MULTI-DISCIPLINARY DESIGN-BUILD PBL AS AN INTRODUCTION TO ENGINEERING

Xiaohua Lu, Yinghui Fan
Shantou University
Stephen Banzaert, Joshua Jacobs
Massachusetts Institute of Technology

ABSTRACT

A project based learning (PBL) project is designed as an introduction to engineering, requiring the student to design and build a computer-controlled tower crane at Shantou University (STU). This project is developed as a result of a recent STU-MIT collaboration. The project is designed in accordance with the CDIO initiative. The students in teams are expected to divide themselves into five different disciplinary subgroups, namely, communication, computer programming, electronic engineering, mechanical engineering and civil/structural engineering. Through the students were freshmen just entering the university, they performed satisfactorily.

The project was proposed by STU, alpha-tested at MIT and beta-tested with a group of students at STU before actually implemented with the full cohort of students at STU. In the beta-test, the group of students approached the solutions in an ad hoc fashion together they did not realize the multi-disciplinary nature of the project and thus did not make due decompositions and coordination to tackle the problems. Therefore, in the actual implementation of the project, targeted support was given to the students. Instead of directly asking the students to divide themselves into disciplinary subgroups, we helped the students to model the operation process of the crane. The process modelling helped the students to understand the different modules (relevant to different disciplines) and the input/output of each module. Thus, they could divide themselves into subgroups according to the modelling modules and coordinate according to the input/output requirements.

The results of the implementation show that the multi-disciplinary project is a good introduction to engineering. The design and build context helped the students to achieve the desired CDIO learning outcomes. The process modelling helped the students to decompose tasks, focus on specific problems and manage the project with confidence.

KEYWORDS

Introduction to engineering, multi-discipline, PBL, design-build exercise, project management

INTRODUCTION

Project based learning (PBL) is an important means to integrate the CDIO skills with disciplinary knowledge. Design-build projects provide excellent experiences for students to appreciate engineering practice. We have developed a freshman-level, multi-disciplinary project-based learning experience for a cohort of 375 students from 5 engineering programs.

In 2009, MIT and Shantou University (STU) worked together to support engineering education at STU. Part of the cooperation was to benchmark the learning projects done at MIT, STU and other universities known for their advanced developments of PBL. This information could be used to further refine the project based approaches at STU. A standard template was developed for the benchmarking and description of PBL experiences, so that a complete and usable description of project-based learning resources could be made available to all instructors at MIT and STU.

Six projects, 2 proposed by MIT and 4 proposed by STU, were designed and alpha-tested at MIT and then beta-tested at STU, to prepare for implementation during the school year. Three MIT staff came to STU for a week of workshops with faculty and selected group of students. The 6 projects, together with 7 additional proposed projects were then further refined and implemented at STU in the Fall semester 2009. These would then be used and summarized as templates of project-based learning in line with the CDIO initiative at STU.

Among the 6 projects, conceiving, designing, implementing, and operating a tower crane was proposed by STU as a freshman introduction to engineering project. Students working in teams were required to design and build a computer-operated, motor-powered tower crane with supplied motors, transistors, bearing, pulleys, and galvanized steel wires. Each team then competed against other teams in the end of the semester.

For the crane project, the multi-disciplinary nature, limited knowledge and experience of the students and the large numbers of students pose a variety of challenges to the organization of the project. In fact, such a project had been conceived for two years without being actually implemented because it is so challenging that we were afraid that we could not handle the problems might be encountered in the course of the project. The STU-MIT collaboration provided us an excellent chance to conduct the two rounds of tests before actually putting the project into practise. From the beta-test, in which a group of students did the project on a compressed timeline, we learned that the critical problem preventing the students from arriving at a good design was that they did not realize the complexity of the project and hence did not go through a well-ordered planning process. Therefore, in the actual implementation, we helped the students to use modelling methods to delineate tasks of different disciplines, and ten pinpoint and overcome major difficulties of individual disciplines separately with confidence. The project template developed by MIT provides us an excellent tool to enhance our project design and correlate the project implementation with the CDIO learning outcomes.

**PROJECT DESIGN**

The crane project is the core part of the course “Introduction to Engineering Design”. The goals of the course include providing the students basic experience with hands-on implementation, project management, teamwork and multi-disciplinary team collaboration as well as disciplinary knowledge. The course is delivered to all freshmen of the College of Engineering in their first semester at STU. It was thus expected that a common project include basic disciplinary content from all five STU engineering programs: mechatronics, civil engineering, electric and electronic

engineering, communication engineering and computer science. To that end, each project team
is required to design and build a computer-controlled tower crane with given parts and materials.
At the end of the semester, each team is required to operate the crane, and a competition is
held to see which team finishes a set of hoisting operations in the shortest time. At the
competition site, a set of hoisting orders are only given to one team member. He/she must
communicate this set of orders without using any vocal visual means to the member operating
the computer, which controlled the overall hoisting process. The students are not allowed to
touch any part of the mechanical setup, including the crane and weights. This project design
includes components from all five disciplines: communication (hoisting instruction transmission),
computer programming (computer interface and digital output programming), electronics (circuits
translating digital signals and power input into motor drive output), mechanical engineering
(mechanism and transmission design) and structural engineering (strength and stability design
of the tower). Each team contains team members from every discipline, using every student to
have this experience in a multi-disciplinary teamwork context.

While specifying the project requirements and constraints we tried to give maximum innovative
leeway but keep the overall level of complexity manageable. No electronic means was provided
for communication. Instead, direct hand-to-hand contact was used as the communication
medium, so that the students could focus on the balance between efficiency and reliability of
communication rather than the underlying technology. Visual Basic is used as the programming
platform. A commercial data acquisition card, Computer Measurements’ USB-1208FS, is used
for outputting digital signals. The DAQ card has accompanying VB libraries removing the need
for hardware configurations and programming, so the programming students can limit their
attention to designing the interface and pulse-width-modulated output (PWM). The electronic
circuit is expected to convert the DC power supply from a battery and the modulated digital
signals from the DAQ card into motor driving and control signals. No IC drivers are allowed --
the students are expected to use transistors and resistors to build H bridges to realize the driving
circuit. The mechanical design must fulfill the specified hoisting operations: transmissions must
be designed and built for motors to hoist the weight and control radial and angular motion. The
tower structures are constructed using 1.6mm galvanized steel wires. The structural group would
have to ensure the overall stability, the strength and stiffness of the structures.

Each team receives 3 DC motors, 10 PNP transistors, 20 NPN transistors, 1 thrust bearing, 20
ball bearings, 15 pulleys, two sets of worm and worm gears, 1kg of 1.6mm galvanized steel
wires, some resistors, a veroboard and some other materials and hand tools.

A tower crane is required to fulfill the following specifications:
1. Maximum lifting loading 1kg;
2. Maximum lifting height 500mm;
3. Working radius within 150mm-350mm;
4. All lifting operation being operated at a computer interface;
5. The crane must support itself in the full course of the operation process without any external
anchorage;
6. During operation, a set of lifting orders are given to a team member, who must communicate
the orders to another member using only hand-to-hand contact.

**PROJECT IMPLEMENTATION**

In the 2009/2010 Fall semester, a total of 361 students were divided into 4 classes, nearly 100
students a class. The students were grouped into 9-10 students per team. Each team was
required to design, build and operate a tower crane at the end of the semester. The students attend a two hour class every other week, making a total of 16 contact hours. About half of the contact hours were used for the students to present and discuss their designs -- the students needed to learn, design and build in their own time. The CDIO Center of the College is open to all students.

It is overwhelming for the students just coming into the university to face such a complex project. During the beta-test, a group of four first- and second-year students, similar to our intended audience, experienced the design and build process. In four full days, they designed and built a crane that could be operated by a computer. However, the crane could not lift the targeted weight of 2kg, with insufficient stability and stiffness. Also, their conduct of the project revealed that the group did not fully appreciate the multi-disciplinary nature of the project and hence did not make due coordination to deal with the complexity, nor did they have clear design ideas.

While facing the project assignment, the first common student reaction is, “We have not yet learned any relevant technical knowledge. Hence we don’t know what to do”. Consequently, they were hardly able to organize disciplinary subgroup and make due plans and designs. Taking lessons from the beta-test, we helped the students to clearly understand the problem through modelling the process as illustrated in Figure 1:

Module M1 requires the student holding the hoisting orders to communicate the orders to another student with hand to hand connections only; they must not use any sound or visual means. This forces them to workout a set of agreements on coding and communication protocol. A team’s performance is measured as the overall time from receiving the hoisting orders to

Figure 1. Process modelling of the crane operation

correctly fulfilling the hoisting tasks. Therefore, time used for communication must be kept to a minimum. By doing so, the students would understand clearly the tradeoffs between efficiency and reliability. This also leads them to understand the basic components and their functions in a communication system.

Module \( M_2 \) requires to program a computer interface that converts mouse clicks on the interface into modulated digital signals from the DAQ digital pins. The Visual BASIC programming environment is provided. The DAQ card supplies a universal library for manipulating the input/output operations. Therefore, the programming task is fairly simple and easy to learn, and achieving control via a computer gives the students a sense of accomplishment and stimulates their interest in learning. They need to program for stopping, reversing and acceleration/deceleration, for which they would need to understand the concept of PWM. Aesthetic and user-friendly interface design is also a part of the considerations the students should pay attention to.

Module \( M_3 \) refers to an electronic driving circuit converting modulated digital signals input from the DAQ card and the DC power supply from the battery into motor driving currents. It is expected to be composed of 6 H bridges using given transistors and resistors. Once the students understand the fundamental principles, it is fairly simple for them to work out the seemingly complex circuit. The module provides them with good opportunities to practice soldering and debugging. There are also a lot of overheating and burning cases due to various reasons. It provides a good starting point for the students to become familiar with electronics within a practical application context.

Modules \( M_4 \) and \( M_5 \) produce the physical working mechanism together. \( M_4 \) determines working mechanisms, the power transmissions and the overall dimensions. \( M_5 \) determines the skeletal structures ensuring the overall stability, the strength and the stiffness of the crane. For \( M_4 \), vertical lifting, radial moving and tower rotation need to be realized through the three motors. Two major issues need to be conceived and designed, one being the mechanisms fulfilling the designated movement, the other being the ways and installations of the power transmissions. For the first issue, reference can be made to tower cranes seen in the real world. The independence axiom of the axiomatic design theory was introduced to help the student make uncoupled designs. The power transmission problem is the most difficult one. Due to limited knowledge, limited machining and fabrication tools and lack of theoretic understanding, it is very difficult for the students to come out with robustly designed, well-installed and reliably working transmissions. Interestingly, radial movements are the most difficult to realize reliably.

The students have learned Newton’s mechanics of force. They understand the concept of equilibrium. With enough experimentation they should be able to fabricate the structure using the assigned steel wires. Unfortunately, reality did not support this assumption. Most groups did not do scientific experimentations to find the best structural configurations. Instead, they tried to avoid using the given steel wires to support the crane. This experience demonstrated that more guidance is needed to lead the students to identify engineering solutions.

By modelling the crane operation process, the students were able to delineate the functions of different modules. From the functions of the modules disciplinary subgroups could be formed. By defining the functions and input/output requirements, each subgroup narrowed down its concentrations. Each subgroup needed only to work out solutions for a specific set of requirements, which helped minimize the students’ panic. Multi-disciplinary group coordination and planning became tangible to the students.
Further modelling should have been carried out for individual subgroups to approach the solutions with a systematic way. However, due to minimal staff levels and limited contact hours such modelling was not commonly practised in the subgroups.

Information for students about the project was given with project social background, crane operation process modelling, background of relevant individual disciplines and quick references to the fundamentals with regard to the project.

As a group project, the students needed to follow project management routines to do the meeting, planning, presentation and report-writing. Because the students were in the process of learning and exploring, they had problems with decomposing the subtasks and making good progress plans.

Figures 2 – 9 show some of the designs and their products.
Figure 3a. Hoisting operation in process

Figure 3b. Hoisting operation in process

Figure 4. Connecting to the data acquisition card
Figure 5. Hoisting order transmission

Figure 6. Group discussion
Figure 7. The circuit board

Figure 8. Rotational movement transmission
LEARNING OUTCOMES WITH REGARD TO THE CDIO SYLLABUS

Based on the project design and the actual conduct of the pilot tests and practical implementation, the learning outcomes with regard to the CDIO syllabus are listed in Table 1. The remarks on the right explains the “I”, “T”, “U” measures to ensure the specific learning outcome is fulfilled.

Table 1
Learning outcomes and the corresponding realization measures

<table>
<thead>
<tr>
<th>CDIO learning outcome</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>1. Technical knowledge and reasoning</td>
<td></td>
</tr>
<tr>
<td>Understand basic ideas of mechanical transmissions</td>
<td>I, U, Realization of transmissions for the three dimensional movements.</td>
</tr>
<tr>
<td>A first exposure to mechanisms</td>
<td>U, Realization of the designated crane functions.</td>
</tr>
<tr>
<td>Reflect on reliability and robustness</td>
<td>I, explain during student consultation</td>
</tr>
<tr>
<td>Equilibrium calculations</td>
<td>I, U, Overall stability</td>
</tr>
<tr>
<td>Structural stability the resist to buckling</td>
<td>I, U, Design and construction of the tower and the beam</td>
</tr>
<tr>
<td>Transistor switching circuit, H bridge</td>
<td>I, U, realization of the motor driving circuit</td>
</tr>
<tr>
<td>Pulse width modulation</td>
<td>I, U, motor acceleration/deceleration control</td>
</tr>
<tr>
<td>A first experience with Visual Basic programming</td>
<td>U, programming of the user interface and the modulated digital output</td>
</tr>
<tr>
<td>Number system</td>
<td>I, U, Choice of number systems in hoisting</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
</tr>
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<td>------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
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<tr>
<td>2. Personal and professional skills and attributes</td>
<td>U, fulfilment of the hoisting order communication</td>
</tr>
<tr>
<td>2.1.2 Modelling</td>
<td>I, U, Process modelling</td>
</tr>
<tr>
<td>2.1.3 Estimation and Qualitative analysis</td>
<td>U, determination of the dimensions of the crane parts</td>
</tr>
<tr>
<td>2.1.5 Solution and Recommendation</td>
<td>U, All problems encountered in the project</td>
</tr>
<tr>
<td>2.2.2 Survey of Print and Electronic Literature</td>
<td>U, This is the major way for the students getting helps</td>
</tr>
<tr>
<td>2.2.3 Experimental Inquiry</td>
<td>U, Can be systematically practised in determining the supporting structures. Trial-and-error for other parts.</td>
</tr>
<tr>
<td>2.3.1 Thinking Holistically</td>
<td>U</td>
</tr>
<tr>
<td>2.3.3 Prioritization and Focus</td>
<td>U</td>
</tr>
<tr>
<td>2.3.4 Trade-offs, Judgement and Balance in Resolution</td>
<td>U</td>
</tr>
<tr>
<td>2.4.2 Perseverance and Flexibility</td>
<td>U</td>
</tr>
<tr>
<td>2.4.3 Creative thinking</td>
<td>U</td>
</tr>
<tr>
<td>2.4.5 Awareness of One’s Personal Knowledge, Skills and Attitudes</td>
<td>U, Assessed from personal reflections</td>
</tr>
<tr>
<td>2.4.6 Curiosity and Lifelong Learning</td>
<td>U, Planning and time schedule are required</td>
</tr>
<tr>
<td>2.4.7 Time and Resource Management</td>
<td></td>
</tr>
<tr>
<td>2.5.1 Professional Ethics, Integrity Responsibility &amp; Accountability</td>
<td>U, Practised in the whole process. Partly assessed from personal reflections</td>
</tr>
<tr>
<td>3.1.1 Forming Effective teams</td>
<td>U</td>
</tr>
<tr>
<td>3.1.2 Team Operation</td>
<td>U, Meetings, minutes taking, brainstorming, etc are required to be recorded. Assessments given.</td>
</tr>
<tr>
<td>3.1.4 Leadership</td>
<td>U, Bonus marks given to team leaders according to team performance</td>
</tr>
<tr>
<td>3.1.5 Technical Teaming</td>
<td>U, Technical subgroups are formed to work together.</td>
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<tr>
<td>3.2.2 Communication Structure</td>
<td>U, All teams are required to do oral presentations and answer questions in front of the whole class.</td>
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<tr>
<td>3.2.3 Written Communication</td>
<td>U, Formal reports are required according to given format.</td>
</tr>
<tr>
<td>3.2.4 Electronic/Multimedia Communication</td>
<td>U, All reports are electronic. Electronic hand-in system used. PowerPoint presentations are required. CAD drawings are recommended.</td>
</tr>
<tr>
<td>3.2.5 Graphical Communication</td>
<td>U, Practised in discussions, presentations and reports.</td>
</tr>
<tr>
<td>3.2.6 Oral Presentation and Inter-Personal Communications</td>
<td>U, Practised in discussions. Oral presentations are assessed.</td>
</tr>
<tr>
<td>3.3.1 English</td>
<td>U, An abstract in English is required</td>
</tr>
<tr>
<td>4.4.1 The Historical and Cultural Context</td>
<td>I</td>
</tr>
<tr>
<td>4.3.2 Defining Function, Concept and</td>
<td>I, U</td>
</tr>
</tbody>
</table>

STUDENT REFLECTIONS

Below we summarize some of the student feedback. These are the most important reasons for introducing PBL into our curriculum. It appeared that a complex, multi-disciplinary project would indeed give students a different learning and enhance their thinking and problem solving skills.

What The Students Feel They Have Learned

I learned how to simplify a complex task. I learned how to fulfil my own job within a group working on a complex task. I understand better the importance of design. ... learnt how to learn better.

I learned to think from objectives before start working. I feel that my thinking skill is improved.

We learned how to approach our teachers and elders independently.

I learned how to effectively use information in the library. I learned how to divide tasks but at the same time collaborate with my team mates. I have better hands on skills and can think more independently. The project broadened my thinking on how to discover a problem and find ways to solve it. This indeed makes me exciting.

Change the ways of Learning
This is an interesting process. You thought it would be ok just learn it. Later on you found it's not as simple as that. Then you wanted to go back to learn it again but you were short of time. So, you just went directly to the point. This way I improved my rapid learning skill.

It is a gradual process, from outside to inside, from simple to complex, from general to specific, step by step until touching the core.

We used septenary system. After many times drilling I found myself skilful converting between septenary and decimal numbers. At the same time, I understand much deeper of the number systems.

Apparently, while transmitting a piece of data, using octal system would need less numbers of signs, ie. higher number systems yield higher efficiency. But they would also need more complex signs to express (more prone to errors).

In the early stage of design, I was responsible for calculating the length of the beam and the lifted weight. I established the equilibrium equations using my mechanical knowledge. It was not difficult. ... This is different from doing exercises in a textbook. I need to determine the initial parameters by myself. I spent five hours to calculate my combinations of parameters and chose the best out of them.

**Change of Attitude**

In difficult situations, I would need to question and select “why” and “how”. It urges me think thoughtfully with different angles. This stimulate our innovative potentials.

In the course of the project, I experienced all kinds of feelings, depressed, obstinate, arrogant, fretting and wanted to give up. Looking back upon completing the work I understand myself better. It encourages me to consummate myself.

I learned that ... we must assume a good attitude toward a task.

While facing a problem, the most important is to figure out the ways to solve it and work on it step by step. Gradually you will find the answer.

**A Different Learning Experience**

In the end, we completed the initially seemed impossible task.

When our painstaking product passed the test and was appreciated, we understand more about our competency. We felt that a team is powerful, so powerful that it can solve hard problems.

We put the end product of our full semester hard working on that piece of paper, looked at the weight being lifted smoothly, everybody of us was excited.

In the evening we passed the test we went to the East to celebrate, celebrate the joy of success after spending great efforts together.

This is a process. In this process we experienced the joys of successes and the depression of failures. In the end we fulfilled our task and learned something.

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I got to know a group of buddies, learned some knowledge and morals, experienced the joy and happiness of the process.

DISCUSSIONS AND CONCLUSIONS

In the beta-test, the group of students approached the solutions in an ad hoc fashion. In the end, they missed important issues such as the overall stability of the crane. This alerted us of the importance of guiding the students to understand the multi-disciplinary nature of the project and identify functional decompositions to simplify the problem. In the first trial of the project, the students panicked because of the complexity. While there may be some benefit to permitting an unstructured, chaotic period before the students finally find a solution, it poses difficulties for the overall project timeline. When they have a poor overall grasp of the project, it is hard for them to decompose the tasks and make working plans. It is a challenge to balance between maintaining the complexity of the project and giving the students enough guidance. Our implementation shows that modelling is a good way of doing so.

The project offers the students a learning experience that nurtures social learning and stimulates innovations. It serves as an introduction to engineering and a first instance of design-build experience. Furthermore, it provides the students an early opportunity to appreciate the multi-disciplinary nature of product development. The design and build context helped the students to achieve the desired CDIO learning outcomes. The process modelling helped the students to decompose tasks, focus on specific problems and manage the project with confidence.

REFERENCES


Biographical Information

Xiaohua Lu is an Associate Professor in the Department of Civil Engineering and the Director of the Teaching Affairs Department, Shantou University, China. His current scholarly interests are in structural engineering/structural assessment and research.

Stephen Banzaert is an Instructor with a joint appointment at the Gordon Engineering Leadership Program and the Edgerton Center, Massachusetts Institute of Technology. His principal focus is project-based learning and the integration of hands-on, real-world projects into engineering education.

Yinghui Fan is an Associate Professor in the Department of Electromechanical Engineering of the College of Engineering at Shantou University, Guangdong Province, China. Her current research interests include modeling and analysis of manufacturing system, scheduling and planning of manufacturing system, manufacturing control architecture and motor control. Meanwhile the teaching methodology is also among her interests.

Joshua S. Jacobs is the Director of Education and Communications for the MIT-Portugal Program, and an advisor to the CDIO Joint Development Project with Shantou University. In his previous role as Director of Education for the Cambridge-MIT Institute, he managed joint faculty projects to incorporate CDIO into the curriculum of Cambridge and other universities in the UK, and helped organize the 2004 CDIO workshop at Cambridge.

Corresponding author
Dr. Xiaohua Lu
Teaching Affairs Department
Shantou University
243 Daxue Road, Shantou
Guangdong, China 515063
86-754-82903480
xhlu@stu.edu.cn