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Enhancing Systems Thinking Skills of Sophomore Students: An Introductory Project in Electrical Engineering*

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A course entitled 'Introductory Project in Electrical Engineering' was developed and implemented at the Department of Electrical Engineering of the Technion—Israel Institute of Technology. The course was designed to expose students in the third semester of their studies to the discipline of electrical engineering and enhance their systems thinking skills. The major component of the course was a team-based design project of a window cleaning robot. The present study, which used quantitative instruments alongside qualitative ones, reveals significant improvement of systems thinking skills among the students who took the course.

Keywords: introductory engineering course; project-based learning; systems thinking

1. Introduction

The Department of Electrical Engineering of the Technion—Israel Institute of Technology—decided to develop and implement a new elective course designed for sophomore students. The course, Introductory Project in Electrical Engineering, was designed to expose students to the discipline of electrical engineering, demonstrate how engineers work and increase the students' interest. Another objective that the course was devised to achieve was an improvement of systems thinking among the students. Systems thinking provides a framework for comprehending the interaction between the system's different components [1]. The main component of the course was a design project of a window cleaning robot carried out by teams of students.

The will to develop systems thinking skills among students within a dedicated course derived from a combination of several factors: technological systems are becoming more complex and interdisciplinary than before and include aspects (e.g. organizational and environmental) outside the traditional ones and therefore this type of thinking is required nowadays [2–3]; studies show one can learn systems thinking [4]; and the lack of a dedicated course dealing with systems thinking and designed for beginner students. Indeed, within the capstone project taking part in the final academic year, students are exposed to systems thinking but the Department was interested in providing students with these skills at the beginning of their professional training without waiting for a later stage.

Introductory courses are offered by universities to freshman and sophomore electrical and computer engineering students [5–7], mechanical engineering students [2, 8] and jointly for all engineering students at the institution [9]. Some of these courses focus on design projects [2], while others integrate theoretical lectures and lab experiments [7]. The uniqueness of the course presented in this paper is that developing systems thinking skills among sophomore electrical engineering students is one of its declared objectives. This sets it apart from other electrical and computer engineering introductory courses that were not designed to achieve this goal but other goals, e.g. increasing students' interest by exposing them to the various topics of electrical and computer engineering and acquaintance with the faculty members [7], promoting innovative thinking [5] or developing basic lab skills and technical writing abilities [6].

The research described below examined changes in students' systems thinking skills following their participation in the course. The changes in interest expressed by the students in the discipline of electrical engineering will be presented elsewhere.

The paper begins with theoretical background that reviews the two subjects that the study is based on: project-based learning and systems thinking. At the end of the theoretical section, the course Introductory Project in Electrical Engineering is described. Next, the study objectives and methodology are presented, including the research instruments used. Finally, the findings are discussed and further research directions are suggested.

2. Theoretical background

2.1 Project-based learning

Project-based learning is learning in which students are involved in executing a project [10]. Thomas [11] defines project-based learning as a model that organizes learning around complex tasks based on challenging problems. During this type of learning, students experience design, problem solving, deci-

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sion making and investigative activities. The students have an opportunity to work in relative independence for lengthy periods of time and learning ends in building an actual or virtual product [12]. One should note that project-based learning is related to problem-based learning, in which students also provide answers to questions; but, they are not involved in carrying out a project [13]. However, since project-based learning includes problem solving, project work is problem-based learning [14].

The theoretical foundation of project-based learning is based on Dewey's concept of 'learning by doing', which encourages students to construct their own knowledge [15]. This idea is expressed in the constructivist approach whereby the individual constructs his or her knowledge through interaction with the environment [16]. Constructing knowledge occurs in the process of relating new knowledge to existing knowledge using assimilation and adaptation mechanisms. Later on, social constructivism placed emphasis on social interaction, believing that knowledge is constructed in the social environment [17]. Then, constructionism claimed effective learning takes place when the individual constructs a product that he can share with others [18].

According to Thomas [11], projects on which project-based learning is based should fulfil the following criteria:

- The project plays a major role in the study program;
- The project addresses issues that expose students to the main concepts of the subject;
- The students are engaged in inquiry;
- The students enjoy a high level of autonomy;
- The project focuses on real-world scenarios.

Studies on project-based learning were carried out in various disciplines, including science [19] and engineering [20]. These studies and others indicate that from the cognitive aspect such learning improves students' thinking skills in general [21] and critical thinking [22–23] and systems thinking [24–25] in particular. Additionally, project-based learning leads to a deeper comprehension of the subject being taught [26], although it is sometimes more time-consuming than traditional learning [27]. From the effective aspect, project-based learning increases students' motivation [28], and from the social aspect, it enables experiencing teamwork that is vital for success in engineering practice [19].

2.2 Systems thinking

A system is a collection of components undergoing dynamic interaction with each other [29]. The most prominent property of the system is its synergy, i.e. being more than the sum of its parts, due to the interaction between its components [30]. Due to this synergy, one cannot forecast the complete system's properties by analysing each component separately.

According to Kasser and Frank [31], the skills required of a systems engineer include personality traits, cognitive properties and knowledge (the knowledge required of systems engineers has been discussed in many sources [32] and is of no concern to this paper). Among the personal properties of ideal systems engineers one can find: openness, curiosity, interpersonal communication skills and teamwork [4]. The cognitive properties required for a systems engineer can be divided into two [31]: critical thinking—including analysis, synthesis and evaluation, and systems thinking, which will be dealt with below.

Systems thinking provides a framework for observing interaction between the system's different components [1] and argues that studying the properties of system components alone is not enough. One must learn the interaction between the different components as well [33]. The characteristics of systems thinking were studied in [34–36]. When comparing the results of these studies [37] one can note the prominent features of systems thinking skills:

- Viewing the entire system beyond its components;
- Comprehending the interaction between the system's components;
- Comprehending system function without requiring all the details;
- Understanding the synergy within the system;
- Observing the system from several points of view;
- The ability to consider non-engineering issues (e.g. financial, organizational, environmental, etc.).

While some believe that these skills are inherent [38], others argue that systems thinking is a combination of inherent talent and experience and may be taught [4]. The application of systems thinking in education was first proposed by Chen and Stroup [39] and, following that, systems thinking skills among high-school students were examined in different contexts, such as the water cycle [40].

Recently, interest in systems thinking in the context of engineering education is on the rise. This is happening in view of the increasing need for modern engineers to handle complex systems that include aspects that are outside traditional engineering, such as organizational and environmental aspects [3, 41]. This issue is expressed on two levels: development of a four-year curriculum for training engineers using the systems approach on the one hand [42], and the development of specific courses designed to provide students with systems thinking skills, on the other hand [2, 25]. Studies among mechanical engineering students [2] and industrial engineering and management students [25] show that systems thinking may be acquired or developed in an active learning environment that includes teamwork and learning from mistakes.

3. Course overview

Some 1800 undergraduate and 400 graduate students study at the Department of Electrical Engineering of the Technion—Israel Institute of Technology—considered to be among the top electrical engineering departments in the world [43]. The teaching and research activities cover, among other topics, the following areas of electrical and computer engineering: electro-optics and opto-electronic systems, VLSI and nanoelectronics, communication and information theory, image processing and computer vision, computer networks, robotics and automatic control.

The course Introductory Project in Electrical Engineering awarded the students with one credit and comprised one two-hour weekly meeting. The course was divided into two halves. The first part of the course comprised lectures that provided the students with the tools that they would use throughout the course, especially in the second half, which focused on executing a design project. The contents studied in the first part of the course were the following: the essence of engineering (week 1), database searching and building an effective presentation (week 2), the discipline of electrical engineering (weeks 3–4), and the engineering approach to problem solving (weeks 5–7).

The opening lecture compared science and engineering, presented prominent engineering achievements through history, named the Draper Prize winners [44] and described the grand engineering challenges of our era. In addition, it specified the abilities required of an engineer, including teamwork. In the second session, useful search engines and popular engineering databases were reviewed, and training was given on efficient search of these information sources and how to build an effective presentation. In the third meeting, an overview of the various topics of electrical engineering was provided. At the end of the lesson, the students were asked to prepare, based on a search of databases, presentations that include extended reviews of a particular teaching and research topic at the Technion's Department of Electrical Engineering, comparing it with leading departments around the world. This task was carried out by teams of five students, with personal instruction by a mentor, a senior engineer in the Department. In the fourth lesson, every team presented its work to their peers and the teaching staff. Senior faculty members took part in this session, spoke shortly about their specialty and the dean greeted the students. The next three lessons dealt with the engineering approach to problem solving. After a short discussion of mathematical and scientific problems, the engineering approach to problem solving was introduced, including the following steps: defining the problem, collecting data, examining alternatives, making a decision, detailed design, examining the proposed solution, and documenting the above process. This approach was demonstrated using the well-known travelling salesman problem. A weekly syllabus of the introductory lectures and accompanying tasks is specified in Table 1. The introductory lectures were based on the books *Creative Problem Solving and Engineering Design* [45] and *Thinking like an Engineer: An Active Learning Approach* [46]. These books were selected from the wide range of existing textbooks (e.g. [47–48]) in view of their focus on the engineering approach to problem solving described above.

Table 1. Introduction lectures: weekly syllabus

Session	Subject	Description	Team task
1	The essence of engineering	Comparison between science and engineering, great engineering achievements, Draper Prize winners, 21st century engineering challenges, abilities required from engineers, teamwork	
2	Database searching and building an effective presentation	Engineering databases, search engines, efficient searching. Types of presentations, presentation structure, building an effective presentation	
3–4	The discipline of electrical engineering	Overview of the various topics of electrical engineering, teaching and research activities at the Technion's Department of Electrical Engineering	In-depth review of a particular teaching and research topic at the Technion's Department of Electrical Engineering
5–7	Engineering approach to problem solving	Classification of problems, problem solving methods, the engineering approach to problem solving, the travelling salesman problem	

As mentioned, the main component of the course was a design project carried out in teams counselled by mentors from the eighth week of the semester. The project, selected in view of Thomas' criteria [11], focused on designing a window cleaning robot. The project opened with an introductory lecture about robotics and a presentation of the design stages on a weekly basis. Each week dealt with one of the following focused subjects: defining the robot's structure and movement (week 8), physical design (week 9), block diagram (week 10), integrating sensors (week 11), selecting microcontrollers and drivers (week 12), and navigation algorithms (week 13). Additional details are given in Table 2. Every stage opened with a review of the design subject at hand and at the end the students received a task that they were asked to complete using the engineering approach to problem solving taught in the first part of the course. On the final week (week 14) every team presented the design of its robot to their peers and the course teachers.

In carrying out the different tasks, the students used tools acquired in the introduction lectures. Beyond ongoing application of the engineering approach to problem solving, the students examined alternatives for their robot and selected the different components (motors, energy sources, sensors, microcontrollers and drivers) after carrying out a comprehensive search through online databases. Additionally, the final presentation was built and displayed based on the principles taught during the relevant meeting.

One should note that allocation of a mentor to each five-student team requires large human resources from the Department, however it was decided to uphold this ratio in order to refrain from damaging the quality of mentoring, but the number of students taking the course was restricted to 25 only.

4. Research question

The research objective was to characterize changes in the systems thinking skills of students taking the course Introductory Project in Electrical Engineering. The following research question was derived from the research goal: Was there a change during the course in students' systems thinking skills? If so—what characterizes this change?

5. Methodology

The study employed both quantitative and qualitative methods as they complement each other [49]. The research population comprised 25 undergraduate electrical engineering students in their third semester of studies who chose to take the elective course Introductory Project in Electrical Engineering. These students, comprising the experimental group, were asked to fill out an anonymous questionnaire at the beginning and the end of the course. The questionnaire was designed to characterize the students' systems thinking skills. In order to complete the information obtained from the questionnaire, at the end of the course five semi-structured interviews were carried out with students. Interview questions focused on the insights gained by the students when carrying out the project and are listed in the Appendix. In addition, 30 electrical engineering students in their third semester of studies, who did not participate in the course, took part in the research. These students, used as the control group, were requested to fill out the questionnaire at the beginning and the end of the semester.

The questionnaire that characterized systems thinking skills was a Likert-like questionnaire based on the CEST (Capacity for Engineering Systems Thinking) questionnaire proposed by Frank et al. [50]. The questionnaire comprised 20

Table 2. Robot design tasks: weekly syllabus

Session	Subject	Description	Team task
8	Introduction to robotics, defining the robot's structure and movement	Introduction to robotics, pros and cons of window cleaning robots, robot requirements, major challenges	Collect data on window cleaning robots, examine alternatives, choose a solution
9	Physical design	Motors: types, properties Energy sources: types, properties	Select motors and energy sources for the robot
10	Block diagram	Objectives, structure of block diagrams, examples (mobile phone, robot)	Draw block diagram of the robot
11	Integrating sensors	Light sensors, position sensors, tactile sensors, proximity sensors, bend sensors	Select sensors for the robot
12	Selecting microcontrollers and drivers	Microcontrollers: history, basic components, properties Drivers: types, properties	Select microcontroller and drivers for the robot
13	Navigation algorithms	Vehicle positioning, path planning, map making	Prepare final presentation
14	Project presentation		

statements that represent the characteristics of systems thinking specified in Section 2.2. The statements were validated by two experts on education in electrical engineering. Cronbach's alpha was found to be equal to 0.80, indicating a good level of internal consistency. Sample statements are given in the Appendix.

6. Findings

Figure 1 shows the experimental group members' mean systems thinking score (ranging between 20 and 100) on the pre-test and post-test questionnaires. The chart displays a clear improvement in systems thinking skills from a medium value at the beginning of the course to a high value at the conclusion.

Table 3 displays the systems thinking score of the experimental and control groups. No significant difference was found between the pre-test score of the experimental group and that of the control group. However, the t-test showed a significant difference between the post-test score of the experimental group and the post-test score of the control group. Cohen's d was found to be equal to 1.15, indicating a very large effect size.

Excerpts from students' interviews reveal that they recognized the importance of understanding the interaction between the system's components:

> [During the design project] we understood you have to look at everything together, that one solution must be compatible with another. . . It is far from the simple, focused problems we solved till now.
>
> Before the course I only had to solve exercises. . . Now for the first time we have to design an entire system together and consider every person's actions.

Additionally, the students acknowledged the importance of seeing the entire system beyond its components:

> When we began to design [the robot] we focused on fine details of everything separately... Later we understood the importance of an overall view.

7. Discussion

The study indicates significant improvement in the systems thinking skills of the students who took the course as they began to assume some of the systems thinking features proposed in [34–36]. After carrying out the project, the students understood that they should consider the interaction between system components and cannot design them separately without seeing the entire picture. The interviews also show that students recognized the great difference between the robot design assignment, requiring systems thinking, and narrow assignments set before them up to this point, such as solving exercises.

These results conform to the findings by [25], who

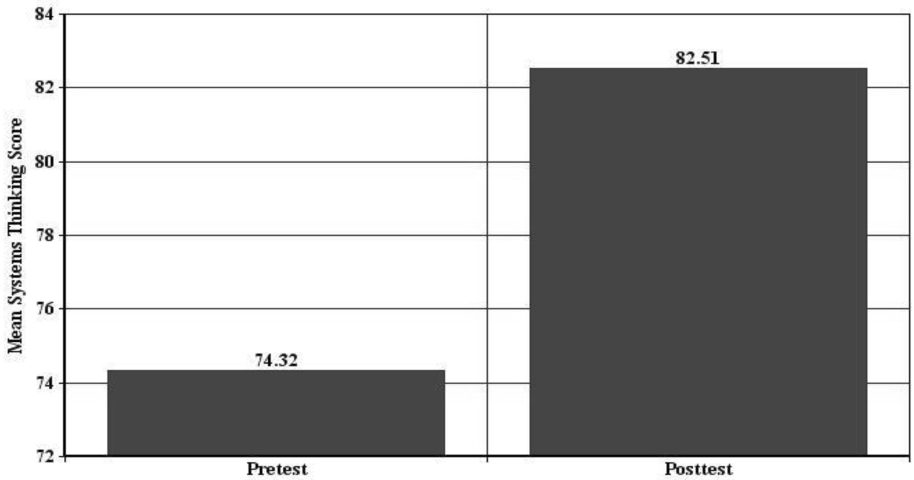

Fig. 1. Mean systems thinking score (experimental group).

Table 3. Systems thinking score

Test	Group	Mean	SD	t	p-value
Pre-test	Experimental	74.32	4.97	1.56	n.s.
	Control	76.22	4.07		
Post-test	Experimental	82.51	3.80	4.24	< 0.01
	Control	76.32	6.41		

showed that project-based learning improves systems thinking skills among management students, and the findings by [51], who presented improvement in systems thinking among high-school students who carried out an electro-optical project.

The study has two major limitations: students were not assigned randomly to the experimental and control groups, and a relatively small sample size. In order to respond to the first limitation, usually characterizing studies in educational institutions, a preliminary test was applied to negate a significant difference between the experimental and control groups. In order to handle the second limitation, use was also made of qualitative tools designed to increase the trustworthiness of the findings.

The theoretical importance of the research lies in characterization, for the first time as far as the author is aware, of systems thinking skills of electrical engineering students at the beginning of their studies. The practical contribution may be expressed in implications of the study conclusions on designing syllabuses for engineers in general and electrical engineers in particular. These contributions are more valid due to the increasing interest in systems thinking in the context of engineering education [3, 41].

In a continuation study the author intends to examine whether the differences found in the current research between the experimental and control group scores will be retained in the students' more advanced courses. Furthermore, it would be interesting to examine, after graduation, the contribution of the course towards training the students to become engineers.

8. Conclusions

The paper presented an electrical engineering introduction course designed to develop systems thinking among students at the start of their way using project-based learning. The present study showed that students taking this course significantly improved their systems thinking skills. Beyond the above quantitative improvement, qualitative findings indicate that students had assumed some of the properties of systems thinking.

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Appendix

Interview questions

Below are the interview questions discussed in Section 5.

- Are the assignments you were faced with in this project different from those you had encountered in your studies to this point? If they are—in what way?
- Did you gain any insights from carrying out the project? If so—please elaborate.
- Describe the most interesting stage of carrying out the project. What was interesting in it? What did you learn from it?
- What is the most important thing that you learned from this experience?

Questionnaire—sample statements

The following statements are based on the CEST (Capacity for Engineering Systems Thinking) questionnaire developed by the authors of [50] and discussed in Section 5. Statements 1, 3, 5, 6, 7 attest to high systems thinking skills while the remaining statements attest to poor systems thinking skills.

- When I am involved as an engineer in an engineering project, it is important for me to understand the overall picture.
- When I am responsible for developing a particular component that is part of a product, I am not interested in the remaining components as I am not responsible for their development.

- When I am involved as an engineer in an engineering project, I should be familiar with the financial aspects of the project.
- The contact with an engineering product's customer should be carried out by marketing personnel only.
- As an electrical engineer, I should acquire knowledge of other engineering disciplines beyond electrical engineering.
- When I am involved as an engineer in an engineering project, I should be acquainted with the work of the other engineers engaged in this project.
- If I am responsible for developing a particular component that constitutes part of a product, I consider mutual relations between this component and other components of the product.

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