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Systems thinking of secondary and post-secondary students majoring in engineering

Aharon Gero

Technion - Israel Institute of Technology
Haifa, Israel

ABSTRACT: Systems thinking, i.e. the ability to understand the interrelationships between the system components and the resulting synergy, occupies a central place in engineering education on all its levels. In view of its importance, the study described in the article characterised the systems thinking level of students majoring in engineering. The research involved 157 participants: high-school, two-year college and university students. During the school year, the students filled out a self-reporting questionnaire or took an achievement test designed to assess their systems thinking. According to the results, the systems thinking score of high-school and university students was moderate, with no significant difference between the two groups. It was also found that the systems thinking skills of two-year college students were significantly lower than that of their peers in high school and academia.

Keywords: Systems thinking, high-school students, two-year college students, university students

INTRODUCTION

Systems thinking, i.e. the ability to comprehend the interdependence between the system components and the resulting synergy, plays an important role in both Industry 4.0 and Industry 5.0 frameworks [1]. Accordingly, systems thinking occupies a central place in engineering and engineering education at the secondary and post-secondary levels [2], and there is a continuous effort to develop systems thinking skills in students at these levels [3][4].

The current study aimed to assess and compare the systems thinking level of students majoring in engineering, namely, high-school, two-year college and university students. To the best of the author's knowledge, such analysis was performed here for the first time. The research findings enrich the relevant body of knowledge and may advance the training of students in various engineering programmes.

The article reviews systems thinking. Then, the study objective and the methodology are presented. Finally, the main findings are discussed.

SYSTEMS THINKING

Systems thinking, in contrast to reductionism, emphasises the interaction between the system components [5]. The concepts of Industry 4.0 and Industry 5.0 [1] and the complexity of engineering systems give systems thinking a central place in engineering education in the current epoch [2-4]. Indeed, systems thinking is reflected in the accreditation criteria of the Accreditation Board for Engineering and Technology (ABET) [6]. Moreover, systems thinking is essential in other fields, e.g. science and medicine [3], and as such, it is mentioned in the Next Generation Science Standards (NGSS) [7].

In the engineering context, systems thinking has several features, and the main ones are detailed below [8]:

- Seeing the entire system beyond its components;
- Understanding the function of the system without having to need all the details;
- Comprehending the interdependence between the system components and the resulting synergy;
- Being able to take into account environmental, economic and organisational considerations.

Beyond these cognitive skills, the so-called systems thinker often has interdisciplinary knowledge and is a team player [9].

Based on the assumption that systems thinking can be promoted [10], there is a lingering effort to advance systems thinking among different populations (high-school and university students) and in various scopes (short courses and multi-year programmes) [11][12]. These educational initiatives include expert lectures, computer simulations and project-based learning [13], especially one that includes dedicated tasks [14].

In order to measure systems thinking, several tools have been developed, such as self-reporting questionnaires [8], achievement tests [15] and rubrics [16]. It is worth mentioning that systems thinking is related to abstract thinking, namely, the ability to distil the information relevant to a given stage and temporarily ignore the irrelevant data [17].

STUDY OBJECTIVE

The research aimed to assess and compare the systems thinking level of students majoring in engineering, namely, high-school, two-year college and university students.

METHODOLOGY

Participants

One hundred and fifty-seven Israeli students took part in the study. The first part of the research involved 30 12th grade students majoring in electrical engineering, 17 electronics students in their first year of study at a two-year college and 32 sophomore electrical engineering students. The second part of the research involved 36 12th grade students majoring in electrical engineering and 42 junior electrical engineering students (Table 1). The age range of the high-school students was 17-18, of the two-year college students 18-20 and of the university students 19-25. All the educational institutions involved are leaders in their field. All participants were similar in their characteristics to students who usually study in the relevant programmes, and none of them took part in any dedicated activity to advance systems thinking.

Table 1: Participants.

Part	Group	*n*
1	High-school students (12th graders)	30
	Two-year college students (first year)	17
	University students (sophomore)	32
2	High-school students (12th graders)	36
	University students (junior)	42

Method

As described in the theoretical background, there are several instruments for measuring systems thinking, e.g. self-reporting questionnaires, achievement tests and rubrics. In the first part of the study, a self-reporting questionnaire, which does not depend on the academic background of the participants, was used. In the second part of the research, an achievement test adapted to the background of the participants, was applied. During the academic year, the students filled out the questionnaire or took the test. The data were statistically analysed, and a comparison was made between the different groups of students.

Instruments

The self-reporting questionnaire was a five-level Likert-like scale, ranging from *strongly disagree* to *strongly agree*. This instrument was based on the capacity for engineering systems thinking (CEST) tool [8]. The anonymous questionnaire was comprised of 20 statements that reflected the cognitive characteristics of systems thinking mentioned earlier. Some of the statements expressed high systems thinking and others - low (Table 2). The statements were validated by two experts in engineering education, and good internal consistency was obtained ($\alpha = 0.80$).

Table 2: Self-reporting questionnaire - selected statements.

Systems thinking	Statement
High	*When I am responsible for the development of a specific system component, it is important that I familiarise myself with the needs of the customer.*
	When I am responsible for developing a specific system component, it is important that I identify the advantages inherent in integrating my *component with the remaining components which are not my responsibility to develop.*
Low	*The economic aspects of a project are only the concern of the project manager.*
	When I am responsible for the development of a specific system component, I do not need to concern myself with the remaining components which are not my responsibility to develop.

The achievement test was an hour-long examination dealing with system analysis in light of the systems thinking features described above. As mentioned, the test was adapted to the academic background of the examinees. The high-school students' test (nine questions) focused on a system controlling a parking lot gate [18], whereas the university students' test (seven questions) dealt with electronic circuits [15]. The questions were validated by two engineering education experts, and a sample of them is given in Table 3.

Table 3: Achievement test - selected questions.

Group	Topic	Question
High-school students	System controlling a parking lot gate	*Which sensor is recommended to detect a vehicle passing through the gate? A sound sensor, colour sensor, motion direction sensor or an infrared proximity sensor?*
University students	Electronic circuits	*Consider a single-transistor inverter, consisting of an NMOS transistor and a resistor. How will the circuit performance change if the resistor is replaced by a PMOS transistor?*

FINDINGS

Figure 1 shows the mean systems thinking score ($1 \leq m \leq 5$) of the different groups, based on the analysis of the self-reporting questionnaire. Table 4 displays the systems thinking score (mean m and standard deviation s).

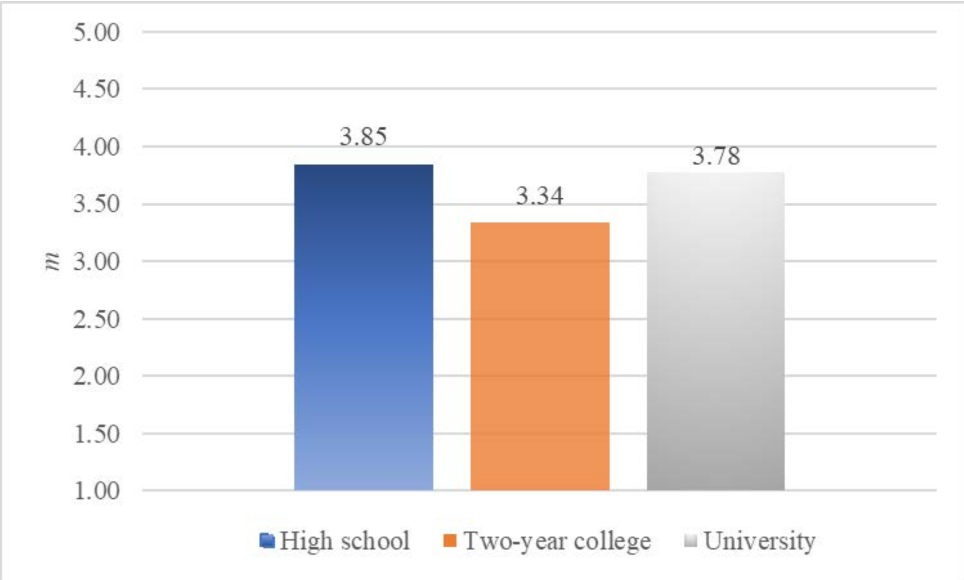

Figure 1: Self-reporting questionnaire - mean scores.

Table 4: Self-reporting questionnaire - scores.

Group	*m*	*s*
High-school students	3.85	0.32
Two-year college students	3.34	0.24
University students	3.78	0.27

According to the Shapiro-Wilk test, a normal distribution of the dependent variables could be assumed ($W \geq 0.95$, $p > 0.05$). Levene's test indicated the equality of variances ($F(2, 76) = 0.93$, $p > 0.05$). Hence, a one-way ANOVA was performed.

The statistical analysis revealed a significant difference between the groups ($F(2, 76) = 18.80$, $p < 0.01$), characterised by a large effect size ($\eta^2 = 0.32$). The results of post-hoc Tukey HSD tests indicated a significant difference between high-school students and two-year college students ($p < 0.01$), and between two-year college students and university students ($p < 0.01$). The difference between high-school students and university students was non-significant ($p > 0.05$).

Table 5 shows the systems thinking score (mean $1 \leq m \leq 5$ and standard deviation s) as obtained from the achievement test analysis.

Table 5: Achievement test - scores.

Group	*m*	*s*
High-school students	3.22	0.83
University students	3.32	0.70

An F-test indicated the equality of variances ($F(35, 41) = 1.41$, $p > 0.05$). According to an equal variance *t*-test, there was no significant difference between the groups ($t(76) = 0.57$, $p > 0.05$).

DISCUSSION AND CONCLUSIONS

The various research tools reveal that the systems thinking level of all participants, i.e. high-school, two-year college and university students, is moderate. These results correspond, in part, to reports based on other instruments [4][19]. The systems thinking score obtained in the achievement test (Table 5) was lower than that in the questionnaire (Table 4). This finding can be explained in view of the measuring bias that often exists in self-reporting tools. According to it, respondents tend to embellish their answers in order to *look good* in self-reporting instruments, even in anonymous questionnaires [20].

In the current study, no significant difference was found in systems thinking between 12th graders majoring in electrical engineering and sophomore or junior electrical engineering students. This may be due to the curriculum taught in the Department of Electrical Engineering involved that does not include dedicated activities for developing systems thinking. Therefore, in the absence of such tasks, systems thinking was not promoted.

It was also found that the systems thinking skills of two-year college students were significantly lower than that of their peers in high school and academia. This result may be due to the characteristics of students in these educational institutions. High-school students majoring in electrical engineering and electrical engineering students have, on average, higher cognitive abilities compared to electronics students in two-year colleges, most of whom belong to the socio-economic periphery [21].

This finding and the other results obtained in the study sharpen the need for the development and implementation of dedicated initiatives to promote systems thinking, such as expert lectures, computer simulations and project-based learning [13], especially among students in two-year colleges. In light of the positive correlation between systems thinking and abstract thinking [17], activities to advance abstract thinking (or computational thinking in general [22]) may also foster systems thinking.

The study had one main limitation: a relatively small number of participants. This was mainly due to the low number of two-year college students majoring in electronics in the year in which the study took place.

The theoretical contribution of the research is in the characterisation of systems thinking of engineering students at the secondary and post-secondary levels. In practice, the study conclusions may improve the training of students in various engineering programmes.

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BIOGRAPHY

Aharon Gero holds a BA in physics (*summa cum laude*), a BSc in electrical engineering (*cum laude*), an MSc in electrical engineering, and a PhD in theoretical physics, all from the Technion - Israel Institute of Technology, Haifa, Israel. In addition, he has an MBA (*cum laude*) from the University of Haifa, Israel. Dr Gero is an Assistant Professor in the Department of Education in Technology and Science at the Technion, where he heads the Electrical Engineering Education Research Group. Before joining the Technion, he was an instructor at the Israeli Air-Force Flight Academy. Dr Gero's research focuses on electrical engineering education and interdisciplinary education that combines physics with electronics, at both the high school and higher education levels. His research interests also include quantum optics and atomic physics. Dr Gero has received the Israeli Air-Force Flight Academy Award for Outstanding Instructor twice and the Technion's Award for Excellence in Teaching 16 times. He received the Israeli Air-Force Commander's Award for Excellence (2006), the Yanai Prize for Excellence in Academic Education (2016) and the Technion's Award for Continuing Excellence in Teaching (2022). Dr Gero is an Associate Editor of IEEE Transactions on Education.