an accurate evaluation of the targeted competencies. A formative written assessment, consisting of several problems, is provided to students (after the closing tutorial) with a detailed model answer for each problem. Besides, competency(ies) involved in each question are identified and weighted. By comparing their answers to the model answer, the students can: estimate their learning achievement, measure to which level each competency is developed, and evaluate their preparation to the written summative exam (see below).

For each PBL-unit, a student is summatively assessed through: the written report presenting his resolution of the problem, and two exams at the end of the PBL-unit and at the end of the term, respectively.

F. Discussion

An advantage of PBL-units is that they promote learning contextualization, by the fact that learning is centered around resolution of various real problems. Another advantage is that students integrate several concepts that were studied separately in different classical courses. Yet another advantage is that during a two-week period, students use about 80% of their time studying concepts related to the current PBL-unit. (The remaining 20% of the time are used for the project, see Sections IV and V). In classical learning, students study in parallel several courses the whole term, which often implies awkward switchings between very different subjects. With the objective of continuous improvement, at the end of each PBL unit, the person in charge for the term has a meeting with students and receives their comments about the PBL-unit. At the end of the term, another meeting is organized with the students so that they can give more global comments about the PBL-units and the project.

IV. Project activities in T1 to T6

As said before, the projects are present at each term. The working day for the projects is usually Thursday of each week. Students will work in teams of 5 to 8 students, depending on the complexity of the project. In the first projects (T1 and T2), students learn how to work in a team and how to plan and manage a project. They use a classical management approach for hardware projects or an Agile management methodology for software projects. Hybrid management methods are conceivable for projects with both hardware and software components.

In the projects of T1, the students have few degrees of freedom, they can only add a few details to an imposed hardware and software. Very few design and verification are needed. Then, gradually at each following term, the students have progressively more freedom for realizing their project, and the designs and tests are increasingly more consistent. But until T6, the complexities of the designs and tests remain moderate.

The cost of each project is modest, less than 500$, and the projects artifacts belong to students.

V. Project activities in T7 and T8

A. Structure and organization

In T7 and T8, the students are involved in capstone projects by teams of 6 to 9 persons, where each capstone project occupies the students during the two terms, i.e. 30 weeks. Some large-scale project may regroup 2 teams, but where the respective mandates of both teams are clearly distinguished. The department receives regularly propositions of capstone projects coming from various origins, like industrial companies, professors, people with special needs, and even students can propose projects. Before the T7, a group of professors consider each project proposition. A project can be retained only if it is relevant, feasible and sufficiently complex. Relevance is estimated mainly at the pedagogical level, by identifying the main learning implied by the project. Relevance is also estimated with other considerations, like social, economical or environmental aspects. By feasible and sufficiently complex, we mean that the project must be feasible by a team of 6 to 9 students, where each student works on average at least 18 hours per week during 30 weeks.

In the first week of T7, the students form teams and select among the retained projects. Each team is supervised by two professors, who are called supervisors. A team meets weekly its two supervisors during 30 minutes, but other meetings can be scheduled if necessary. The supervisors follow and advise the team to ensure that the project evolves correctly, A supervisor can for example intervene when the team faces a problem, like a conflict between team members. A supervisor is not necessarily expert in all the domains related to the project of the team, but he can refer the team to an expert if the team needs help for a technical problem.

Some big projects may involve several student teams. For example, some complex projects on EV involve three teams, as follows. A team of mechanical engineering students work on the mechanical part of the vehicle, a team of electrical engineering students work on the traction part of the vehicle, and a mixed team of computer and electrical engineering students work in the control of the vehicle. Note that in this kind of situations, each team is assessed separately and independently of the other complementary teams.

B. Assessment

Each assessment is based on specific criteria related to some or all of the following aspects: technical, project management, and communications. The assessed activities and productions are as follows:

- In four occasions (in the middle and end of each T7 and T8), each team makes an audit of their project. An audit lasts about 45 min and consists of an oral presentation, a demonstration of what has been achieved and a period of questions. The objective of an audit is to show that the project is progressing well and that the students have control over all the aspects that may influence the project evolution. The teams are assessed by the four professors who supervise the projects, based on technical, project management and communication criteria.
- In the first half of T7, each team produces two written documents which are assessed based on engineering, project management and communication criteria. At the end of T7, the team produces a technical report which is assessed based on technical and communication criteria.
- At the end of T8, each team produces a final report of their project which is assessed based on engineering, project management and communication criteria.
- At the end of T8, a public event is organized at Faculty level, where the teams can expose and explain their realizations to a diverse audience of all ages (the event lasts 2 days). Each team is assessed based on communication criteria.
- Each team meets weekly her two supervisors, with 12 meetings in each term T7 and T8. The participation of the students and the quality of their documentation are assessed individually at the end of each term, based on project management and communication criteria.
- In six occasions, students evaluate their team members. These evaluations are used to weight the above mentioned evaluations.

An important aspect in the project is financing. Sometimes, students need to search for partners or sponsors giving resources or money. This activity must be planned and completed at an early stage of the project. The assessment of this aspect is based on project management criteria.

C. Examples of capstone projects

- **Formule SAE** [4] was the first project on electrical vehicles, actually on hybrid vehicles (Fig. 5). The projet obtained the fist place in general category of the Formula Hybrid at Loudon in New Hampshire, in 2012.

Fig. 5: Formule SAE

- **VUE** [5]: In this project the students transform a Smart car into a Smart electrical car (Fig. 6). An innovation is that the electrical vehicle has independent motors for the traction.

Fig. 6: VUE: transformation of a smart car

- **EMUS** [6] The objective of this project was to design and build a high performance electric motocycle in order to participate in races (Fig. 7).

Fig. 7: EMUS: electrical motocycle

- **BEYOND** [7]: This project was the winner of the Shell Eco-Marathon Americas of 2016, in the Battery-Electric Prototype category (Fig. 8).
- **E-VOLVE** [8] This project was the winner in 2014 at the Shell Eco-Marathon Americas [9], in the Urban

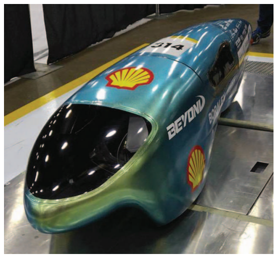

Fig. 8: BEYOND: concept

Concept/Battery-Electric category. It is presented in more detail in the next subsection.

D. E-VOLVE project details

For the annual challenge Shell Eco-Marathon, the *Université de Sherbrooke* was presenting the result of its Capstone project E-VOLVE (Fig. 9) in the category Electrical Vehicle-Urban Concept. During the 2014 annual challenge, held in Houston, Texas, USA, in April 2014, E-VOLVE prototype was ranked first with a record of energy consumption of 3.0 Wh/km (or 325 km/kWh). In the last 20 years, this event promoted by the Shell company, has attracted more than 100 energy-efficient prototypes of vehicles coming from universities around the world. The E-Volve was entirely designed, drawn and built by at the *Université de Sherbrooke* under final year capstone projects. The challenge consisted in driving a 10 km distance with the least electrical energy consumption. E-VOLVE prototype focuses its novelty in mass reduction and high efficiency Permanent Magnet electrical motor (Fig. 10) with Halbach array [10], newly drawn aerodynamics and solar panels. As result of the integration of three Capstone projects (mechanical, electrical and computer/electrical engineering) at the *Université de Sherbrooke*, a 90 kg, one-seater vehicle with carbon-fiber shell equipped with only a 1 kg Lithium-Polymer battery, is successfully designed and developed.

Fig. 9: E-VOLVE: the vehicle

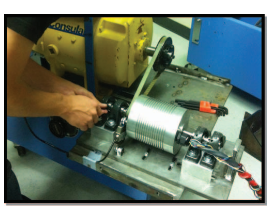

Fig. 10: E-VOLVE: the motor

VI. Conclusion

This paper presents how students are prepared in the electrical engineering and computer engineering programs at the *Université de Sherbrooke* and how they are trained regarding large-scale projects, as are the multi-disciplinary EV prototypes for race or competitions. This success is certainly related with the constant and continuous participation in projects (6 on the program) before the beginning of their Capstone project. These projects have different degrees of freedom within the content of the project. In the Capstone project definition and accomplishment, degree is let to the students. The projects can be in one domain or multidisciplinary, as the specific case of EV prototypes. In the last case, projects imply electrical engineering, software engineering and mechanical engineering. As in the examples of capstone, some projects go to engineering competitions obtaining very good results. For instance, the volume and quality of the already EV prototypes built by our students is the demonstration that the proposed program is well fitted to the new challenges and demanding of the industrials: competencies in problem solving and project realization. Typically, the themes related with electric machines, power electronics, modelling and control are not so attractive to engineering students, but with the inclusion of real projects, with concrete objectives and specific timeframe, a growing interest for these thematic have been seen, and of course EVs were instrumental for this results. In fact, the Problem-based and Project-based learning approaches empower students to be innovative designers and problem solvers. The process of implementing this learning approach is iterative, and some improvements can be done, for example: finding a better balance in the topics touched in the problems and project during a term and/or on the program.

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