IEEE Transactions on Education, Volume 63, Issue 1, 2019, pp. 10-16
DOI:10.1109/TE.2019.2926054

The Effectiveness of a Systems Engineering Course in Developing Systems Thinking

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***Abstract*—Contribution: An evaluation of the effectiveness of Systems Engineering (SE) courses in developing students' Systems Thinking (ST) capacity in both the cognitive and affective domains. A combined cognitive ST performance and affective engagement with ST assessment is proposed as an approach to assess students' ST in both domains. The results can support course change decisions and guide learning experience development.**

Background: SE education aims to produce graduates with strong knowledge and skills in SE and a strong appreciation of the practical value of ST, which addresses the cognitive and affective domains in education. Consequently, it is important to evaluate the effectiveness of SE courses in developing students' ST in these domains, an area that studies do not consider.

Intended Outcomes: An understanding of the ST ability of undergraduate students in an SE course in a domain specific engineering program in both the cognitive and affective domains.

Application Design: A study evaluated the effectiveness of two SE classes in developing students' ST capacity using a combined cognitive and affective assessment tool developed and validated in previous studies. ST assessment is determined by combining ST performance and affective engagement. To observe the transformation of students' ST capacity, a longitudinal design collected data at two times in each of two offerings of an SE course offered by the same university in two locations – Australia and Singapore.

Findings: The course developed students in most dimensions of cognitive ST, but did not appear to improve students' affective engagement with ST.

***Index Terms*—Affective domain, assessment tools, cognitive domain, student assessment, systems engineering, systems engineering education, systems thinking, undergraduate**

I. Introduction

Systems engineering (SE) is an engineering discipline that applies an interdisciplinary approach to realizing complex systems by ensuring that all stakeholders' needs are satisfied throughout the system life cycle. The term "SE" was first used by Bell Laboratories in the early 1940s, and the early applications of SE were during World War II to address the complexity raised by the war [1]. The first formal teaching on SE was in 1950 at MIT by G.W. Gilman, Director of SE at Bell Laboratories [1], [2]. This was followed by the publication of a number of textbooks and articles that identified SE as a distinct discipline [3]. The first journal to publish a special issue on SE and SE education, the *Institute of Radio Engineers (IRE) Transactions on Education*, provided general descriptions of SE programs and a set of technical issues confronting engineers at the system level [4], [5].

SE as a discipline has a specific focus on coherent whole systems by considering the whole product system, its performance in the context of intended use, and system lifecycle issues [6]. SE commonly deals with problems involving partial knowledge and conflicting objectives [3]. To deal with these characteristics, SE education needs to produce graduates with systems thinking (ST) capability, by demonstrating an holistic view and addressing systems element interactions to enable problem solving and justify decision making in SE processes [6]. ST refers to conceptual understanding or mental constructs of the system of interest [7], [8], and involves perceiving and conceptualizing processes that apply systemic rules. These rules include: questioning the system boundary, system structure and interrelationships; adopting multiple perspectives; considering dynamic characteristics; and applying wholeness and a "big picture view" in knowing and using various ST methods or tools.

Teaching and learning processes in a well-structured SE course could be effective in helping students to develop higher level ST skills [9]. One intended learning outcome (ILO) of SE education is that the graduate has strong knowledge and skills in ST to support their SE practice. The ILOs include a strong appreciation of the practical value of ST so that SE practice is characterized by thoughtful application of ST [10]. This additional dimension is the manifestation of the development of the student's engagement with ST, that is, a form of development as described by the Bloom group as the affective domain [11], [12]. By emphasizing the student's affective dimension, the intention is that the student's beliefs are transformed, so that the student becomes characterized by ST, and can fluently use the structured theories and methods in practice and as their default approach to engineering challenges. Consequently, the effectiveness of SE courses in developing students' ST needs to be evaluated by investigating students' ST development in both the cognitive and affective domains to understand their depth of learning.

Although some studies have assessed students' ST development in other disciplines in various educational grade

Manuscript received September 27, 2018; revised April 23, 2019; accepted June 9, 2019.

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levels, most are based only on the cognitive perspective [7], [8]. Furthermore, studies assessing ST in SE education are limited [7], [8], [13]. The absence of research on both students' ST development and affective domain development in SE education motivated this study, which evaluated the impact on developing students' ST capacity, in both the cognitive and affective domains in two classes in an undergraduate SE course. The empirical results can be used to support course change decisions and to guide learning experience development in a way that supports SE workforce development.

II. Method

A. Participants

The participants were students in two classes in an undergraduate SE course taught by an Australian university in 2014. The SE course, built upon the ideas of ST, was intended to develop students' understanding of systems in engineering contexts and introduce them to the design and development of engineered systems. This course showed how ST provides insights into tackling complex systems challenges, and understanding, designing and developing engineered systems.

Two independent classes were taught by different lecturers but with same objectives. Class 1 was delivered on-campus, and Class 2 was delivered off-shore for transnational students. Class 1 was taught in a standard mode over 13 weeks of the semester, with lectures and tutorial classes in Australia. Class 2 was ostensibly the same course, but offered in a one-week intensive teaching mode in Singapore over five four-hour sessions on consecutive evenings. Most students in this class worked full-time during the day prior to class. Assessment tasks were completed in the weeks after the intensive class sessions.

All students in these classes were invited and encouraged to participate in this study, which consisted of them giving permission to access their assignments and completing a questionnaire early in the course and at the end. Twenty-five students in Class 1 and 22 in Class 2 participated, representing 22% and 61% of the classes, respectively.

Participants in the study were limited to the subset of students in the class who completed consent documentation according to the requirements of University of South Australia ethics protocol 0000031508.

B. Research Design

Longitudinal design studies are suitable for evaluating the effectiveness of an SE course in developing students' ST because they collect data from the same sample at different times, so that continuity and change in the sample characteristics can be observed [14]. Longitudinal performance was investigated using a rubric to assess two student assignments; the first assignment (A1) and the last assignment (A2) of the semester were selected, presuming that these would indicate a transformation of students' performance through the course.

This study was constrained to use the assessment task products as the study materials because the authors could not change the course outline, method of teaching or assessment, due to the following considerations:

1. The ethical consideration that an experimental course change can only be offered if students have a free choice to study the experimental or non-experimental versions.
2. The practical impossibility of offering two parallel versions, and preventing 'leakage' of learning from students of one form to those of the other.
3. The required timeline for course modification demanding approval of changes to teaching or assessment in June of the calendar year preceding the date of delivery.
4. The consequential reduced number of students in each course type cohort, making it being unlikely that statistically significant differences would be observed.

These considerations led to the study being conducted in an observational design, as a first step towards experimental studies that could be justified if it yielded appropriate results. In Class 1, A1 was an individual assignment and A2 was a group assignment. In Class 2, A1 was a group assignment and A2 was an individual assignment. Given the constraints of the available course assessment materials, the rubric score of the group assessments was assumed to reflect individual performance. This assumption is commonly adopted by lecturers when assessing group tasks in which all students attain the same grade. A longitudinal survey was conducted using an attitude scale, administered near the beginning (Q1) and end (Q2) of the course to evaluate students' development of affective engagement with ST.

C. Materials

The most viable approach to assess students' ST in both the cognitive and affective domains was to combine a performance assessment with its rubric and an attitude scale test. A rubric is commonly used to analyze students' written assignments, to examine their cognitive domain performance [15], [16]. A self-report measurement is a suitable method to measure students' affect in education [17], [18]. Hence, here, to evaluate the effectiveness of an SE course in developing students' ST, a rubric was employed to score cognitive development in ST related tasks, and an attitude scale was applied to assess students' engagement with ST. The reliability and validity of the rubric and scale used in this study have been examined and reported in other papers [7], [13], [19].

One dimension of the cognitive ST development measurement rubric is derived from Biggs' Structure of the Observed Learning Outcome (SOLO) taxonomy [20]; the other is derived from the ST rules for understanding a system [13]. Based on Biggs' SOLO hierarchy, the rubric includes the increasing structural complexity of students' cognitive learning outcomes specified in four levels: pre-structural, uni-structural, multi-structural, and relational and extended abstract. The criteria for assessment, the second dimension of the rubric, were developed from the ST definition stated in Section I, based on an extensive ST literature review [21].

A scale to measure students' affective engagement with ST development was developed as a three-factor, 16-item scale with a mix of positively- and negatively-worded questions tested by the authors and demonstrated to be a suitable instrument to measure students' affective engagement with ST [7], [19], [21]. Items in the scale were developed based on a literature review on students' affective engagement with ST in SE, and on Frank's interest inventory for assessing Capacity for Engineering Systems Thinking [22]. The questionnaire uses a seven-point Likert scale for each item. The scale reflected theoretical, methodological and practical aspects of ST [8], [19].

The internal consistency to support the reliability of the scale was calculated using Cronbach's alpha coefficient, which was also used to validate rubric intra-rater reliability by having the same person assess students' assignments on two occasions.

D. *Statistical Methods*

Prior to analyzing the questionnaire data, a Missing Values Analysis (MVA) was made to check for the missing completely at random (MCAR) assumption [23]. Should missing data be classified as MCAR, remedies such as replacement of missing data can be employed, since there is no potential bias in the pattern of missing data [24].

Descriptive statistics were used to summarize and display the data to present students' scores in both parts of the work. Normality tests were applied to determine whether the distribution was normal, which in turn justifies applying either parametric or non-parametric inferential statistical tests to determine whether significant improvement occurs between the two measurement events. To determine whether a score improves significantly during a semester, a dependent T-test was used as parametric inferential statistical tests and the Wilcoxon Signed Ranked test was used as a non-parametric inferential statistical test. To compare students' scores between Class 1 and Class 2, an independent T-test was used where parametric tests were suitable; the Mann-Whitney U test was used where non-parametric tests were needed.

III. RESULTS

A. *Class 1*

1) *Participants*

The 25 participants in Class 1 were fewer than a quarter of the 112 enrolled students. Of these participants, 84% were male and 16% female. Around 12% were part-time students, and the rest were full-time. Twenty-eight percent worked part-time, 8% full-time and the rest were not working. The average age was 26 years. They gave their permission to access their first and last assignments (A1 and A2) during a semester and completed the questionnaire at the beginning (Q1) and end of the course (Q2).

2) *Rubric Result*

In the first assignment (A1) students individually wrote an analysis of the impact of the fundamental inputs to capability (FICs) for a mobile tactical air defense system (MTADS) to support preliminary work on acquisition process plans a new MTADS for the Australian Defence Force (ADF). The FICs are: "organization, personnel, collective training, major systems, supplies, facilities, support and command structure" [25], indicating that this task is directing students to perform a fundamentally broad systemic analysis of the proposed system, thus pointing them in a direction which makes it appropriate to evaluate their demonstration of ST. In the last assignment (A2), together with their group members, students prepared documents describing the preliminary function, performance specifications, and operational and test concepts for the MTADS.

Descriptive statistics of students' cognitive ability in ST scores, Table I, include the results of the Shapiro-Wilk normality test, which indicates that most of the distributions are not normal ($Sig < 0.05$) and thus non-parametric tests must be used for analysis. Table I also includes Cronbach's alpha intra-rater reliability values based on scoring of assignments twice. One of these values is less than, but close to, 0.7, which was accepted as indicating sufficient intra-rater consistency.

The Wilcoxon Signed Ranked Test, a non-parametric test for repeated measures that is an alternative to the parametric T-test, was used to test significant improvement in these six aspects of cognitive ST and in the overall score of students' cognitive performance between A1 and A2 [26]. The tests revealed statistically significant improvement in most ST aspects ($n = 25$) and in overall cognitive ST performance, except for the category of systems boundary, Table II.

TABLE I
CLASS 1 STUDENTS' COGNITIVE SYSTEMS THINKING ASPECT MEASURES AT A1 AND A2

Factor	A1 Measurement								A2 Measurement							
	Min	Max	Mean	SD	Skew-ness	Kurto-sis	α	Shapiro-Wilk Sig.	Min	Max	Mean	SD	Skew-ness	Kurto-sis	α	Shapiro-Wilk Sig.
Systems boundary	1.00	3.00	1.800	0.595	-0.097	-0.882	0.748	0.003	1.00	3.50	1.980	0.699	0.772	1.199	0.944	0.000
Structure and interrelationships	1.00	2.50	1.740	0.459	-0.813	-0.751	0.656	0.000	2.00	3.00	2.500	0.433	0.000	-1.702	0.720	0.000
Multiple perspectives	0.00	2.00	1.440	0.546	-0.578	-0.012	0.860	0.000	2.00	3.00	2.720	0.410	-1.021	-0.673	0.792	0.000
Dynamic characteristics	0.00	2.00	.600	0.577	0.459	-0.501	0.880	0.001	2.00	3.00	2.680	0.405	-0.782	-0.988	0.711	0.000
Wholeness and big picture thinking	0.00	2.00	1.400	0.595	-0.548	-0.575	0.842	0.001	2.00	3.50	2.940	0.486	-0.633	-0.354	0.728	0.002
Systems thinking tools	0.00	2.00	.100	0.408	4.593	21.750	0.940	0.000	2.00	3.00	2.640	0.468	-0.619	-1.638	0.913	0.000

TABLE II
WILCOXON SIGNED RANK TESTS RESULTS FOR THE SIX COGNITIVE SYSTEMS THINKING ASPECTS IN A1 AND A2 CLASS 1

Factor	Median (A1)	Median (A2)	*Z*	*p*
Systems boundary	2.000	2.000	-0.697	0.486
Structure and interrelationships	2.000	2.500	-3.654	0.000
Multiple perspectives	1.500	3.000	-3.963	0.000
Dynamic characteristics	0.500	3.000	-4.310	0.000
Wholeness and big picture thinking	1.500	3.000	-4.303	0.000
Systems thinking tools	0.000	3.000	-4.403	0.000

3) Questionnaire Result

Missing data analysis was conducted by examining the pattern of the missing data and remedying that missing data. No data was missing in the Q1 dataset, but some was missing in the Q2 dataset. However, no significant difference was found ($\chi^2 = 31.696$, $df = 29$, $p = 0.333$), so the missing data is classified as MCAR and missing values were addressed by substituting the mean value of the variable based on all valid responses. Thus, three missing values were replaced in a matrix of 25 x 16 (= 400) data items or 0.75% of the total dataset. In the Q2 set, the missing data was also classified as MCAR ($\chi^2 = 14.206$, $df = 15$, $p = 0.510$). Thus, one missing value was replaced in a matrix 25 x 16 (= 400) data items or 0.25% of the total dataset. The Cronbach's alpha obtained was 0.815 in Q1 and 0.793 in Q2, both indicating very good internal consistency [27].

Descriptive statistics of students' affective engagement with ST score and normality test results are provided in Table III. To examine any significant differences between these three factors and the overall score, a dependent T-test was conducted. For these three factors, the test for students' preference for ST theories revealed a significant decline from the beginning ($M = 5.1$, $SD = 0.913$) to the end ($M = 4.7$, $SD = 0.950$) of the course; $t\,(24) = 2.124$; $p = 0.04$.

For students' interest in ST methodologies there was no significant difference between the beginning ($M = 5.2$, $SD = 0.663$) and the end ($M = 5.2$, $SD = 0.563$) of the course; $t\,(24) = 0.636$; $p = 0.531$. Although students' inclination toward ST practice increased slightly, the difference was not significant between the beginning ($M = 4.9$, $SD = 0.780$) and end ($M = 5.1$, $SD = 0.634$) of the course; $t\,(24) = -1.004$; $p = 0.325$. These findings suggest that although the course succeeded in improving the students' cognitive performance in ST, it was unsuccessful in improving students' affective engagement with ST in Class 1.

B. Class 2

1) Participants

More than half of the Class 2 enrolled students (22 of the 36 students) gave permission for the researchers to access their first and last assignments (A1 and A2) during a semester and completed the questionnaire at the beginning (Q1) and at the end of the course (Q2). All of these participants were male part-time students and full-time workers. The average age of these participants was 31 years.

2) Rubric Result

For the first assignment (A1), a group assignment, students wrote an outline system design proposal based on SE principles and processes taught in the course. In the last assignment (A2) students individually wrote a complete conceptual design report using SE principles and processes, which would complete the project outlined in A1.

Descriptive statistics of the students' cognitive ability in ST score are provided in Table IV. The Shapiro-Wilk normality test indicates that most of the distributions are not normal ($Sig < 0.05$), indicating non-parametric tests must be used for analysis. Table IV also includes Cronbach's intra-rater reliability values which were calculated based on double scoring of assignments A1 and A2. All these values are above 0.7, which indicates sufficient intra-rater consistency.

The Wilcoxon Signed Ranked Test was used to determine whether significant improvement occurred in the six cognitive aspects of ST between A1 and A2 [26]. The tests revealed a statistically significant improvement in all six ST aspects ($n = 22$), see Table V.

TABLE III
CLASS 1 STUDENTS' ENGAGEMENT WITH THE SYSTEMS THINKING DIMENSIONS AT Q1 AND Q2

Factor	Q1 Measurement							Q2 Measurement						
	Min	Max	Mean	SD	Skewness	Kurtosis	Shapiro-Wilk Sig.	Min	Max	Mean	SD	Skewness	Kurtosis	Shapiro-Wilk Sig.
Students' preference for systems thinking theories	2.67	6.50	5.1067	0.91399	-0.717	0.808	0.265	2.00	6.17	4.6831	0.95088	-0.982	1.415	0.122
Students interest in systems thinking methodologies	4.20	6.60	5.2394	0.66297	0.289	-0.332	0.373	4.20	6.20	5.1600	0.56273	0.271	-0.822	0.286
Students inclination toward systems thinking practice	3.60	6.20	4.9180	0.78034	0.134	-1.088	0.336	3.80	6.00	5.0560	0.63382	-0.108	-0.639	0.273

TABLE IV
CLASS 2 STUDENTS' COGNITIVE SYSTEMS THINKING ASPECT MEASURES AT A1 AND A2

Factor	A1 Measurement								A2 Measurement							
	Min	Max	Mean	SD	Skew-ness	Kurto-sis	α	Shapiro-Wilk Sig.	Min	Max	Mean	SD	Skew-ness	Kurto-sis	α	Shapiro-Wilk Sig.
Systems boundary	0.0	3.0	1.1	0.967	0.570	-0.642	0.925	0.021	1.00	4.00	2.205	0.734	1.088	1.00	0.851	0.004
Structure and interrelationships	0.0	2.5	1.1	0.774	-0.164	-0.901	0.924	0.018	1.50	4.00	2.432	0.904	0.809	1.50	0.928	0.001
Multiple perspectives	0.0	2.5	0.9	0.653	1.026	2.118	0.872	0.000	.50	4.00	2.227	1.110	0.138	0.50	0.930	0.218
Dynamic characteristics	0.0	2.0	0.8	0.481	0.035	0.953	0.804	0.000	0.00	4.00	1.705	1.306	0.774	0.00	0.924	0.005
Wholeness and big picture thinking	1.0	2.0	1.4	0.434	0.485	-1.532	0.946	0.000	.50	4.00	2.409	0.934	-0.240	0.50	0.839	0.119
Systems thinking tools	0.0	2.0	1.4	0.754	-1.037	-0.306	0.940	0.000	1.00	3.00	1.909	0.570	-0.460	1.00	0.880	0.001

TABLE V
WILCOXON SIGNED RANK TESTS RESULTS FOR THE SIX COGNITIVE SYSTEMS THINKING ASPECTS IN A1 AND A2 CLASS 2

Factor	Median (A1)	Median (A2)	Z	p
Systems boundary	1.0	2.0	-3.553	0.000
Structure and interrelationships	1.0	2.0	-3.852	0.000
Multiple perspectives	1.0	2.0	-4.016	0.000
Dynamic characteristics	1.0	1.3	-3.255	0.001
Wholeness and big picture thinking	1.3	2.3	-3.889	0.000
Systems thinking tools	1.5	2.0	-2.553	0.011

3) *Questionnaire Result*

No data was missing in the Q1 set, but some was missing in the Q2 set. The missing data is classified as MCAR ($\chi^2 = 20.444$, $df = 15$, $p = 0.156$), so missing data were substituted by the mean value of that variable. This resulted in replacing one missing value in a matrix 22 x 16 (= 352) or 0.28% of the total dataset. The Cronbach's alpha obtained in Q1 was 0.827 and in Q2 0.848. Both indicate good internal consistency [27].

Descriptive statistics of students' affective engagement with ST score and normality test results are provided in Table VI.

To examine whether significant differences are found in these three factors a parametric dependent T-test was conducted. The test revealed that although the scores declined slightly, there is no significant difference between the beginning of the course ($M = 4.4$, $SD = 1.168$) and the end ($M = 4.1$, $SD = 1.304$); $t\,(21) = 0.984$; $p = 0.337$ for students' preference for ST theories. There is no significant difference between the beginning of the course ($M = 5.5$, $SD = 0.682$) and the end ($M = 5.4$, $SD = 0.890$); $t\,(21) = 0.435$; $p = 0.668$ for students' interest in ST methodologies. There is no significant difference between the beginning of the course ($M = 5.5$, $SD = 0.644$) and the end ($M = 5.5$, $SD = 0.702$); $t\,(21) = 0.342$; $p = 0.736$ for students' inclination toward ST practice.

This finding suggests that, like Class 1, although the course succeeded in improving students' cognitive ability in ST, the course was unsuccessful in improving the three aspects of students' affective engagement with ST: students' preference for ST theories; students' interest in ST methodologies and students inclination towards ST practice.

IV. DISCUSSION AND CONCLUSION

This paper reports the application of a combined performance assessment using a rubric and a self-report test of student attitude to assess students' ST in two classes of an undergraduate SE course. These methods were used to test the effectiveness of an SE course in developing students' ST in relation to cognitive domain competencies and affective domain engagement with ST perspectives.

TABLE VI
CLASS 2 STUDENTS' ENGAGEMENT WITH THE SYSTEMS THINKING DIMENSIONS AT Q1 AND Q2 CASE STUDY 2

Factor	Q1 Measurement							Q2 Measurement						
	Min	Max	Mean	SD	Skewness	Kurtosis	Shapiro-Wilk Sig.	Min	Max	Mean	SD	Skewness	Kurtosis	Shapiro-Wilk Sig.
Students' preference for systems thinking theories	2.00	6.17	4.439	1.168	-0.136	-0.724	0.427	2.00	6.00	4.129	1.304	-0.262	-0.934	0.116
Students interest in systems thinking methodologies	4.20	7.00	5.455	0.682	-0.066	0.036	0.149	4.00	7.00	5.377	0.890	-0.063	-0.985	0.167
Students inclination towards systems thinking practice	4.40	6.60	5.509	0.644	-0.056	-0.823	0.527	4.00	6.60	5.464	0.702	-0.422	-0.477	0.622

A longitudinal study design which used data of both types collected from both early and late in a one-semester course was used to compare the two measures to determine what changes occurred in the students. The study was observational because, for the reasons stated in Section II, an intervention-based study was not possible.

A rubric was used to interrogate the assessment materials submitted by students to provide evidence of their ST performance and a self-report questionnaire using a Likert scale was used to measure the students' engagement with the subject matter.

This study confirmed that in the cognitive domain, students' performance in ST at the beginning of the course was at low and moderate levels, and increased to moderate to high performance at the end of the course. In the affective domain, however, although students valued ST in their everyday activities as developing engineers, no significant improvement in performance was found through the course.

Traditionally, teaching and learning in higher education, especially engineering education, focused on the acquisition of knowledge, which led engineering to be regarded as an object- rather than people-oriented field [28], [29]. Current engineering education has overlooked the affective domain [28], although studies in other fields have shown its importance as an essential learning condition, 'a catalyst', to facilitate cognitive processes and cognitive success [30].

This study's finding, of significant improvement of cognitive performance not accompanied by a significant increase in the affective domain, can also be caused by the students' approach to learning. Students can show a transformation in ST cognitive performance without demonstrating transformation in their affective engagement through the course if they adopt a surface or procedural approach to learning, where their intention is to gain sufficient knowledge to successfully complete the assessment tasks, as opposed to developing deep interest and commitment to the topic [31]. By contrast, it is believed that students' interest in the subject matter can determine their choice of learning approach. The affective dimension of learning can foster a deep approach to learning that can improve students' performance because of the improved understanding arising from deep engagement with the course content [31], [32]. This forms a positive feedback loop, where the affective dimension of learning may lead to adoption of a deep approach to learning that reinforces student affective engagement with the subject matter. Therefore it is important to design an effective teaching and learning environment that stimulates a deep learning approach for affective and cognitive development.

The affective domain is concerned with transforming the student to become characterized by their belief in, and the high value they put on, the material they have learned. However, the true value of SE education, in particular, lies in the fluent and intuitive application of the SE principles, concepts and methods in scenarios, even under pressures such as project timelines, budget constraints or company culture [10]. Therefore, augmenting the usual focus on the students' cognitive development with their affective development, through generating an intuitive appreciation of the value of the SE methods and theory, SE educators can enhance student potential to incorporate learning content into their professional belief and value systems, and subsequently into their practice [10]. SE educators need to include affective engagement with SE content as a vital aspect of learning that content. Affective engagement needs to be developed during courses so that students develop the fluent, natural and preferred application of the SE methods and theory in engineering work.

These findings are not surprising, since the study was observational, making no change to the original learning objectives, course outline, method of teaching and assessment. No intervention treatment or experiment was performed to promote affective domain development. Therefore finding an absence of affective development through the course is unsurprising, because no action was taken with the specific intention of developing students' affective engagement with ST. Furthermore, a single-semester course is a short interval for such a change to occur without a specific stimulus.

The findings are consistent with evidence from research in higher education and engineering education that supports the view that teaching and assessment in undergraduate SE education focuses on developing students in the cognitive rather than affective domain [28], [33]–[34]. This necessity implies that an integrated cognitive–affective teaching framework is needed; the present study has shown that this is not achieved in a particular example of a traditionally developed SE course, and by reasonable extension, probably is not developed effectively in other similar courses. Generic development of the affective domain relating to SE competencies, including outcome descriptors and potential assessment tools, is presented in the *Graduate Reference Curriculum for Systems Engineering (GRCSE)* for Master's qualifications [4]. The equivalent has not yet been incorporated into undergraduate SE education curricula. Further study is important for developing an integrated cognitive–affective teaching and learning framework in undergraduate SE education to guide undergraduate SE educators. To support this framework, development experimental research that proposes, applies and evaluates an integrated cognitive-affective learning approach with an appropriate control using traditional method can be conducted, as recommended by Lashari *et al*. [35].

Sample learning objectives that integrate cognitive and affective domains in learning ST in SE education that could be used in this experimental study, are that students should be able to:

- Discuss and demonstrate belief in the value of ST in contributing in the SE field;
- Discuss and demonstrate belief in the value of ST theories and methodologies for improving SE work;
- Use and demonstrate preference for the use of a range of ST-originated theories and methodologies in an SE environment.

A project-based learning approach is considered an appropriate teaching and learning approach to enable students' experiential learning and to provide the motivational context that builds affective learning. This position is supported by the finding of a previous study [8] that showed an experiential learning environment supports the development of students' engagement with ST practice, the affective domain. With a project-based learning approach, over a semester students can assume the role of a systems engineer and become involved in the development of a complex systems project, for example the design of a five-star hotel, a water desalination plant, or an amusement or theme park. These are good projects in SE education because they involve many stakeholders, and affect the community and environment. The complex project must be started right at the beginning of the semester; students' involvement throughout the semester is expected to increase their engagement with the project and improve affective engagement with the course [21].

A series of workshops, each to perform specific ST tasks for the project, can be held as part of the course to guide students through the project. Several techniques for promoting affective learning in engineering education, recommended by Alias *et al*. [28], can be implemented during the workshops. These include question and answer sessions, a motivational talk or video, positive reinforcement such as rewarding remarks, to motivate continuous effort in learning, and student-teacher interaction that promotes empathy, modelling, peer learning, and group processing [28], [35].

Assessment methods that integrate cognitive and affective learning approaches include formative assessment such as Q&A, group presentation and reflective writing. Summative assessments can include a project report that requires an analysis of the usefulness of ST theories and methods in their project, or an assignment that requires students to analyze the impact of ST on their project as methods for improving their own practice [4]. Well-designed experiments with a teaching and learning environment that stimulates a deep learning approach for affective and cognitive development can support the development of an integrated cognitive–affective teaching and learning framework in undergraduate SE education, to guide undergraduate SE educators.

The findings also suggest the on-campus class delivered in a semester-long face-to-face mode with lectures and tutorial classes developed higher cognitive performance in ST than did the class delivered in an intensive teaching mode with five four-hour sessions on consecutive evenings. However, more research is needed to identify whether the different teaching method was the cause of the differences in students' cognitive performance in ST. Such further research would also need to consider others factors (including the lecturer's ability, style, and methods, and students' educational background, learning styles, and national and cultural background) in the development of students' cognitive and affective performance during an SE course.

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The effectiveness of a systems engineering course in developing systems thinking

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2019-07-12

Camelia F, Ferris TLJ, Behrend MB., (2019) The effectiveness of a systems engineering course in developing systems thinking. IEEE Transactions on Education, Volume 63, Issue 1, 2019, pp. 10-16

https://doi.org/10.1109/TE.2019.2926054