Framework for an Engineering Design Course Using a Project-Based and Competency-Based Learning Approach

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Abstract

The rapid changes in technology and the new business environments around the world require the formation of future engineers not only with technical and scientific knowledge but also with professional skills and attitudes to be successful in the global workforce. Therefore, it is critical to change the paradigms in engineering education to introduce learning experiences where students can successfully integrate technical knowledge and professional skills in their formation. The aim of this work is to develop a framework for collaborative design projects based on competencies that effectively exposes students to knowledge, skills and attitudes required for global competitiveness. This project-based collaborative learning approach requires students to work in teams solving a design challenge that creates a learning environment that facilitates the development not only of the knowledge of design models and principles but also the development of social, ethical and management skills.

Keywords: Collaborative projects, competencies, engineering education.

1. Introduction

The development of new technologies in communication, and the globalization phenomena have had a tremendous impact on the way the companies are organized and are doing business today. The establishment of new regional economic alliances beyond the frontiers of a single nation has required that engineers be prepared to work in an economy that is now best seen as essentially international in nature. Almost all major corporations now operate globally, and engineers are being challenged to design and develop, in a timely manner, new products that will impact a global market (Esparragoza and Devon, 2005). Due to this tendency, future engineers will be facing the new worldwide market where the barriers of the corporate world are disappearing. The global engineer must understand and accept diversity, be able to work in multi-national corporations, be able to work in multi-cultural teams, be able to propose solutions to problems impacting a wider and more diverse population, be able to communicate and socialize with people from different cultures, be able to use the technology to exchange ideas, solve problems and present solutions (Esparragoza, 2005). As a result, the industry is demanding a change in the paradigm of engineering education to educate world-class engineers who possess technical expertise and professional skills.

The new global trend is calling for internationalization of the engineering curricula and the incorporation of professional competencies in the curriculum that complement the technical profile of engineers. Therefore, exposing the engineering students to international experiences and learning environments that foster the development of professional skills as part of their formal education from the very beginning and in a consistent and effective manner must be a main task of every engineering program. One of the most effective ways of doing this is through a project-based learning approach using multinational design projects (Devon, et.atl. 1998; Pollard, et. al., 2002; Ion, et.al., 2004). This type of initiative allows engineering students to work with geographically disperse teams while they solve an engineering design problem. Through this experience, students will enhance many technical and professional skills including problem solving, decision-making, analysis, synthesis, creativity, teamwork, communication, and global awareness. However, the real impact of this practice is measured by a rigorous assessment process. In order to do that, it is important to clearly define the activities, learning objectives and expected competencies outcomes to develop the appropriate assessment tools. The aim of this paper is to present the framework for a project-based collaborative design project based on competencies. This work is the first phase of a bigger project that includes the development of the assessment tools and the final deployment and test of those instruments.

2. BACKGROUND

This work is part of the tasks imposed by the Department of Mechanical Engineering at Technical University Federico Santa Maria (UTFSM) in Chile with the aim of ensuring the competitiveness and quality of its engineering program in response to the assessment conducted in 2011 by the National Commission on Accreditation. Among the objectives set by the program, those of particular relevance for this work are: (a) to strength professional skills and English language in the graduates; (b) to facilitate educational experiences project-based learning (PBL) experiences; and (c) to use formal mechanism to assess periodically the progressive learning of technical content on engineering concepts and the progressive development of professional skills and English language proficiency.

Therefore, the challenge is to develop an educational model that actively engages students in their learning process by promoting students' curiosity and formal inquiry, reflection and analysis, collaboration and active participation, ingenuity and creativity, hands-on and concrete experiences, synthesis and evaluation, and professional skills and attributes. This work proposes to incorporate the project-based learning (PBL) approach in a series of longitudinal courses of the mechanical engineering curriculum at UTFSM. This approach calls for the need of formal assessment tools for both specific competencies in each subject, as well as transverse competencies to be developed throughout the formation of the profile of mechanical engineers. This paper will focus on the first stage that consists of defining specific competencies for a core set of design courses and in particular for the collaborative design project to be embedded in the curriculum.

2.1 PROJECT-BASED LEARNING (PBL)

As it was explained before, engineers nowadays must be prepared to work in teams made up of people from different countries with different languages and cultures, and should know how to use proper communication technologies, solve problems and present their solutions (Maury, et.al, 2008). Consequently, engineering program accreditation agencies such as ABET have considered these demands of the industry and have included this in their Professional Outcomes (ABET, 2011). As a result, engineering programs should provide their students, as early as possible, academic experiences to promote the development of professional skills and international experience as part of their training.

One way this can be achieved is through global design projects in which students develop engineering jobs that are geographically dispersed teams to solve an engineering problem (Duque, et.al, 2010). The methodology of project-based learning (PBL) is based on the idea that a problem or a question, guide learning activities for the construction of a particular device in a real context (Papanikolaou, 2010). In this process, students seek solutions to open problems by formulating research questions, plan design, collection, analysis and integration of information, explanations and building models, and creating artifacts or products of their understanding. Students also have the opportunity to control the learning process, making decisions about the pace, sequence and content of learning, and evaluating the results of their efforts and their learning strategies. This learning context involves both vertical learning (referring to the accumulation of knowledge of the subject) and horizontal learning (referring to generic competencies such as project management, social skills and collaboration) (Helle, et.al, 2006).

Using project-based environments introduces cognitively complex tasks in the process of learning, experimentation, self-direction and high-level metacognitive control. These environments are necessary for students to effectively undertake PBL (Barron, et.al, 1998; Jonassen, 1999; Land and Zembal-Saul, 2003). However, the strength of PBL appears to lie in giving students the opportunity and motivation to work in a more meaningful way (personally) to a "solution". Several researchers observed deficiencies in the performance of students in the various activities of PBL, referring to self-directed learning skills and metacognitive knowledge (Beretier and Scardamalia, 1993; Hannafin and Land, 1997; McLoughlin and Hollingworth, 2001; Schank and Cleave, 1995). Therefore, strengthening metacognitive skills and reflection in students is essential in such innovative learning environments to help them to adopt strategies and reasoning processes that enable them to define, plan and self-monitor their thinking and learning style. In this sense, metacognitive and reflective skills of students better rely on social learning environments (McLoughlin and Hollingworth, 2001). Social interaction promotes the development of cognitive structures of individuals, when individuals reconcile the differences between their own ideas and the ideas of others, and when they ask questions and explain their reasoning for solutions (O'Donnell and King, 1999; Teasley, 1997; Teasley, 1999). Research studies suggest that teamwork provides opportunities for the development of cognitive structures of members and cultivate positive attitudes and stronger motivation toward the task, compared with individual work (O'Donnell and Kelly, 1994). However, research on collaborative learning has shown that its effectiveness depends on the richness and intensity of interactions among group members (Dillenbourg, 1996).

The project-based learning approach guides students through a process that starts with a given problem or challenge that takes them to identify what they need to know about the content of the course to solve the challenge. This is followed by an inquiry stage to learn about the material and the problem. The next step requires a process of analyzing and synthetizing information followed by an application stage characterized by critical-thinking, problem-solving, and decision-making to solve the problem. Finally, students are required to present their solution using written and/or oral presentation. The whole process is accompanied by a set of professional skills required to complete the project including creativity, teamwork, leadership, communication and global and cultural awareness. A depiction of the PBL approach is shown in Fig. 1.

2.2 COLLABORATIVE DESIGN PROJECTS

A collaborative design project is basically a design project where several people work together to solve an engineering challenge. This particular work considers the collaborative environment in which people working on the project are not necessary located in the same site. This implies the use of information technology tools to manage and solve the design problem. According to Jenkinson (2000), there are different types of collaborative projects that can be adopted in the academia in international settings (see Table 1). The complexity and resources necessary to implement them vary from simple and low cost projects to more complex and expensive ones. Usually the simple and less expensive project consists of a case study where the students just report the final result to their international partners. Minimum interaction is required and is usually a one-time in class experience. In contrast, the international projects named "integrated teams" require more interaction between the students since they work together in multinational teams. These projects are usually a long term, professional projects, and demand high level of commitment of students and staff. Some personal interaction might be required and they might be expensive.

Table 1: Types of Collaborative Design Projects

TYPE	DESCRIPTION	LENGTH
Case Studies	The single reporting of the final result of a design project to their opposite group.	One time; In-Class experience
Show and Tell	Work in separates projects in the different countries (remote places) and come together to progressively explain to the other team(s) how the work is developing.	Short term; In-Class experience
Parallel Teams	The students in teams in each country (remote location) work independently on the same design proposal. Students are encouraged and required to share data and ideas.	Short term; In-Class experience
Integrated Teams	Students in each country (remote location) work together on a joint design project.	Long term; Out of class professional experience

The criteria to select the appropriate type and level of collaboration depends on the general objectives, rank and content of the course in which the project will be offered, the level of commitment of faculty and students, and the resources available (Esparragoza, et.al, 2007). The project structure considered for this paper is the parallel design project in which the teams in each remote location work independently on the same design proposal but they are required to share and discuss data and ideas with their collaborative peers to enrich the final solution (see Fig. 2). However, the ultimate goal is to move this idea forward and include integrated teams type of collaboration using a similar framework.

Figure 1: Project-Based Learning approach diagram

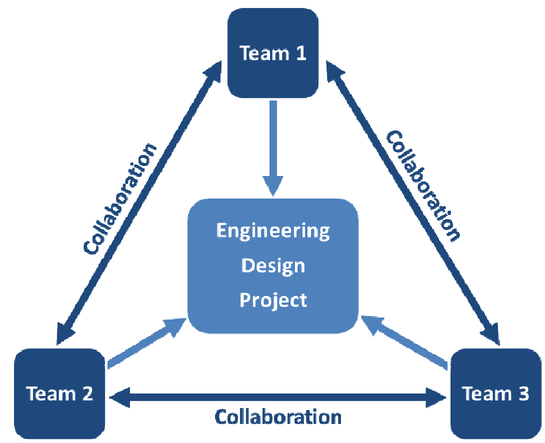

Figure 2: Collaborative Design Project Based on Parallel Teams

2.3 COMPETENCIES IN ENGINEERING

Competencies are defined as sets of knowledge, skills, behaviors and attitudes required to successfully perform specific tasks.

The new global environment in which corporates are doing business are requiring that engineers have a balanced set of global competencies in three dimensional spaces consisting of technical , professional and global domains (Allert et al., 2007). It is expected that a world-class engineer is a graduate with technical knowledge, analytical skills, creative abilities, ethical values and social responsibility who has a clear understanding of the dynamics of globalization and the impact of the interconnection of global issues in the economy, culture, politics, and environment of local communities. A global engineering is a person who is capable of acting locally but thinking globally; a person who accepts and respects diversity (Esparragoza and Petrie, 2008).

It is evident that the future engineer has to have a new set of attributes to be competitive in the global market. The National Academy of Engineers (2004) identified the following characteristics for the engineer 2020:

a. Strong analytical skills.
b. Practical ingenuity - skill in planning, combining, and adapting.
c. Creativity (invention, innovation, thinking outside the box, art).
d. Communication.
e. Business and management.
f. Leadership.
g. High ethical standards and professionalism.
h. Dynamism, agility, resilience, and flexibility.
i. Lifelong learners.

In addition to these attributes, a global engineer is a professional who:

a. knows the fundamentals and dynamics of globalization;
b. understands, accepts and appreciates diversity;
c. is able to work in multinational corporations;
d. is able to work in multicultural/multinational teams;

e. is able to communicate and socialize with people of different cultures;
f. is knowledgeable in other language;
g. is able to use the technology for communication, exchange ideas and solve problems;
h. is an entrepreneur;
i. is an ambassador.

Those characteristics and attributes described above should be translated into learning objectives and outcomes expressed in terms of knowledge, skills and attitudes needed to become world-class engineers. Global competencies are the result of an adequate integration of the learning experiences resulting from an effective curriculum which is based on appropriate learning objectives and outcomes. Figure 3, which is a modified version of the hierarchal relationship graph presented by Jones et al (2002), shows the relationship between learning experiences and the development of competencies, and the transformation from a local freshman student with basic foundation, and personal qualities and traits, to a world-class engineer through the development of knowledge, skills and attributes with a global scope to be competitive in the worldwide market.

3. EDUCATIONAL MODEL BASED ON COMPETENCIES

An educational model based on competencies is that one in which all learning experiences are designed, executed and assessed to ensure that the learning outcomes are properly aligned with real work conditions and professional expectations (Competency-to-Curriculum, 2008). This educational model requires a clear understanding of the industry and professional environments demands to be able to align the content and delivery methods of the courses with those demands. Additionally, this approach also calls for the development of competencies in two dimensions: (a) the level of mastery of the competency from novice to expert, and (b) the complexity of the competency from basic knowledge to advance application (Competency-to-Curriculum, 2008).

Developing a curriculum based on competencies requires the definition of competencies domains, core and discipline specific competencies, leaning objectives, learning activities mapped to the learning objectives, and the design of assessment tools. Figure 4 summarizes the steps required to complete a competency-based curriculum.

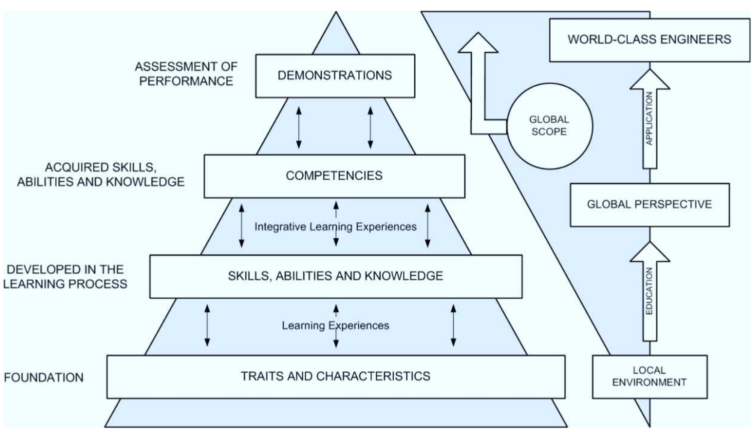

Figure 3: Hierarchy of post-secondary outcomes in perspective with global engineering education

Figure 4: Steps for Developing Competency-Based Curriculum

4. FRAMEWORK FOR A DESIGN COURSE

The proposed framework for a design course is developed with the aim of using the PBL and the competency-based learning approach for the instruction of technical knowledge, and professional and global skills in an engineering course. The framework for this learning experience is based on the following premises:

a. Technical knowledge and professional and global skills can be integrated effectively in different courses along the curriculum.
b. PBL approach promotes a suitable learning environment to integrate technical, professional and global competencies.
c. Collaborative projects offer the flexibility to introduce content and competencies at different level of mastery and complexity.

According to these premises and using the steps described in Fig. 4 and adapted for an introductory course of engineering design, the following frame work is proposed:

Step 1: Identify the course:

Introduction to Engineering Design: *Introduction to engineering design processes, methods, and decision making using team design projects; design communication methods including graphical, verbal, and written*

Step 2: Course objectives:

At the conclusion of the course, students should be able to:

a. use the design process in the solution of engineering design challenges;
b. extend the design process to general problem solving, and recognize the value of creativity in the engineering design process;
c. recognize the importance and accept diversity and cultural differences as essential issues in building trust and cooperation in the global market and as key issues in the development of new products;
d. use the technology to exchange ideas, solve problems and present solutions in an international setting
e. be creative and innovative in the solution of problems impacting a wider and more diverse population;
f. communicate and summarize ideas, designs and results by means of reports, and presentations, and use the tools for communication for multinational collaboration;
g. interact, collaborate, and socialize with people from different cultures and different countries
h. operate well within a team, solve inter-team problems and develop organizational skills;
i. work and be leaders in multi-national, multi-cultural, and diverse teams

Step 3: Competencies areas:

a. Technical:
    i. Engineering Design and Innovation knowledge
    ii. Problem solving
b. Professional:
    i. Teamwork
    ii. Leadership
    iii. Communication
    iv. Ethics
    v. Entrepreneurship
c. Global
    i. Global Awareness

Step 4: Engineering core competencies domains and competencies:

a. Analytical thinking: *demonstrate the ability to analyze and solve problem following a systematic, coherent and logical approach.*
    i. Applies logic
    ii. Analyzes problems
    iii. Translates theory in practical applications
b. Creativity and innovative: *demonstrate the ability to use knowledge, imagination and different perspectives to generate new ideas and methods for the solution of engineering challenges.*
    i. Understanding the problem
    ii. Process planning
    iii. Generating ideas
    iv. Planning for action

c. Systems thinking: *demonstrate the ability to design and work with systems, and understand and take into consideration the synergy between individual components and the entire system.*
   i. Components interrelation
   ii. Systems integration
   iii. Holistic vision
d. Dexterity in modern engineering tools: *demonstrate the ability to use information technology and computer applications for the professional practice of engineering.*
   i. Digital competence
   ii. Computer-aided engineering
e. Researcher: *demonstrate the ability to find and evaluate information for the solution of engineering challenges and the ability to design experiments, and collect and interpret data for discovering of new knowledge.*
   i. Inquire
   ii. Collect data
   iii. Data management
   iv. Interpret
   v. Compare
   vi. Validate
f. Knowledge of Underlying Sciences: *demonstrate the ability to apply knowledge of math and basic and engineering sciences in the engineering practice.*
   i. Apply mathematics to the analysis
   ii. Apply knowledge of science (physics, biology, and/or chemistry)
g. Lifelong learning skills: *demonstrate the ability to continue searching for new knowledge and staying current with the advances in technology and the engineering field.*
   i. Independent and continuous learning
   ii. Value added
h. Communication skills: *demonstrate the ability to communicate properly in oral and written form in different scenarios, with different stakeholders and by using different means.*
   i. Exchange information
   ii. Communication Technologies
   iii. Oral expression
   iv. Writing skills
   v. Nonverbal strategies
i. Ethical responsibilities: *demonstrate the ability to identify ethical issues and the ability to carry out the course of actions for the judgment and solution of ethical dilemmas in the professional practice.*
   i. Cognizance
   ii. Sensibility
   iii. Reflection
   iv. Cultural dimension
   v. Motivation
   vi. Application
j. Teamwork: *demonstrate the ability to collaborate with others and work effectively in diverse and multidisciplinary teams.*
   i. Technical Contributions
   ii. Collaboration
   iii. Working with Team
   iv. Time Management
   v. Contribution
   vi. Attitude
   vii. Communication
k. Leadership: *demonstrate the ability to motivate and direct others, look for opportunities, and take responsibility for new initiatives.*
   i. Planning
   ii. Coordination
   iii. Distribute workload
   iv. Resources management and supervision
   v. Motivation
   vi. Facilitator (Conflict Resolution)
l. Entrepreneurship: *demonstrate the ability to take risks, set direction, and manage the process to develop new businesses.*
   i. Self-confidence
   ii. Motivation
   iii. Effort
   iv. Sense of responsibility
   v. Initiative
   vi. Resourcefulness
   vii. Perseverance
   viii. Determination
   ix. Solidarity
   x. Team Spirit

m. Global awareness: *demonstrate the ability to understand the global nature of engineering, be sensitive to cultural differences, and be able to interact and work effectively with people of diverse backgrounds and culture.*
   i. Interaction
   ii. Application
   iii. Collaboration
   iv. Exploration
   v. Intercultural Sensitivity
   vi. Perception

Step 5: Course mapping

Using the nomenclature identified above for course objectives and competencies domains, they are mapped to the course content.

Table 2: Mapping course content with engineering competencies domains and course objectives

Course content	Learning Experiences	Competencies Domains	Course Objectives
Teamwork	• Lecture (definition, characteristics of a team, team development, team rules, diversity, communication, conflict management, leadership definition, characteristics, becoming a leader) • Team building exercise • Leading change exercise	d.i e.i, e.ii h.i, h.ii, h.iii, h.iv, h.v j.i, j.ii, j.iii, j.v, j.vi, j.vii k.i, k.ii, k.iii. k.iv	c f g h i
Ethics	• Lecture (definition, type of ethics, sensibility, ethical frameworks, ethical thinking, global issues, sensibility to cultural issues, global ethics) • Online blog discussion of ethical case (video, text and research material available) • Team case study of a real engineering ethical case	d.i e.i, e.ii h.i, h.ii, h.ii, h.iv, h.v i.i, i.ii, i.iii, i.iv, i.v, i.vi, i.vii j.i, j.ii, j.iii, j.v, j.vi, j.vii k.i, k.ii, k.iii. k.iv m.iv, m.v, m.vi	f h i
Engineering Design Process	• Lecture (definition, problem solving, design process, reverse engineering, global design, customers' needs, design objectives, functional analysis, specifications internal and external search, conceptual design, design for X) • Project 1: redesign of a product • Project 2: multinational collaborative design	a.i., a.ii b.i, b.ii, b.iii, b.iv c.i, c.ii d.i, d.ii e.i, e.ii f.i, f.ii h.i, h.ii, h.iii, h.iv, h.v i.iii, i.iv, i.v., i.vi j.i, j.ii, j.iii, j.iv, j.v, j.vi, j.vii k.i, k.ii, k.iii, k.iv, k.v, k.vi m.i, m.ii, m.iii, m.iv, m.v, m.vi	a b c e f g h i
CAD	• Engineering graphics • SolidWorks: Part modeling, drawings and assemblies. • CAD assignments • CAD project	d.i, d.ii h.v	d f h i

5. Conclusions and Future Work

There is a good amount of literature about curriculum based on competencies in different disciplines. This paper uses previous works and the authors experience to propose a framework that can be used by others to develop courses based on competencies in an effective way. This particular work focuses on the core engineering competencies as described above and incorporates the global dimension that has been ignored in other approaches. The competencies and objectives were defined by a multinational team as an effort to enrich them with the diversity, global perspective and multicultural dimension of the research team.

The idea of using the core competencies is because of the nature of the course under consideration; however, more specialized courses in specific disciplines can easily incorporate the scientific or specific competencies in the framework described above in the technical area.

It is evident that the effectiveness of this approach must be determined by a rigorous assessment of this educational model. The next step in this work is to develop the assessment tools to measure the impact of this model in the learning process of technical knowledge and professional skills.

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