International Journal of Engineering Education Vol. 35, No. 1(A), pp. 59–75, 2019
Printed in Great Britain
0949-149X/91 $3.00+0.00

Effective Assessment of Student Outcomes in Computer Engineering Programs using a Minimalistic Framework*

ISSAM DAMAJ and JIBRAN YOUSAFZAI
Department of Electrical and Computer Engineering, American University of Kuwait, Salmiya, Kuwait.
E-mail: idamaj@auk.edu.kw, jyousafzai@auk.edu.kw

Effective frameworks for the assessment of student outcomes are vital to the success of a technical higher-education program. While ensuring the accuracy of the student outcomes assessment usually translates to employing complicated setups, thoughtful abstraction can lead to the desired reliability of assessment with great simplicity. In this paper, a minimalistic framework for the assessment of student outcomes is proposed. The proposed framework is based on senior design experiences of undergraduate computer engineering students. Senior design experiences provide unique opportunities for students to demonstrate their abilities, skills, and experiences that are attained throughout a Bachelor of Engineering program. The proposed framework is based on capstone design projects and a selection of senior design courses of complementary nature. The learning outcomes of the proposed selection of courses are carefully designed to map to all student outcomes. The proposed minimalistic assessment framework leads to results that are only marginally different from those based on a large bouquet of courses ranging from sophomore to senior years of study and thus demonstrates its reliability. The effectiveness of the proposed framework is supported by evaluative and comparative statistical analysis of student outcomes assessments within a multi-year case-study.

Keywords: capstone design projects; senior courses; embedded system design; signal processing; assessment; programmatic accreditation

1. Introduction

Assuring quality of education is essential for the advancement of the engineering profession. To ensure quality education, engineering programs seek national and international accreditations from relevant accreditation agencies [1–7]. ABET, a non-profit and non-governmental accreditation agency for academic programs in technical education, has provided an initial set of eleven student outcomes (SOs) labelled (a) through (k) for computer engineering programs [2] (See Appendix A). SOs are statements that describe the attributes, skills and abilities that students should have acquired by the time of graduation. Student outcomes assessment is the key point of discussion in the programmatic accreditation process.

Accurate and thorough assessment of student outcomes requires data collection from a broad spectrum of relevant core courses that computer engineering students undertake throughout their undergraduate training [3–7]. Assessment data, therefore, is usually obtained from a bouquet of courses that range from the introductory core courses that are offered during the sophomore or junior year of study, to the senior year courses including the capstone design project. While conclusions based on assessment data obtained from such a broad range of courses are accurate and can also provide insights into the progression and evolution of the academic program, the assessment process itself is time-consuming and complicated. Furthermore, curricular changes and the cultivation of a culture of assessment can prove to be major hurdles for a process of such a wide scope [3–6, 8]. To this end, a minimalistic assessment approach that does not compromise the accuracy of the assessment results is worth investigation.

Previous studies have highlighted the unique role of capstone design projects (CDPs) in developing students' technical skills [9–11] as well as in the assessment of the ABET SOs [12, 13]. In a CDP course, students apply all the knowledge and skills they have acquired throughout their undergraduate studies. Furthermore, a CDP offers a large span of learning outcomes that can map to all ABET student outcomes at the program level. Various works on good practices and methodologies for management and assessment of capstone design courses exist in the literature [9–17]. In our previous work [13], we presented an approach for unified assessment of capstone projects and ABET student outcomes through student performance in the capstone design projects. Furthermore, the presented work addressed various challenges ranging from non-uniformities related to the varied nature of the projects, to the inconsistencies in project evaluation arising from various sources. In another study [12], the capstone course was used as a tool for curriculum modifications and improvements as well as the ABET accreditation process.

In addition to CDPs, senior design courses in engineering hold great significance in the assessment of student outcomes [18–21]. Senior design courses

* Accepted 30 August 2018.

in computer engineering, such as, microprocessors, microcontrollers and interfacing, embedded systems design, signal processing, etc. can be developed not only to provide a thorough preparation towards CDPs, but also to provide a comprehensive list of course learning outcomes (CLOs) that map to many or even all SOs. In fact, senior design courses serve as the major vehicle to inculcate the skills required by employers and by accreditation bodies, such as ABET. Furthermore, given that the SOs define the skills and abilities that students acquire by the end of their undergraduate training, senior design experiences of the students should be the focal point of an accurate and effective SOs assessment strategy.

In this paper, a minimalistic framework for SOs assessment based on a linear combination of senior design courses and the capstone design project is proposed. Results obtained from such a combination are not only more reliable than those obtained from a single source, such as in [12, 13, 22], but can also iron out any inconsistencies arising from limited data. The paper follows the general methodology of developing a robust and thorough capstone design project (CDP) course setup and two concrete and complementary senior design courses to provide assessment triangulation and guarantee an all-outcomes coverage. For the presented multi-year study, two senior design courses of complementary nature, namely, Embedded System Design (ESD) and Signal Processing (SP) are considered in combination with the CDP. These courses are carefully developed to strengthen the design, analysis and mathematical skills of the students and to serve as the culmination of different tracks of study within the computer engineering program.

The proposed minimalistic framework provides a simple and accurate assessment of SOs. The simplicity comes from the limited set of courses where the assessment tools are deployed. The accuracy is demonstrated through statistical analysis of a two-year case-study. Finally, a comparative statistical analysis among the three sources of measurements in the context of SO assessment is performed. Our results show that the assessment scores of the senior design courses (ESD and SP) and the CDP justify a combination of the three measurements for accurate and reliable assessment.

This paper is organized as follows: Section II presents the proposed measurement framework with its CDP, ESD and SP dimensions. Section III presents the measurement components of the proposed framework. Evaluation and analysis of the case-study are presented in Section IV. Finally, Section V presents conclusions and an outlook towards future work.

2. The assessment framework

2.1 Closely related work

Yousafzai et al. in [13] presented the development and testing of the CDP tool which is adopted in the current investigation. The results in [13] were focused on the calibration of the tool within a pilot study that included a single group of 43 students during a single CDP setup. Another pilot study based on the same group of students was reported by Damaj et al. in [22]. The work in [22] studied the correlation between the SO assessment scores in CPDs, an ESD course, and a combination of both. The conclusion stressed the need of combining attainments from multiple sources rather than relying on one.

he current investigation makes several contributions over the work reported in [13, 22]. The validation of the proposed framework provides a multi-year study that critically examines the use of the tool presented in [13]. In addition, the proposed framework adopts a further combination with a course on SP to strengthen the triangulation and enhance the expected accuracy of results as compared with [22]. The current investigation presents a multi-year assessment framework based on accurate findings from a set of multiple core courses as compared to only CDPs in [13], and an ESD course and CDPs in [22]. Moreover, the investigation provides a statistical analysis framework with added accuracy that employs the differences in scores and the root mean square of differences and is not only based on correlations as in [22]. The reported comparisons rely on the multi-level core courses (MCC) scores reported in [4] to serve as accurate baseline references.

2.2 Capstone Design Project

In the proposed assessment framework, CDPs are selected as one of the main components of the minimalistic set of sources of measurements. The CDP setup, assessment, and evaluation follows the structure and criteria of the tool presented in [13]. As per the adopted setup, CDPs are scheduled over a period of two regular semesters. The pre-requisite for the CDP is a senior design experience provided in the courses on Microprocessors, Microcontrollers and Interfacing, and Embedded System Design. The pre-requisite courses are equipped with extensive practical laboratory components. The following assessment tools are used to assess the CDPs and the performance of each student:

- CDP proposal (beginning of Semester I).
- Periodic meetings with the CDP supervisor.
- Progress reports (middle of Semesters I and II).
- Oral examination of individual students by the supervisor (end of Semesters I and II).

Table 1. The developed criteria, key indicators, and weights per criterion and indicator [13]

A. **Content**
(Total %55, Supervisor %35 and Examination Committee %20)

1. Literature review: summarizes, compares and evaluates various concepts, research findings and current theories and models in core content areas of computer and electrical engineering (10%)
2. Identify engineering principles and techniques that are relevant to the project and apply them within specific problem domain (5%)
3. Novelty and the adequacy of the design approach (10%)
4. Alternative designs (10%)
5. Identification, mastering, and use of hardware/software tools (5%)
6. Robustness of conducting, analyzing, testing and interpreting experimental results (5%)
7. Further improvements (10%)

B. Integrity, values, and impact of engineering solutions
(%5, Supervisor and Examination Committee Members)

1. Clear understanding of and adherence to scientific and professional ethics (2%)
2. Aware of the impact of engineering solutions in a global, economic, environmental, and/or societal context (1%)
3. Evaluate engineering solutions that consider global, economic, environmental, and/or societal factors (2%)

C. Project Management and Teamwork skills
(%10, Supervisor)

1. Work individually, or as part of team where appropriate, to formulate, analyze, design, and implement a significant engineering project (3%)
2. Contribution to the team project/work (3%)
3. Taking responsibility (4%)

D. Written Communication
(%10, Supervisor and Examination Committee Members)

1. Organization and logic (4%)
2. Writing style (word choice, grammar and sentence structure) (4%)
3. Use of References (2%)

E. Presentation and Oral Communication
(%20, Supervisor and Examination Committee Members)

1. Mechanics (4%)
2. Organization (4%)
3. Delivery (4%)
4. Relating to audience (4%)
5. Response to questions (4%)

- An essay related to integrity, values, and impact of engineering solutions (end of Semester II).
- CDP presentation, demonstration, and committee exam.

The assessment of CDPs is based upon the following criteria:

(A) Content.
(B) Integrity, values, and impact of engineering solutions.
(C) Project management and teamwork skills.
(D) Written communication.
(E) Presentation and oral communication.

The criteria, key indicators, and percentage weight assignments are shown in Table 1 and Table 2 shows the mapping among of the CDP evaluation criteria and ABET SOs (a) through (k). As the mappings are many-to-many; a weighted calculation is used to quantify the assessment for SOs. The assessment tool, including the complete set of analytic rubrics, is presented in detail in [13]. Criterion "A" is the most significant part of the assessment and covers the content of the project. The weight of Criterion "A" is 55% of the overall CDP evaluation. The criterion measures the quality of the literature review, the engineering principles and the techniques applied in the project, the adequacy of the design approach, the use of hardware/software tools, analysis and robustness of the results, and opportunities for further improvement. Criterion "A" is built upon the seven key indicators

Table 2. Mapping among CDP evaluation criteria and ABET SOs (a) through (k) [13]

Student Outcomes	CDP Indicator
a	A2
b	A5, A6, A7
c	A3, A4, A7
d	C1, C2, C3
e	A1, A2, A4
f	B1
g	D1, D2, D3, E1, E2, E3, E4, E5
h	B2, B3
i	A2, A5
j	A1, A2
k	A2, A5, A6

as shown in Table 1. The remaining criteria look at a variety of CDP aspects including the clear understanding of and adherence to scientific and professional ethics, evaluating engineering solutions that consider global, economic, environmental, and/or societal factors, project management, documentation, demonstration and presentation, etc. The developed indicators and the weights for all criteria and indicators are shown in Table 1. The CDP is evaluated at the end of Semesters I and II.

2.3 Senior courses with major design experience: the case of embedded systems

Embedded System Design (ESD) is a common course in computer engineering programs. ESD [18–21] course can be prepared to enable a wide range of student abilities demonstrated through a rich set of Course Learning Outcomes (CLOs) that map to all SOs [22]. The proposed ESD course has nine CLOs, adopts [23] as the textbook, comprises two additional chapters [24, 25] and follows the project development methodology of [26]. The CLOs of the ESD course map to ABET SOs with three levels of emphasis (See Table 3). An SO mapping emphasis is either high (H), medium (M), or low (L); the emphasis depends on the extent of coverage of a CLO in the course material in relation to an SO. For a typical ESD course, with computer organization and architecture as a pre-requisite, the following set of CLOs is adopted:

(1) Demonstrate understanding of what are embedded systems.
(2) Demonstrate understanding of embedded system design challenges.
(3) Identify the adequate use of different embedded systems.
(4) Identify the adequate implementation technology of embedded systems.
(5) Design and implement single-purpose processors.
(6) Design and implement application-specific instruction set processors.
(7) Use different memory arrangements in embedded systems.
(8) Interface FPGA boards with different peripherals.
(9) Write VHDL programs with advanced features.

2.4 Senior courses with emphasis on mathematical formulation and analysis: the case of signal processing

In contrast to the Embedded Systems Design course, an undergraduate course in Signal Processing (SP) is rich is mathematical formulation and analysis of complex processes [27]. The concepts and techniques that form the core of the signal processing course are of fundamental importance in computer and electrical engineering disciplines and key application areas such as telecommunication and multimedia [28,29]. For the SP course, a set of seven CLOs is adopted. The CLOs map to ABET SOs as shown in Table 4. The proposed course adopts [28, 29] respectively as the textbook and

Table 3. The mapping of the ESD CLOs (1 through 9) to the SOs (a through k) with the level of emphasis

	a	b	c	d	e	f	g	h	i	j	k
1	M							L		L	
2	H	M	L		M	M		M			
3	H	M	L		M						
4		M	L		M						
5	H	H	H	H	H	H	H	H	H	H	H
6	M	H	H		H				H		H
7	L	H	H		H				H		H
8	L	M	L		M					L	
9	M	H	H		H				H		H

Table 4. The mapping of the SP CLOs (1 through 7) to the SOs (a through k) with the level of emphasis

	a	b	c	d	e	f	g	h	i	j	k
1	H	M	H	L	H						
2	H	M	M	L	H						
3	H	M	H	L	H						H
4	H	M	H	L	H						H
5	H	M	H	L	H						H
6	M	H	M	M	H						H
7	M	M	H	M	M			M	M	M	M

reference. For a signal processing course, with either linear circuits or differential equations as a pre-requisite, the following set of CLOs is proposed:

(1) Demonstrate understanding of the fundamentals of signals and systems.
(2) Apply frequency domain transform methods to different signals and systems.
(3) Design frequency-selective filters.
(4) Demonstrate understanding of sampling of continuous-time signals.
(5) Realize FIR and IIR discrete-time systems.
(6) Design and implement software simulations of signal processing systems in MATLAB.
(7) Identify and investigate key application areas of digital signal processing.

3. Research objectives and methodology

This paper is based on the concept that a carefully designed minimalistic set of corner-stone courses, such as, CDPs and senior design courses can lead to accurate assessment results with an added-value of simplicity. The success of deploying the proposed framework is totally reliant on developing a thorough and reliable CDP setup as in [13]. Two additional senior design courses with complementary characteristics need to be well-developed to join the CDP course in providing a complete framework for the assessment of SOs.

This investigation studies the validity and the reliability of a minimalistic approach for assessment of SOs without compromising the accuracy of the results. Two strategies for the assessment of SOs are compared. One strategy relies on an extended set of MCCs scores. The selected set of MCCs range from sophomore to senior year courses, and it is used as the reference measurement for comparison. The second strategy adopts a minimized set of senior courses. However, the question remains as to the type and number of adopted courses so that the accuracy of results is maintained. For the second strategy, three sources of assessment results of SOs are studied. The three sources are CDPs, and senior courses on ESD and SP. The study comprises careful, well-rounded, and incremental integrations of the three sources that obtain results with an accuracy comparable to that of the MCCs set. The incremental integration is based on paired characteristics of the adopted courses and not based on trial and error. Initially, the results based on MCCs is compared to CDPs. Then, the results from the ESD course are integrated with those of CDPs; and finally, the results from the SP course are carefully added. The adopted courses or rich learning outcomes that are complementary in covering SOs. The study investigates and criticizes the potential sole use of CDPs or senior design courses in assessing SOs. The proposed minimalistic approach stresses the need for triangulation of attainment scores based on complementary course characteristics.

The proposed minimalistic framework provides a simple and accurate assessment of SOs. The simplicity comes from the limited set of courses where the assessment tools are deployed. The accuracy is demonstrated through statistical analysis of a two-year case-study. The study is carried out over two full assessment cycles, where each cycle is a single academic year. The targeted academic years were the 2013–2014 and 2014–2015.

4. Measurements

4.1 CDP measurement tool

For the CDP assessment and evaluation, the adopted tool enables the calculation of the attainment scores of SOs for each student based on their scores in the indicators (See Table 1) [13]. The key indicators and their analytical rubrics are strategically designed and selected within the context of the CDPs and require deep understanding of the underlying discipline. The following summarizes the characteristics of the tool:

- It consists of 21 indicators.
- Many indicators map to each SO.
- The rubric used for rating for each indicator follows the scale: Beginning, Developing, Competent and Accomplished.
- The rater assigns percentages that corresponds to the scale points, specifically, [0–70, 71–80, 81–90, and 91–100].
- The scores for each indicator are combined by the following weighted average equation (1) to calculate the overall performance evaluation score for each student:

$$S = \sum_{k=1}^{K} \boldsymbol{\gamma}_k \, p(I_k) \qquad (1)$$

  where S is the aggregate score, $p(I_k)$ is the percentage score obtained for the k^{th} indicator I_k and $\boldsymbol{\gamma}_k$ is the weight associated with the k^{th} indicator I_k such that $0 < \boldsymbol{\gamma}_k < 1$, $k = 1, \ldots, K$ and $\sum_{k=1}^{K} \boldsymbol{\gamma}_k = 1$, where K is the total number of indicators i.e., in our case, $K = 21$.
- The scores for each indicator are averaged, according to the mapping presented in Table 2, to calculate the overall attainment score for every SO.

Criterion A consists of a wide variety of indicators focusing on the overall quality of the project ranging from its inception to its execution and completion via well-defined rubrics as shown in Table B.1 in Appendix B. The indicators look at the evidence of an extensive background study leading to the use of sound principles of engineering design in the project. In addition to that, the indicators probe the novelty of the proposed design approach and exploration of feasible alternatives. The criterion also includes indicators that question the appropriateness of the hardware and software tools and the robustness of the experiments and their results. A student is considered competent regarding the content of the project if he/she has exhibited a deep understanding of engineering design principles and an extensive use of the appropriate engineering tools. Furthermore, any assertions made should be supported by robust experimental results with clear directions for further improvements.

Criterion B relates to professional ethics and responsibilities with strong emphasis on the global, economic, societal and/or environmental factors associated with engineering solutions. The indicators of criterion B and detailed rubrics are shown in Table B.2 in Appendix B. Competent students are expected to exhibit and uphold all principles of academic integrity and professional ethics during the CDP in addition to understanding and evaluating the impact of their proposed solutions.

Criterion C has several indicators as shown in Table B.3, in Appendix B, that allow the CDP supervisors to assess the project management skills of the students in addition to their individual contributions to the development and implementation of the project. Furthermore, the effectiveness of the team in achieving major milestones in a timely fashion is also investigated. Note that, due to the nature of the indicators associated with this criterion, correct assessment requires overseeing the performance of students throughout the course of the project. Therefore, assessment for this criterion is performed solely by the supervisor(s). A student is considered competent if he/she demonstrates active participation in all aspects of the project development. Furthermore, he/she tries to elevate the quality of the project by providing good ideas in addition to being reliable with performing the assigned tasks in a timely manner.

Criterion D assesses the written communication skills of the students. The indicators of Criterion D and detailed rubrics are shown in Table B.4 in Appendix B. The rubric focuses on the organization of the report, creative presentation of ideas and logical flow of the written content. Furthermore, acknowledgement of prior work by citing good and most relevant references is emphasized. Students are considered to have competent written communication skills if their report is well organized, demonstrates an interesting presentation of key ideas and cites important and relevant works to support their assertions and findings.

Finally, the presentation and oral communication skills of the students are assessed using the indicators of Criterion E as shown in Table B.5 in Appendix B. The indicators probe the quality, organization and delivery of the presentation. Students are considered to have competent oral communication skills if their presentation is well organized, focuses on the most important aspects of the project and leads to convincing conclusions. Moreover, they should be well prepared and provide satisfying answers to most of the examination committee's questions.

4.2 Evaluation and assessment of senior design courses

The assessment and evaluation in the ESD course adopts the unified approach presented in [4]. In [4], the authors propose a framework for both assessing SOs and evaluating student performance based on assessment components in ESD courses. In the current investigation, a variety of assessment components are employed including course work that comprises three practical assignments, a design project, a midterm exam, and a final exam. The evaluation of student performance is calculated using a weighted average formula to produce the student's total percentage score in the course. The attainment of CLOs is calculated based on the scores of specific assessment components. The adopted mapping of assessment components onto CLOs and the assigned weights are shown in Table 5. A sample midterm exam question is shown in Fig. 1; the question maps onto CLOs 3, 5 and 7.

Table 5. The matrix of weighted Assessment Components for all CLOs of the ESD course as presented in Table 3

CLO	Assessment Components	Weights
1	Design Project Component 1	100%
2	Midterm Exam Question 1	60%
	Design Project	40%
3	Midterm Exam Question 4	70%
	Design Project Component 1	30%
4	Midterm Exam Question 2	50%
	Design Project Component 2	50%
5	Midterm Exam Question 4	30%
	Final Exam Question 2	40%
	Design Project	30%
6	Final Exam Question 1	100%
7	Midterm Exam Question 4	50%
	Final Exam Question 2	10%
	Design Project Component 3	40%
8	Course Work	100%
9	Course Work	30%
	Design Project Component 4	70%

Design a processor that implements the midpoint method $F(n)$ for calculating the integral $F(x)$. The input parameter and the output are bytes.

$$F(x) = \int_{1}^{3} (-1 + x^2)\,dx = F(n) \approx \frac{2}{5}\sum_{n=0}^{4}\left(-1 + \frac{4}{25}(3+n)^2\right)$$

a. Develop a datapath
b. Draw the design hierarchy
c. Develop an FSMD and an FSM
d. Implement your datapath and control unit using VHDL

Fig. 1. Sample midterm exam question that maps onto CLOs 3, 5, and 7.

Table 6. The matrix of weighted assessment components for all CLOs of the SP course as presented in Table 4

CLO	Assessment Components	Weights
1	Quiz 1	30%
	Midterm Exam Question 1	35%
	Midterm Exam Question 2	35%
2	Quiz 2	30%
	Midterm Exam Question 3	35%
	Final Exam Question 1	35%
3	Quiz 3	30%
	Final Exam Question 2	70%
4	Quiz 4	30%
	Final Exam Question 3	70%
5	Quiz 5	30%
	Final Exam Question 4	70%
6	Design Project	100%
7	Design Project	100%

At this point, the attainment of an SO is calculated as the average of attainments of all mapped CLOs only with high (H) emphasis (See Table 3). An alternate calculation of the attainment that employs a weighted average formula based on all the three emphasis levels H, M, and L is also considered.

4.3 Signal processing

Like the ESD course, assessment in the proposed signal processing course is carried out using a midterm exam, five short quizzes, a design project, and a final exam. In Table 6, the course learning outcomes of the SP course are mapped to the assessment components. A sample final exam question is shown in Fig. 2; the question maps to CLO 4.

4.4 A baseline: Assessment with major core courses

With a background in mathematics and basic sciences, sophomore computer engineering students are introduced to the major core courses. To achieve thorough and accurate results, an extended sample of major core courses from different levels is usually selected for SO assessment. The current investigation builds its reference measurement of attainment based on several MCCs. All major core courses follow the same CLO-to-SO mapping style presented in Section 2. The attainment scores result from the mappings with only high emphasis from a set of ten courses. The selected sample of MCCs for the assessment of attainment of SOs is as follows: logic design, electric circuits, electric circuits laboratory, computer organization and architecture, microprocessors and interfacing, microprocessors and interfacing laboratory, embedded systems design, signals and systems, engineering economy, and capstone projects.

5. Analysis of results and evaluation

Several benefits are noted for the proposed framework including its minimalistic size due to the adopted small set of courses. The minimalistic set of courses enables simplicity of deployment and application of the assessment process. In addition, the proposed framework maintains measurements accuracy and triangulation of results. The framework enjoys a clear structure and is supported by use of rubrics. Furthermore, the framework is scalable—as it can include additional senior-level courses. The framework is portable—it can be easily

A continuous-time signal $x(t) = 3\,\mathrm{sinc}^2(4\pi t) + \sin 16\pi t$ is sampled at three rates: 8, 16 and 17 Hz.

For each sampling rate:

a. Sketch the frequency spectrum of resulting sampled signals.
b. Can $x(t)$ be reconstructed by lowpass filtering the sampled signal? Explain your answer.

Fig. 2. Sample final exam question that maps onto CLO 4.

adopted by other disciplines without changing the statistics or the measurement structure. Indeed, the framework adopts a unified evaluation of project and course qualities and the assessment of attainment of student outcomes. The proposed minimalistic framework promises positive impact on the productivity of academic departments. Faculty and staff workloads can be significantly reduced without sacrificing the integrity of the obtained assessment results or the accuracy of the identified improvements. In adopting the proposed framework, cultivating a culture of assessment is faced with less resistance at lower workloads.

5.1 Results

The developed framework is applied through a study for a single institution using a case-study methodology. The study included several CDPs, senior design course offerings, supervisors, and examiners from a higher education institution. The steps of data collection are as follows:

(1) The testing, tuning, and calibration of the projects measurement tool from [13].
(2) Data collection using the projects measurement tool in several CDPs, ESD, and SP course sections.
(3) Data collection using the direct assessments in the ESD and SP course sections.
(4) Repeating the measurements for two assessment cycles.

The results of the study reflect satisfactory attainment of SOs results in addition to identifying opportunities for improvement. The analysis is based on the following:

- **α(ESD-HLM)**: The attainment scores α from the ESD course while considering the high-, medium-, and low-emphases (HLM) mappings among CLOs and SOs (See Tables 3 and 4).
- **α(ESD-H)**; written in short as **α**(ESD): The attainment scores α from the ESD course while considering only the (H) mapping points; here, (L) and (M) points are discarded.
- **α(SP)**: The attainment scores α from the SP with H emphasis.
- **α(CDP)**: The attainment scores α from the CDPs.
- **α(MCC)**: The attainment scores α from the MCCs.

Ranking is applied to attainment scores according to the following rubric:

- **Beginning:** Percentage attainment is below 65%.
- **Developing:** Percentage attainment is between 65% and 75%.
- **Competent:** Percentage attainment is between 75% and 85%.
- **Accomplished:** Percentage attainment is above 85%.

To calculate the difference in attainment scores between any two sources of measurements, for example **α**(CDP) and **α**(ESD), the root-mean square (RMS, **ε**) of the differences (**δ**) in attainments is used; the obtained error readings are classified according to the following scale:

- **Marginal: ε** is below 3.
- **Small: ε** is between 3 and 5.
- **Somewhat Significant: ε** is between 5 and 10.
- **Significant: ε** is above 10.

To further examine the similarity between the obtained attainment scores from any two sources of measurements, we calculate the two-dimensional correlation factor **$\varrho(x, y)$**. Here, **x** and **y** are the correlated datasets. The classification based on the **$\varrho(x, y)$** calculations is as follows:

- **Low: ϱ** is below 0.34.
- **Medium: ϱ** is between 0.34 and 0.67.
- **Somewhat High: ϱ** is between 0.67 and 0.83.
- **High: ϱ** is above 0.83.

The results show that the differences in the calculated attainments of **α(ESD-H)** and **α(ESD-HLM)** has **ε** of $1.13_{marginal}$ and 4.13_{small}, and **ϱ** of 0.93_{high} and 0.81_{high} – over two academic years. The obtained marginal differences between the small root-mean square of differences and high correlations are in favor of the minimalistic mapping. Here, only the high-emphasis is considered and the CLO-to-SO mappings with low and medium emphases are discarded (See Tables 3 and 4). Calculations based only on considering high-emphasis mappings enable minimalistic and effective measurements, besides achieving simple and reduced assessment setups as compared to considering all mapping points. The scores based on only high emphasis mapping points are adopted in the following calculations.

The **ε** and **ϱ** of differences in attainment scores among the ESD, CDP, and MCC are shown in Table 7. The differences among the scores of the ESD course, CDP, and the MCC reflect significant dissimilarities among all. The significant difference is evident and consistent for most of the SOs (See Table 7). The obtained differences support the conclusion that the measurements from the ESD course and CDPs are not redundant and can be combined. In addition, using only the ESD course or the CDP is not sufficient to produce results that are close to the MCC reference measurements. The correlations among the ESD, CDP, and MCC are all found to be low—which emphasizes the need for combining additional sources. Combining additional sources aims at reducing the score differences from the MCC measurements.

Based on the results of only the CDP and ESD course, a combined attainment score **$Ç_{67/33}$ (α(ESD), α(CDP))** is calculated with a weight of 67% given for the CDP (See Table 8). Such an assignment of weights is considered because the CDPs constitute a total of 6 credit-hours of study, whereas the ESD is a 3 credit-hours course. Evidently, the combination **$Ç_{67/33}$** successfully leads to reduced differences from the scores obtained by the set of MCC (See Table 8). However, the differences are still somewhat significant with low correlation. Indeed, the persistent differences in scores reconfirms the need for additional sources of assessment information to close the accuracy gap with the measurements obtained from the set of MCC.

In addition to combining the attainment scores from the ESD course and CDPs, the proposed framework attempts to include the assessment scores of the proposed Signal Processing (SP) course (See Table 4). The SP course is rich in analysis, problem-solving, and mathematics. The results of combining CDP with ESD and SP courses are presented in Table 8. Here, **Ç(α(ESD), α(CDP), α(SP))** is the weighted average of attainments from the ESD, SP, and CDP scores. The weights of the combination are based on outcomes relevance to the course and its corresponding time-allocation within each course. For example, the weights assigned for the assessment of SO(a) are 80%, 10% and 10% for CDP, ESD and SP courses. The suggested weights and differences between the proposed combination **Ç(α(ESD), α(CDP), α(SP))** and **α(MCC)** are presented in Table 8.

As compared to the MCC measurements of SO(a) (See Table7), both the ESD course and the CDP results are significantly dissimilar with differences of **12.58** and **27.94** during the academic year 2013–2014, and **15.62** and **28.74** during the academic year 2014–2015. Furthermore, the attainment scores in **$Ç_{67/33}$(α(ESD), α(CDP))** yields significant differences with **α(MCC)**. For example, differences of **22.87** and **22.41** are observed between **$Ç_{67/33}$(α(ESD), α(CDP))** and **α(MCC)** during academic years 2013–2014 and 2014–2015. Combining the scores of the SP course in the calculation, the difference in SO(a) attainment score in **Ç** is dropped to marginal with a value of **1.68** during the academic year 2013–2014 and **1.00** during the academic year 2014–2015. The overall root-mean square of differences of the combination also significantly drops to small and marginal levels and the correlation increases to high levels. Accordingly, the combination of CDP, ESD, and SP produces results that are highly similar in conclusion to those using the MCCs. Table 9 summarizes the similarity analysis

Table 7. The differences in attainment scores among CDP, ESD, and MCC

SO	δ (α(ESD), α(CDP))		δ (α(ESD), α(MCC))		δ (α(CDP), α(MCC))	
	Academic Year 13–14	**Academic Year 14–15**	**Academic Year 13–14**	**Academic Year 14–15**	**Academic Year 13–14**	**Academic Year 14– 15**
a	$15.36_{\text{significant}}$	$13.12_{\text{significant}}$	$12.58_{\text{significant}}$	$15.62_{\text{significant}}$	$27.94_{\text{significant}}$	$28.74_{\text{significant}}$
b	1.76_{marginal}	0.23_{marginal}	0.59_{marginal}	$6.59_{\text{somewhat significant}}$	1.17_{marginal}	$6.82_{\text{somewhat significant}}$
c	$9.83_{\text{somewhat significant}}$	$7.74_{\text{somewhat significant}}$	$5.92_{\text{somewhat significant}}$	3.12_{small}	3.91_{small}	$10.86_{\text{significant}}$
d	1.36_{marginal}	$9.65_{\text{somewhat significant}}$	2.04_{marginal}	4.83_{small}	3.40_{small}	4.82_{small}
e	$18.94_{\text{significant}}$	$18.73_{\text{significant}}$	$5.46_{\text{somewhat significant}}$	2.74_{marginal}	$13.48_{\text{significant}}$	$15.99_{\text{significant}}$
f	2.91_{marginal}	$13.57_{\text{significant}}$	0.26_{marginal}	$10.13_{\text{significant}}$	3.18_{marginal}	3.44_{small}
g	2.28_{marginal}	$17.10_{\text{significant}}$	3.94_{small}	3.18_{small}	$6.22_{\text{somewhat significant}}$	$13.92_{\text{significant}}$
h	$7.55_{\text{somewhat significant}}$	$13.57_{\text{significant}}$	2.45_{marginal}	$5.18_{\text{somewhat significant}}$	$5.10_{\text{somewhat significant}}$	$8.39_{\text{somewhat significant}}$
i	$12.35_{\text{significant}}$	$20.69_{\text{significant}}$	$10.06_{\text{significant}}$	$14.64_{\text{significant}}$	2.29_{marginal}	$6.05_{\text{somewhat significant}}$
j	$8.71_{\text{somewhat significant}}$	$9.96_{\text{somewhat significant}}$	$5.96_{\text{somewhat significant}}$	4.54_{small}	2.76_{marginal}	$5.42_{\text{somewhat significant}}$
k	$10.02_{\text{significant}}$	$15.54_{\text{significant}}$	3.03_{small}	$9.93_{\text{significant}}$	$6.99_{\text{somewhat significant}}$	$5.61_{\text{somewhat significant}}$
(ε, ϱ)	**$(10_{\text{significant}}, 0.05_{\text{low}})$**	**$(13.84_{\text{significant}}, -0.26_{\text{low}})$**	**$(5.99_{\text{somewhat significant}}, -0.02_{\text{low}})$**	**$(8.53_{\text{somewhat significant}}, -0.12_{\text{low}})$**	**$(10.12_{\text{significant}}, -0.17_{\text{low}})$**	**$(12.22_{\text{significant}}, 0.16_{\text{low}})$**

Table 8. The differences in attainment scores between the composite score Ç67/33 and MCC, and differences in attainment scores between the composite score Ç and MCC with weights CDP/ESD/SP for each SO

	δ (Ç$_{67/33}$, α(MCC))			**δ (Ç, α((MCC))**	
SO	**Academic Year 13–14**	**Academic Year 14–15**	**SO$_{\text{CDP/ESD/SP}}$**	**Academic Year 13–14**	**Academic Year 14–15**
a	22.87$_{\text{significant}}$	24.41$_{\text{significant}}$	**a$_{80/10/10}$**	1.68$_{\text{marginal}}$	1.00$_{\text{marginal}}$
b	0.59$_{\text{marginal}}$	6.74$_{\text{somewhat significant}}$	**b$_{50/25/25}$**	1.29$_{\text{marginal}}$	2.74$_{\text{marginal}}$
c	0.66$_{\text{marginal}}$	8.31$_{\text{somewhat significant}}$	**c$_{50/40/10}$**	2.06$_{\text{marginal}}$	7.69$_{\text{somewhat significant}}$
d	2.95$_{\text{marginal}}$	1.63$_{\text{marginal}}$	**d$_{67/33/0}$**	2.95$_{\text{marginal}}$	1.65$_{\text{marginal}}$
e	7.23$_{\text{somewhat significant}}$	9.81$_{\text{somewhat significant}}$	**e$_{50/40/10}$**	4.00$_{\text{small}}$	4.19$_{\text{small}}$
f	2.22$_{\text{marginal}}$	1.04$_{\text{marginal}}$	**f$_{67/33/0}$**	2.22$_{\text{marginal}}$	5.65$_{\text{somewhat significant}}$
g	5.46$_{\text{somewhat significant}}$	8.28$_{\text{somewhat significant}}$	**g$_{67/33/0}$**	5.46$_{\text{somewhat significant}}$	2.46$_{\text{marginal}}$
h	2.61$_{\text{marginal}}$	3.91$_{\text{small}}$	**h$_{67/33/0}$**	2.61$_{\text{marginal}}$	0.70$_{\text{marginal}}$
i	1.78$_{\text{marginal}}$	0.78$_{\text{marginal}}$	**i$_{67/33/0}$**	1.78$_{\text{marginal}}$	7.81$_{\text{somewhat significant}}$
j	0.12$_{\text{marginal}}$	2.13$_{\text{marginal}}$	**j$_{67/33/0}$**	0.12$_{\text{marginal}}$	1.25$_{\text{marginal}}$
k	3.68$_{\text{marginal}}$	0.48$_{\text{marginal}}$	**k$_{50/25/25}$**	1.23$_{\text{marginal}}$	3.10$_{\text{small}}$
(ε, ϱ)	**(7.65$_{\text{somewhat significant}}$, –0.17$_{\text{low}}$)**	**(9.04$_{\text{somewhat significant}}$, 0.04$_{\text{low}}$)**	(ε, ϱ)	**(2.69$_{\text{marginal}}$, 0.81$_{\text{high}}$)**	**(4.13$_{\text{small}}$, 0.76$_{\text{somewhat high}}$)**

Table 9. Summary of correlation analysis among the different measurement datasets

Dimensions	**(ε, ϱ)$_{13–14}$**	**(ε, ϱ)$_{14–15}$**	**Rank**	**Conclusion**
α(H), α(HLM)	(1.13$_{\text{marginal}}$, 0.93$_{\text{high}}$)	(4.13$_{\text{small}}$, 0.81$_{\text{high}}$)	Constantly in agreement	Assessment based on only H-emphasis mapping is in agreement with HLM-emphasis. The H-emphasis mapping is recommended for adoption due to simplicity, accuracy, and effectiveness.
α(ESD), α(CDP)	(10$_{\text{significant}}$, 0.05$_{\text{low}}$)	(13.84$_{\text{significant}}$, –0.26$_{\text{low}}$)	Constantly not in agreement	Triangulation and composition of both dimensions leads to increased accuracy.
α(ESD), α(MCC)	(5.99$_{\text{somewhat significant}}$, –0.02$_{\text{low}}$)	(8.53$_{\text{somewhat significant}}$, –0.12$_{\text{low}}$)	Constantly somewhat different	Single-course scores by themselves do not provide an accurate evaluation of attainment at the program level.
α(CDP), α(MCC)	(10.12$_{\text{significant}}$, –0.17$_{\text{low}}$)	(12.22$_{\text{significant}}$, 0.16$_{\text{low}}$)	Constantly not in agreement	CDP scores by themselves do not provide an accurate evaluation of attainment at the program level.
Ç$_{67/33}$, α(MCC)	(7.65$_{\text{somewhat significant}}$, –0.17$_{\text{low}}$)	(9.04$_{\text{somewhat significant}}$, 0.04$_{\text{low}}$)	Constantly somewhat different	The composition of the ESD course and CDPs alone does not provide an accurate evaluation of attainment at the program level.
Ç, α(MCC)	(2.69$_{\text{small}}$, 0.81$_{\text{high}}$)	(4.13$_{\text{small}}$, 0.76$_{\text{somewhat high}}$)	Constantly in agreement	Measurements are constantly in agreement over the two cycles; the composite attainment scores are accurate. The proposed combination of CPD, ESD, and SP can replace the set of MCC.

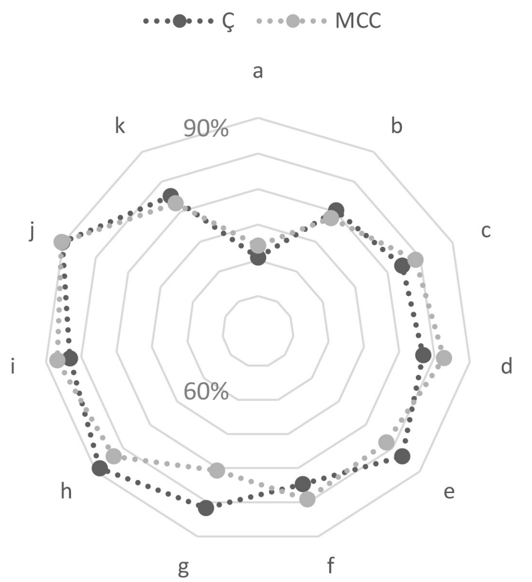

Fig. 3. A radar chart for the recommended composite attainment **Ç** in comparison with the extended set of major core courses MCC for the academic year 2013–2014.

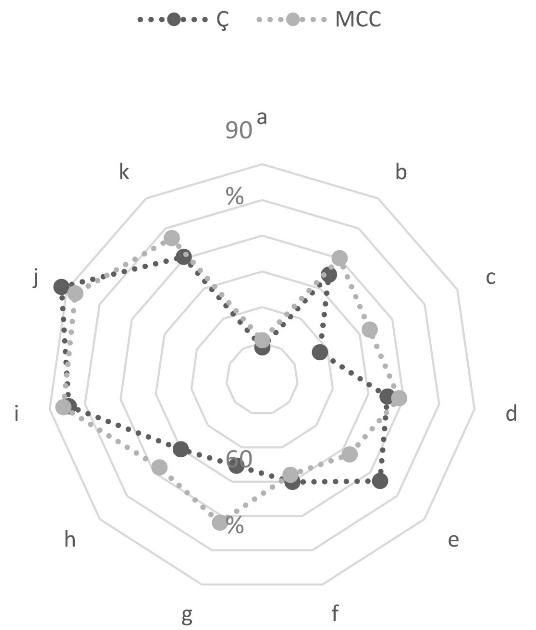

Fig. 4. A radar chart for the recommended composite attainment **Ç** in comparison with the extended set of major core courses MCC for the academic year 2014–2015.

using the root-mean square of differences and the correlation values. The result trends over multiple cycles confirm the adequacy of the combination (**Ç**) and the validation of the proposed minimalistic framework.

In Figs. 3 and 4, radar charts are shown for the composite attainment score **Ç** over the two academic years in comparison with the extended sample of MCCs scores. The radar charts show strong correlation of the assessment results obtained with the proposed minimalistic set of courses and those using an extended set of major core courses. Based on the results, we recommend considering the score of **Ç** obtained by using the presented minimalistic combination of courses with the proposed proportions as a good approximation for assessment of student outcomes. Fig. 5 is an illustration of the philosophy of the proposed mini-

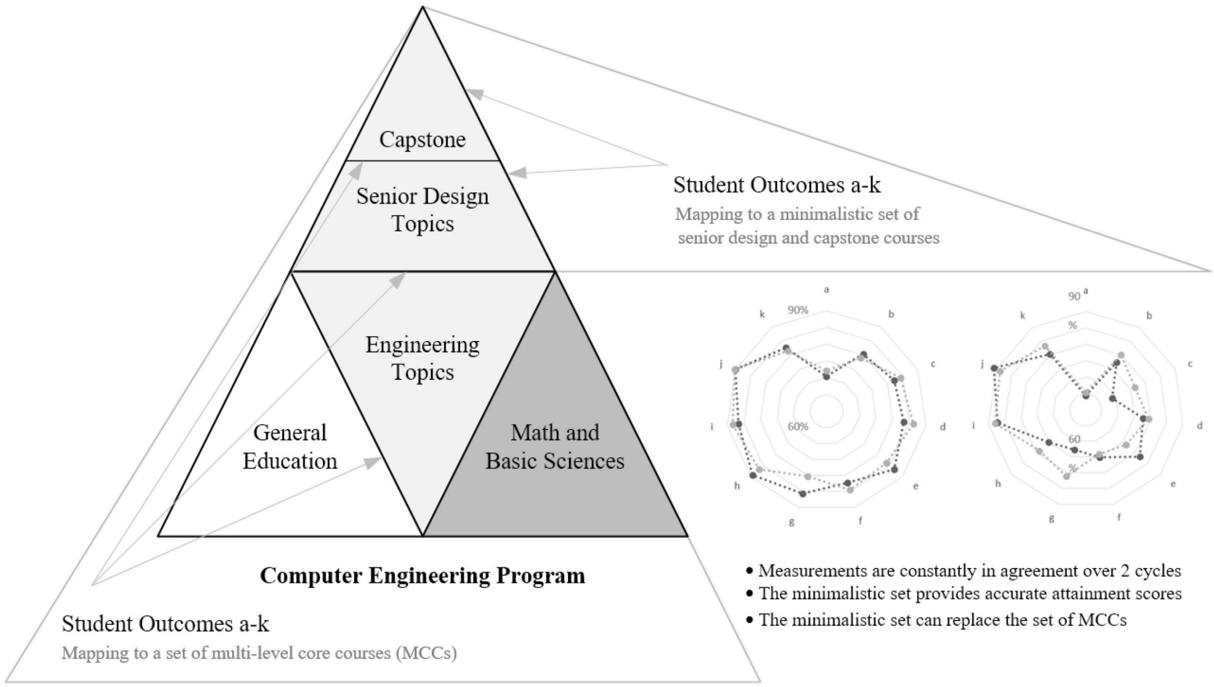

Fig. 5. An illustration of the philosophy of the proposed minimalistic framework, its mappings to MCCs and the minimalistic sets of courses in a computer engineering program, and the attained scores with minimum difference between the two mappings.

malistic framework, its mappings to MCCs and the minimalistic sets of courses, and the attained scores with minimum difference between the two mappings.

5.2 Challenges and limitations

While the goal of the proposed framework is to promote principles of simple, accurate, fair and objective evaluation, it faces a few challenges regarding its execution. First, it relies on the commitment of the evaluators to design assessments components and thoroughly review the course material and provide concrete evidence. Furthermore, evaluators are required to thoroughly review the measurement artefacts such as project reports, essays, presentations etc.

Although the case-study provides the opportunity for deep reasoning and analysis of the proposed framework, a few limitations are noted and set the ground for future work. The executed case-study is for a single institution. Accordingly, a multi-site study can provide an increased-level of confidence in the results and opens the research questions and conclusions for a wider discussion.

The proposed case-study relies on the integration of CDP and senior design courses based on their descriptions and CLOs. Although the proposed pattern is generic and can be used by any program, specific course structures and outcomes do not necessarily apply to other programs. Indeed, curricular developments must be carried out by programs to arrive at a similar minimalistic arrangement.

6. Conclusions

In this paper, the use of a minimalistic set of senior courses, including CDPs, to assess the SOs at the program level is investigated. Different strategies and tools are defined, developed, and adopted in courses on embedded systems, signal processing, and in an extensive CDP setup. The presented strategy enabled the application of systematic measurements of attainments of CLOs. The attainments of CLOs are triangulated and statistically combined to assess SOs at the program level. The combination of scores is based on the characteristics of the integrated courses.

Extensive statistical analysis was used to examine the adequacy of the selected minimalistic set of courses. The statistical model calculated the differences in attainment scores, RMS of differences, and correlations among the selected set of courses, the CDP, and a reference measurement carried out using an extended sample of MCCs. The results confirmed the accuracy of results from the minimalistic set of courses, with a combined score **Ç**, with marginal errors and high-correlation with-respect-to the reference set of MCCs. Over a course of two assessment cycles, the reported small RMS of differences has been less than 4.13 with a somewhat high correlation among the datasets with a value greater than 0.76.

Future works include the deployment of the framework within a multi-program case-study for further refinement and reassurance of results. The case-study setup can cover additional assessment cycles to validate the framework deployment over longer periods of time. Investigations on multi-programs and setups over longer periods can increase the confidence in the proposed approach, capture wide ranges of result trends, and tune the framework for high accuracies. Furthermore, future work can consider the identification of courses with complementary features, other than ESD and SP, to form minimalistic sets of courses for effective assessment of SOs. Indeed, future investigations can deeply address the impact of adopting standard assessment practices; as against the adoption of the suggested minimalistic approach; on faculty and staff workloads, academic department productivity, and the cultivation of a culture of assessment.

References

1. W. M. Phillips, G. D. Peterson and K. B. Aberle, Quality assurance for engineering education in a changing world, *International Journal of Engineering Education*, **16**(2), 2000, pp. 97–103.
2. ABET Engineering Accreditation Commission. Accreditation criteria and supporting documents, http://www.abet.org/accreditation/accreditation-criteria/. Accessed August 10, 2018.
3. S. A. Al-Yahya and M. A. Abdel-halim, A successful experience of ABET accreditation of an electrical engineering program, *IEEE Transactions on Education*, **56**(2), 2013, pp. 165–173.
4. I. Damaj, A. Zaher and J. Yousazai, Assessment and evaluation framework with successful application in ABET accreditation, *International Journal of Engineering Pedagogy*, **7**(3), 2017, pp. 3–91.
5. R. M. Felder and R. Brent, Designing and teaching courses to satisfy the ABET engineering criteria, *Journal of Engineering Education*, **92**(1), 2003, pp. 7–25.
6. H. Gurocak, Planning and implementing an assessment process with performance criteria for ABET accreditation, *International Journal of Engineering Education*, **25**(6), 2009, pp. 1236–1248.
7. H. Al-Twaijry, M. Mekhallalati, H. Abachi and G. Muhammad, A rubrics based quality improvement methodology for ABET accreditation, *International Journal of Engineering Education*, **28**(6), 2012, pp. 1266–1273.
8. J. C. McNeil and M. W. Ohland, The influence of ABET accreditation practices on faculty approaches to engineering, *International Journal of Engineering Education*, **32**(3A), 2016, pp. 1151–1159.
9. M. Steiner, J. Kanai, C. Hsu, E. Ledet, J. Morris, M. Anderson, S. Miller, K. Anderson and B. Bagepalli, Preparing engineering students for professional practice: using capstone to drive continuous improvement, *International Journal of Engineering Education*, **31**(1A), 2015, pp. 154–164.
10. L. J. McKenzie, M. S. Trevisan, D. C. Davis and S. W.

Beyerlein, Capstone design courses and assessment: A national study, *American Society of Engineering Education Annual Conference & Exposition*, 2004, pp. 1–14.
11. F. De Rego, C. Zoltokowski, L. Jamieson and W. Oakes, Teaching ethics and the social impact of engineering within a capstone course, *ASEE/IEEE Frontiers in Education Conference*, 2005, pp. 1–5.
12. G. L. Dempsey, W. K. N. Anakwa, B. D. Huggins and J. H. Irwin, Electrical and computer engineering curriculum assessment via senior miniproject, *IEEE Transactions on Education*, **46**(3). 2003, pp. 350–358.
13. J. Yousafzai, I. Damaj and M. El Abd, A unified approach for assessing capstone design projects and student outcomes in computer engineering programs, *IEEE Global Engineering Education Conference*, 2015, pp. 333–339.
14. D. G. Meyer, Capstone desgin outcome assessment: instruments for quantitative evaluation, *ASEE/IEEE Frontiers in Education Conference*, 2005, pp. 1–5.
15. M. Djassemi, A lean approach to manage a capstone senior project course, *ASEE/IEEE Frontiers in Education Conference*, 2006, pp. 1–6.
16. S. Beyerlein, D. Davis, M. Trevisan, P. Thompson and O. Harrison, Assessment framework for capstone design courses, *ASEE Annual Conference*, 2006.
17. D. Davis, S. Beyerlein, P. Thompson and K. Harrison, Assessment for three performance areas in capstone engineering design, *ASEE Annual Conference*, 2007.
18. V. Subbian and C. Purdy, Redesigning an advanced embedded systems course: a step towards interdisciplinary engineering education, *IEEE Integrated STEM Education Conference*, 2013, pp. 1–4.
19. K. G. Ricks, D. J. Jackson and W. A. Stapleton, An embedded systems curriculum based on the IEEE/ACM model curriculum, *IEEE Transactions on Education*, **51**(2), 2008, pp. 262–270.
20. K. Nickels and M. Sealey, Embedded systems in an engineering science curriculum, *IEEE Frontiers in Education Conference*, 2009, pp.1–6.
21. J. Oliver, L. A. Slivovsky, B. Benson and J. Harris, A semi-autonomous embedded systems course, *IEEE Frontiers in Education Conference*, 2013, pp. 1043–1045.
22. I. Damaj and J. Yousafzai, Student outcomes assessment: a unified approach using senior computer engineering design experiences, *IEEE Global Engineering Education Conference*, 2016, pp. 204–211.
23. F. Vahid and T.Givargis, Embedded system design: a unified hardware/software introduction., John Wiley & Sons, New York, NY, 2002.
24. I. Damaj, High-level synthesis, Wiley Encyclopedia of Computer Science and Engineering, 2008.
25. I. Damaj, Programmable logic arrays, Wiley Encyclopedia of Computer Science and Engineering, 2008.
26. I. Damaj and H. Diab, Performance Analysis of linear algebraic functions using reconfigurable computing, *The Journal of Super Computing*, **24**(1), 2003, pp. 91–107.
27. K. E. Wage, J. R. Buck, C. H. G. Wright and T. B. Welch, The signals and systems concept inventory, *IEEE Transactions on Education*, **48**(3), 2005, pp. 448–46.
28. A. V. Oppenheim, A. S. Willsky and S. H. Nawab, Signals & systems (2nd Ed.), Prentice-Hall, Inc., 1997.
29. B. P. Lathi, Linear systems & signals (2nd Ed.), Oxford Univ. Press, 2009.

Appendix A. ABET Student Outcomes of Engineering Programs

(a) an ability to apply knowledge of mathematics, science, and engineering;
(b) an ability to design and conduct experiments, as well as to analyze and interpret data;
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability;
(d) an ability to function on multidisciplinary teams;
(e) an ability to identify, formulate, and solve engineering problems;
(f) an understanding of professional and ethical responsibility;
(g) an ability to communicate effectively;
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context;
(i) a recognition of the need for, and an ability to engage in life-long learning;
(j) a knowledge of contemporary issues;
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Appendix B. Capstone Design Project Evaluation Rubric [13]

Table B.1. Indicators and detailed rubric for Criterion A (Content)

A. **CONTENT**				
[Mapping to ABET outcomes]	**Beginning**	**Developing**	**Competent**	**Accomplished**
Literature review: summarizes, compares and evaluates various concepts, research findings and current theories and models in core content areas of computer and electrical engineering. **[e, j]**	Literature review is incomplete and/or omits important research findings, includes excessive discussion of unrelated issues; significant errors in content; assertions are made without adequate support from evidence.	Literature review is brief, with insufficient detail; unrelated issues are introduced and/or minor errors in content; some assertions are made without adequate support from evidence.	Literature review is brief but complete; review focuses only on issues related to question; review is factually correct; assertions are clearly supported with evidence and appropriate use of logic.	Literature review is complete; sufficient detail is provided to support assertions; assertions supported with evidence; includes original and relevant insight or analysis of topic.

Identify engineering principles and techniques that are relevant to the project and apply them within specific problem domain. **[a, e, i, j, k]**	Basic understanding of engineering principles; fails to apply them within specific problem domain.	Basic engineering principles and techniques relevant to project are included, but some are missing; fails to develop complete theoretical or design framework for the project.	Provides good engineering framework for the project; applies principles and techniques correctly to problem domain.	Project is completely grounded in engineering principles and techniques; applies them to problem correctly and clearly establishes their relevance.
Novelty and adequacy of the design approach. **[c]**	Approach to the problem has serious deficiencies; the design does not consider constraints and standards of any kind.	Approach to the problem has some deficiencies and is not novel; considers some constraints and standards; but does not deal with realistic constraints, or does so weakly.	Approach to the problem is adequate and somewhat novel; considers at least one realistic constraint and standard, and deals with them appropriately.	Approach to the problem is highly adequate and innovative; considers more than one realistic constraint and standard, and deals with them effectively.
Alternative designs. **[c, e]**	Only one design presented or clearly infeasible alternative that does not consider any realistic constraints is given.	Shortcomings in exploring and identifying alternative designs; the alternatives consider at least one realistic constraint, but do so weakly.	Alternative approaches identified to some fair degree; feasibility of the alternatives within the context of some realistic constraints is discussed.	Final design achieved after review of reasonable alternatives; feasibility of the alternatives within the context of a complete set of realistic constraints is extensively discussed.
Identification, mastering, and use of hardware/ software tools **[b, i, k]**	Serious deficiencies in understanding the correct selection and/or the mastering and use of hardware and software tools.	Minimal application, mastering, and/or use of appropriate hardware and software tools.	Hardware and software tools are mastered and used with effectiveness to develop designs. Further improvement could be made.	Hardware and software tools are mastered and used highly effectively to develop and analyze designs; final product is highly professional.
Robustness and adequacy of conducting, analyzing, testing and interpreting experimental results. **[b, k]**	Almost all the experiments and tests are inconclusive; results are disappointing or incomplete.	Testing of the design is somewhat fair; results are inconclusive and not usable for further investigation.	Testing is adequate; analysis and results are acceptable and complete.	Testing is thorough; analysis and results are robust and usable.
Further improvements. **[b, c]**	No direction for further improvement is provided.	One or two ideas for future expansion are listed but may not be novel or practically feasible within realistic constraints.	Several ideas, of which one or two are novel and consider at least one realistic constraint, for further improvements are explained.	Several novel directions that take into consideration various realistic constraints for important expansions of the current ideas are thoroughly explained.

Table B.2. Indicators and detailed rubric for Criterion B (Integrity, Values and Impact of Engineering Solutions)

B. **INTEGRITY, VALUES AND IMPACT OF ENGINEERING SOLUTIONS**

[Mapping to ABET outcomes]	**Beginning**	**Developing**	**Competent**	**Accomplished**
Clear understanding of and adherence to scientific and professional ethics. **[f]**	Lack of understanding of scientific and professional ethics.	Exhibits incomplete understanding but still complies with principles of scientific, professional and/or academic integrity.	Exhibits understanding and complies with principles of scientific, professional and/or academic integrity.	Clear documentation of compliance with all relevant ethical guidelines; clearly establishes authorship of the project work.
Aware of the impact of engineering solutions in a global, economic, environmental, and/or societal context. **[h]**	No articulation of the impact of engineering solutions in a global, economic, environmental, or societal context.	Limitedly articulates the impact of engineering solutions in a global, economic, environmental, and/or societal context.	Articulates the impact of engineering solutions in a global, economic, environmental, and/or societal context.	Clearly articulates the impact of engineering solutions in a global, economic, environmental, and/or societal context.

Evaluate engineering solutions that consider global, economic, environmental, and/or societal factors. **[h]**	No evaluation of the impact of engineering solutions global, economic, environmental, or societal context.	Limitedly evaluates the impact of engineering solutions in a global, economic, environmental, and/or societal context.	Evaluates the impact of engineering solutions in a global, economic, environmental, and/or societal context.	Clearly evaluates the impact of engineering solutions in a global, economic, environmental, and/or societal context.

Table B.3. Indicators and detailed rubric for Criterion C (Project Management and Teamwork Skills)

C. **PROJECT MANAGEMENT AND TEAMWORK SKILLS**

[Mapping to ABET outcomes]	**Beginning**	**Developing**	**Competent**	**Accomplished**
Work individually, or as part of team where appropriate, to formulate, analyze, design, and implement a significant engineering project. **[d]**	Project work contains numerous faults; significant milestones in timeline not met; implementation falls below expected minimum standards; unable to work effectively as team member (if applicable).	Project work contains some faults; some milestones in timeline not met; implementation exceeds minimal requirements but does not represent a significant engineering project; demonstrates marginal effectiveness as team member (if applicable).	Project work contains no faults, but retains areas for significant improvement; major milestones in timeline are met within acceptable timeframe; implementation represents a significant engineering project with minor mistakes; demonstrates effectiveness as team member (if applicable).	Well-formulated, designed, and implemented project; completes project according to timeline; implementation represents a significant engineering project; demonstrates effectiveness as team member (if applicable).
Contribution to the team project/work. **[d]**	Does not collect any relevant information; no useful suggestions to address team's needs.	Collects information when prodded; tries to offer some ideas, but not well developed, and not clearly expressed, to meet team's needs.	Collects basic, useful information related to the project; occasionally offers useful ideas to meet the team's needs.	Collects and presents to the team a great deal of relevant information; offers well-developed and clearly expressed ideas directly related to the group's purpose.
Taking responsibility. **[d]**	Does not perform assigned tasks; often misses meetings and, when present, does not have anything constructive to say; relies on others to do the work.	Performs assigned tasks but needs many reminders; attends meetings regularly but generally do not say anything constructive; sometimes expects others to do his/her work.	Performs all assigned tasks; attends meetings regularly and usually participate effectively; generally reliable.	Performs all tasks very effectively; attends all meetings and participates enthusiastically; very reliable.

Table B.4. Indicators and detailed rubric for Criterion D (Written Communication)

D. **WRITTEN COMMUNICATION**

[Mapping to ABET outcomes]	**Beginning**	**Developing**	**Competent**	**Accomplished**
Organization and logic. **[g]**	No logical order to information provided; information is missing or difficult to understand; further explanation is often needed.	Weak organization; needs work on creating transitions between ideas.	Report is organized; somewhat clear argument for research position/ project rationale is present.	Clear and logical written report; good development of argument/project rationale; transitions made clearly and smoothly; information is thorough and relevant and at times enriches reader's knowledge and interest.

Writing style (word choice, grammar and sentence structure). **[g]**	Occasional problems with word choices and sentence structure, leaving the reader unsure of the meaning.	Words and sentences are adequate in general but lack energy; reader has to struggle to keep reading to the end.	Good writing style; sentences flow smoothly and evenly.	Compelling writing style; connects strongly with the reader and keeps him or her engaged right to the end.
Use of References. **[g]**	Little attempt is made to acknowledge the work of others; most references that are included are either inaccurate or unclear.	References are provided but some are not accurate and most are not relevant.	With an occasional oversight, prior work is acknowledged by referring to sources for theories, assumptions and findings; with some minor exceptions, references are relevant and exact with author, journal, volume number, page number, and year.	Prior work is acknowledged by referring to sources for theories, assumptions and findings; references are relevant and exact with author, journal, volume number, page number, and year.

Table B.5. Indicators and detailed rubric for Criterion E (Presentation and Oral Communication)

E. **PRESENTATION AND ORAL COMMUNICATION**

[Mapping to ABET outcomes]	**Beginning**	**Developing**	**Competent**	**Accomplished**
Mechanics. **[g]**	Slides seem to have been cut-and pasted together haphazardly at the last minute; numerous mistakes; speaker not always sure what is coming next.	Boring slides; no glaring mistakes but no real effort made into creating truly effective slides.	Generally good set of slides; conveys the main points well.	Very creative slides; carefully thought out to bring out both the main points of this part of the presentation as well as the relation to the rest of the team presentation; maintains audience interest throughout.
Organization. **[g]**	Bland presentation; sequencing and pace of topics seems random; doesn't lead up to any clear conclusions.	Some of the ideas are presented well; others are lacking; offers plausible conclusions.	Ideas are well organized and help the audience move along; the key points are presented; leads up to convincing conclusions.	The presentation is clear and focused; relevant, quality details give the audience important information; helps the audience develop insight into the topic.
Delivery. **[g]**	Mumbles the words, audience members in the back can't hear anything; too many filler words.	Low voice, occasionally inaudible; some distracting filler words; articulation mostly, but not always, clear.	Clear voice, generally effective delivery.	Natural, confident delivery that does not just convey the message but enhances it; excellent use of volume, pace etc.
Relating to audience. **[g]**	Reads most of the presentation from the slides or notes with no eye contact with audience members; seems unaware of audience reactions.	Occasional eye contact with audience but mostly reads the presentation; some awareness of at least a portion of the audience; only brief responses to audience questions.	Generally aware of the audience reactions; maintains good eye contact when speaking and when answering questions.	Keeps the audience engaged throughout the presentation; modifies material on-the-fly based on audience questions and comments; keenly aware of audience reactions.
Response to questions. **[g]**	Unprepared; misunderstood questions and did not respond appropriately.	Partially prepared; understood questions but had difficulty responding/ explaining.	Well prepared; understood questions and provided mostly correct responses.	Fully prepared; anticipated questions and responded with more information than required; demonstrated deep understanding of the project material.

Appendix C. List of Acronyms

Acronym	Definition
CDP	Capstone Design Project
CLO	Course Learning Outcome
ESD	Embedded System Design
H	High
L	Low
M	Medium
MCC	Multi-Level Core Courses
RMS	Root-Mean Square
SO	Student Outcome
SP	Signal Processing
α	Attainment Score
δ	Difference in Attainment Score
ε	Root-Mean Square Error
ϱ	Two-Dimensional Correlation Factor
Ç	Composite Attainment Score

Issam Damaj, PhD, is an Associate Professor of Computer Engineering at the Electrical and Computer Engineering (ECE) Department at American University of Kuwait (AUK). Since 2011, he has been the ABET Accreditation Lead and Institutional Representative of the ECE Department. He was the Founding Chairperson of the ECE Department and Program Lead between September 2009 and August 2016. He was awarded a Doctor of Philosophy Degree in Computer Science from London South Bank University, London, United Kingdom in 2004. He received a master's Degree in Computer and Communications Engineering, in 2001, from the American University of Beirut. He received a bachelor's Degree in Computer Engineering from Beirut Arab University in 1999. His research interests include hardware/software co-design, embedded system design, automation, Internet-of-things applications, parallel processing, formal methods, and engineering education. He is a Program Evaluator (PEV) with ABET Engineering Accreditation Commission (EAC), a Senior Member of the IEEE, a Professional Member of the ASEE, and a member of the Order of Engineers in Beirut. He is the Founding Counselor of the AUK IEEE Student Branch. He is a reviewer for the Journal of Computers and Electrical Engineering, Elsevier; Journal of Intelligent and Fuzzy Systems, IOS Press; European Journal of Engineering Education, Taylor & Francis; Journal of Evaluation and Program Planning, Elsevier; IEEE International Conference on Communications; ASEE Annual Conference & Exposition; and IEEE International Conference on Engineering Education. He maintains an academic website at www.idamaj.net.

Jibran Yousafzai, PhD, is an Assistant Professor of Computer Engineering at the Electrical and Computer Engineering (ECE) Department at the American University of Kuwait (AUK). He received the BS degree in computer system engineering from Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Pakistan in 2004, the MSc degree in digital signal processing and PhD degree in electronic engineering in 2006 and 2010, respectively, from King's College London, UK. During his PhD research, he worked on a project funded by the UK's Engineering and Physical Sciences Research Council (EPSRC) on resolution of the robustness issues of automatic speech recognition systems. During his MSc research, he investigated methods for the reconstruction of perceptual soundfields for a spatially extended surround sound technology. His research interests are in the broad area of signal processing, ranging from theoretical aspects of signal analysis to applications in automatic speech recognition, machine learning and digital audio processing for surround sound technology. He has also published papers in the field of Engineering Education. He is a member of the Institute of Electrical and Electronics Engineers (IEEE), International Speech Communication Association (ISCA) and the European Association for Signal Processing (EURASIP).