DEVELOPING SYSTEMS THINKING SKILLS: A HIGH-SCHOOL COURSE ON ENGINEERING DESIGN

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Abstract *–A unique course has recently been developed at the Technion – Israel Institute of Technology for 12th grade students majoring in physics and electronics. During the course students are required to complete – on a team basis – various engineering tasks. The aims of the course are to increase its graduates' motivation to study science and engineering, to develop their systems thinking skills, and to train them in teamwork. The study described in the paper examined to what degree the course's second goal (developing systems thinking) had been attained. Thirty-two 12th graders participated in the study, which utilized quantitative tools alongside qualitative ones. The students were asked to fill out an anonymous questionnaire at the beginning and the end of the course. The questionnaire was a five-level Likert scale based on the CEST (Capacity for Engineering Systems Thinking) questionnaire. Additionally, semi-structured interviews were held with students at the end of the course. The study indicates an improvement in students' systems thinking skills – characterized by a large effect size.*

Keywords: Engineering design, high-school curriculum, systems thinking.

1. INTRODUCTION

Due to the current shortage in engineers, many universities take extensive actions to enhance the interest of high-school students in engineering [1]-[2]. A unique course has recently been developed at the Technion – Israel Institute of Technology for 12th grade students majoring in physics and electronics. The course, "Introduction to Engineering Design", allows students to experience engineering design. The course is intended to increase its graduates' motivation to study science and engineering, develop their systems thinking skills [3]-[4] (e.g. understanding the interrelations and synergies among the system components) and train them in teamwork.

The study described in this paper used quantitative and qualitative methods to examine changes in the systems thinking skills of students participating in the course. The study's contribution is in characterizing – for the first time, as far as we are aware – systems thinking skills in high-school students attending a unique course in engineering design.

The paper begins with a concise review of systems thinking. Next, the course is described, and the chosen methodology is presented. Finally, the main findings are discussed.

2. SYSTEMS THINKING

Systems thinking involves looking at the complete picture and is a frame of reference for observing the interrelations and mutual influences between the system's different components [3]-[4].

Richmond [5], Frank [6] and other researchers have formulated the main characteristics of systems thinking, including:

- Seeing the complete system beyond its components and understanding the system's function without needing every detail;
- Comprehending the interrelations and synergies between system components;
- Observing the system from different viewpoints, such as the temporal viewpoint (examining the system's behavior as a function of time) and the generic viewpoint (looking for similarity between systems);
- The ability to take into account non-engineering considerations, such as economic and organizational considerations.

The application of systems thinking to education was first suggested by Chen and Stroup [7], and studies conducted among engineering students indicate that systems thinking can be acquired in an active learning environment that includes analyzing and designing systems and learning from errors [8]-[9].

3. THE COURSE

The course "Introduction to Engineering Design" consisted of 16 weekly lessons (100 minutes each), and was held at the Technion – Israel Institute of Technology. The course utilized the LEGO® MINDSTORMS® Education EV3 robotic kit [10]. This kit was selected because it allows the student to construct electro-mechanical systems equipped with diverse sensors through a relatively simple process. The course faculty included three experienced engineers with a rich background in teaching.

The core of the course consisted of seven study units, each extending over two lessons, as shown in Table 1.

On the first lesson, the course format was presented. According to this format, at the beginning of each study unit the students would divide into teams of four. Each team would appoint a leader who would be responsible for leading the team and executing its task, a hardware engineer who would be responsible for the robotic system's physical structuring, a software engineer who would be responsible for writing the program, and a physicist who would be responsible for defining the physical model. After selecting the functions, the different jobholders would obtain directions from the instructors.

Lessons 2-3 were dedicated to familiarization with the robotic kit and to performing simple actions, such as moving the robotic vehicle in a straight line and measuring instantaneous speed and average speed with a timer and rotary encoder.

On lessons 4-5, the students were requested to plan and implement a navigation system for the robotic vehicle, to enable it to move through a rectangular course (with an unknown perimeter) by utilizing a color sensor that could identify small colored squares located in proximity to the rectangle's vertices.

On lessons 6-7, the students planned and implemented a navigation system allowing the robotic vehicle to move through a course with the shortest motion time, based on Fermat's principle.

Lessons 8-9 covered the way to display a graphical presentation of a parametric equation on the robot controller screen.

On lessons 10-11, the students were requested to find the approximate area of a polygon with the robotic vehicle, by using Riemann sums. The area of each rectangle was calculated with a rotary encoder on the axis of the robot's motion (x-axis) and an ultrasonic range sensor on the axis perpendicular to the robot's motion (y-axis).

On lessons 12-13, the students wrote a program that calculated the robot's location in Cartesian coordinates in relation to a corner of the room that constituted the origin, by using the ultrasonic range sensor.

Table 1: "Introduction to Engineering Design" course.

Lesson	Subject
1	Introductory lesson
2-3	Familiarization with the robotic kit
4-5	Navigation along a rectangular course
6-7	Course optimization based on Fermat's principle
8-9	Graphical presentation of a parametric equation
10-11	Calculating the area of a polygon with Riemann sums
12-13	Calculating a location in Cartesian coordinates
14-15	Final project: real-time control system for an electric motor
16	Course summary

Lessons 14-15 were dedicated to planning and implementing the final project: a real-time speed control system for an electric motor. The system consisted of a man-machine interface displaying relevant data and allowing convenient operation, real-time measuring capability and closed-loop control, as well as suitable software and hardware components. The purpose of the last lesson was to summarize the course.

Throughout the entire course, the faculty insisted on maximum student involvement in the planning and implementation considerations, refraining as much as possible from excessive guidance. Additionally, the instructors permitted the students to err and correct their errors on their own.

4. RESEARCH GOAL AND METHODOLOGY

The goal of the study was to characterize changes in the systems thinking skills of students participating in the course "Introduction to Engineering Design".

Thirty-two top 12th grade students majoring in physics and electronics who had chosen to attend the course participated in the study. The students were asked to fill out an anonymous questionnaire at the beginning (pretest) and the end (posttest) of the course. The questionnaire was a five-level Likert scale based on the CEST (Capacity for Engineering Systems Thinking) questionnaire [11]. The questionnaire consisted of 20 statements reflecting the systems thinking characteristics mentioned in Section 2, such as "If I'm responsible for writing the software program for the project, it's important for me to understand how it integrates with the project's hardware that is being developed by other team members". The statements were validated by two experts in engineering education. Cronbach's alpha (0.80) indicates good internal consistency. A sample of the statements is provided in the Appendix.

Additionally, semi-structured interviews were held with students at the end of the course. The quantitative findings were statistically analyzed, and the corresponding effect size calculated. The qualitative findings were classified into categories by using content analysis.

5. RESULTS AND DISCUSSION

Table 2 shows the systems thinking score (between 20 and 100) at the beginning and the end of the course, as well as the effect size. It can be seen that the students' systems thinking skills at the end of the course were higher than at the beginning, and that the effect size is large.

The findings from the interviews suggest that students began adopting some of the systems thinking skills:

• Comprehending interrelations between system components

"There are several areas within the system – hardware, software and physics – and the purpose is to have everything integrate together."

• The ability to take into account non-engineering considerations

"[When I design a component that is part of a product] I don't design the best component, but leave some ideas for later, so I would be able to upgrade the product and make more money."

The improvement in the students' systems thinking skills can be assigned to the course learning environment – an active learning environment that includes practical experience and learning from errors – which had been found to be suitable for developing systems thinking [8]. The study findings match the results of similar studies conducted among engineering students [9].

The study has two main limitations: a relatively small number of participants and the lack of a control group. In order to deal with these limitations, we used quantitative tools alongside qualitative ones, in order to increase the trustworthiness of the findings.

The study's theoretical contribution is in characterizing – for the first time, as far as we are aware – systems thinking skills in high-school students attending a unique course in engineering design. Its practical contribution may be reflected in the development of similar courses for high-school students. This contribution becomes important in light of the necessity to develop systems thinking skills among engineering students [12].

Table 2: Systems thinking score.

Test	Mean	SD	Cohen's *d*
Pretest	78.10	8.88	0.82
Posttest	84.67	7.04	

6. CONCLUSIONS

The study described in this paper was intended to characterize changes in the systems thinking skills of high-school students participating in a unique course on engineering design. The study indicates an improvement in students' systems thinking skills – characterized by a large effect size.

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APPENDIX: QUESTIONNAIRE

The questionnaire for assessing systems thinking skills as mentioned in Section 4 is a five-level Likert scale based on the CEST (Capacity for Engineering Systems Thinking) questionnaire [11]. The questionnaire consisted of 20 statements. Below is a sample of the statements. Statements 1 and 3 reflect high systems thinking skills whereas the others express low systems thinking skills.

1. If I'm responsible for writing the software program for the project, it's important for me to understand how it integrates with the project's hardware that is being developed by other team members.
2. When I'm responsible for developing a certain project component, I prefer not to be involved in the way "my" component integrates with other components that I didn't develop.
3. When I'm responsible for developing a certain project component, it's important that I understand the economic aspects of the project.
4. I'm not interested in the work of others taking part in the project.