A Review of the State of Integrated Engineering Frameworks and Outcome Dimensions

Dr. Bahar Memarian, Arizona State University

Bahar Memarian is a researcher and educator with more than 10 years of experience at the intersection of applied and social sciences. Her research and teaching interests are in the areas of Engineering Education (Engineering Design, Use of Technology, Problem-solving, Outcomes Assessment, Experiential Learning, and Creativity) and Human Factors Engineering (Artificial Intelligence in Education, Human-centered Systems, and Cognitive-Systems Engineering).

Dr. Shawn S. Jordan, Arizona State University

SHAWN JORDAN, Ph.D. is an Associate Professor of engineering in the Ira A. Fulton Schools of Engineering at Arizona State University. He teaches context-centered electrical engineering and embedded systems design courses, and studies the use of context an

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Abstract

This theory/methods paper seeks to understand what dimensions of integration and types of integrated learning outcomes have been explored in Integrated Engineering and identify areas for future work. A review of the literature is conducted, and using an interpretive and grounded theory approach, the state of Integrated Engineering is examined using established frameworks [1], [2], [3]. The review findings indicate that Integrated Engineering research, models, and competencies are rather broad, not well-focused, and connected to higher education and Engineering Education literature. We propose areas for future research and further suggest using a heatmap conceptualization/framework to measure the interest of the model and competencies in Integrated Engineering.

Keywords: Integrated Engineering, Engineering Education, Review

1. Introduction

This theory/methods paper seeks to expand and enhance understanding of Integrated Engineering models and competencies and offer areas for future work. We review the literature, and following an interpretive and grounded theory approach, we chart and characterize the state of Integrated Engineering principles and learning competencies in each study. The contribution of this work is to engage readers to reflect on their views towards Integrated Engineering within Engineering Education literature, gain an understanding of models and competencies of Integrated Engineering often explored within Engineering Education literature, and inform content from the gathered data that is useful for teaching and learning Integrated Engineering.

1.1 What is Integrated Engineering, and why is it important in Engineering Education

Integrated Engineering, motivated by pushes to connect topics across disciplines in practical contexts better, was noted by Froyd et al. to begin with three programs in 1988 [4]. Engineering Education is often noted as a complex system that requires helping students to think critically concerning real-world problems that are often ill-structured [5]. Integrated Engineering was developed to de-center generic theoretical teaching in the classroom and instead emphasize real-world application and contextual engineering work, often carried out by multiple disciplines, and requires holistic and worldly perspectives. [6]. The authors note that integrated curricula connect to a larger movement in higher education—learning communities, which help learners build interdisciplinary and social links within a community [7]. In engineering specifically, views such as Froyd's and others considering integrated curricula, such as interdisciplinary thinking, have been considered. Attempts have been made to make teachers teach and students develop a wide range of knowledge and skills.

1.2 Work to date and the identified gap

Mitchell et al. [8] developed a programmatic framework across engineering departments to ensure students achieve a range of competencies, including technical (in a specific engineering discipline), scientific, and mathematical knowledge, along with transferable skills such as communications, teamwork, business acumen, and critical analysis. Such programs are developed with alignment to the philosophies, pedagogies, and outcomes of an educational-based project, which creates a connected curriculum. [8]. Trevelyan and colleagues focused on enhancing the learning side by developing an Integrated Engineering foundational course with what the authors call a “combination of variation theory and capability theory, content framed in terms of threshold concepts, and delivery using cooperative peer learning method[s]” (p. 1) [9].

Lin and Low have recently proposed an Integrated Engineering Education Alignment Model for Industry 4.0. The authors report that the integrated alignment model nurtures synergy among Engineering Education activities such as applied learning, applied research, and continuous education training (CET) programs to share a common Industry 4.0 vision with diverse stakeholder groups such as students, faculty, industry partners, and recipients of CET programs. The authors use the Singapore Smart Industry Readiness Index (SIRI) to achieve alignment between engineering activities. This tool, which was developed in 2017, SIRI, was designed to be a comprehensive tool to help industrial companies harness the potential of Industry 4.0 [10].

Cheng focuses on creative engineering design courses as an example to introduce various design methods into interactive teaching by using the problem/project-based learning (PBL) and science, technology, engineering, arts, and mathematics (STEAM) model [11]. The findings of their study show that students prefer to work in groups, interact with peers to learn in real-time, and apply what they learn for future career development. The authors find that their education model integrates academic theory and industrial practice, reducing the gap between learning and industry practice.

1.3 Goal and research questions

While research exists on integrated curricula and Integrated Engineering curricula specifically, less is known about the overall state of the literature on the models and competencies surrounding Integrated Engineering Education. We thus find a timely review of Engineering Education literature to help explore the integrated models and competencies associated with Integrated Engineering in this field.

We review the literature and seek to examine the following research question:
1. What are the models associated with Integrated Engineering in the literature?
2. What competencies are associated with Integrated Engineering in the literature?

These questions are posed to understand better what Integrated Engineering entails and how to help measure interest.

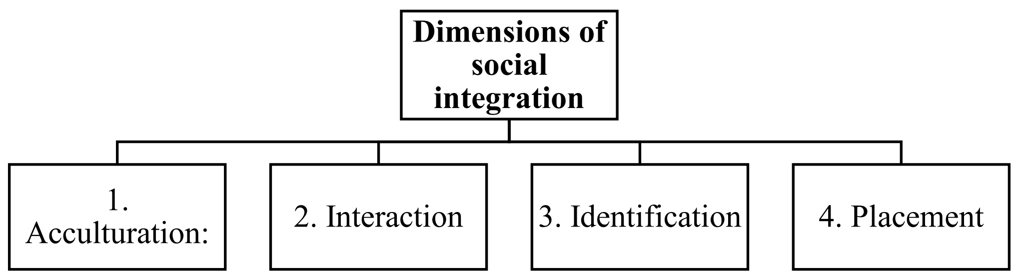
1.4 Frameworks

This paper utilizes established frameworks of integrated assessment. [1], and competence [12]. As shown in Figures 1 and 2, we seek to chart the state of Integrated Engineering in the Engineering Education literature.

The dimensions of integrated assessment are adapted from [1] and shown in Figure 1 are comprised of:

1. Acculturation: knowledge, language competencies, human capital
2. Interaction: Social relations, communication, network position, social capital
3. Identification: Values and norms, subjective feeling of belonging
4. Placement: rights, positions, economic capital

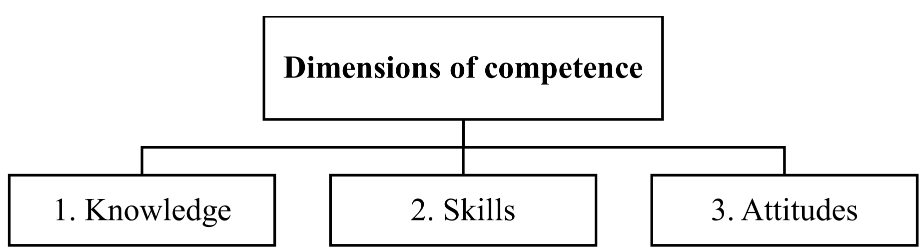
Figure 1
Dimensions of integrated assessment and modeling adopted from [1]



The dimensions of competence are adapted from [2], [3] and shown in Figure 2 are comprised of:

1. Knowledge: Understanding and familiarity with information
2. Skills: Applied behavior
3. Attitudes: Feelings and beliefs

Figure 2
*Dimensions of competencies adapted fr*om [2], [3]



2. Methods

We follow a systematic search process. [13] and use the thematic coding described below to extract data surrounding our research questions.

2.1 Search process

The Web of Science (WOS) and Scopus databases were used to search for review papers (accessed July 6, 2024). Following the criteria, the authors screened and assessed the studies for eligibility until a consensus was reached. We included articles published in international peer-reviewed journals, conference proceedings, and books. Our search included publications written in English during an unlimited time frame. We used the following search string:

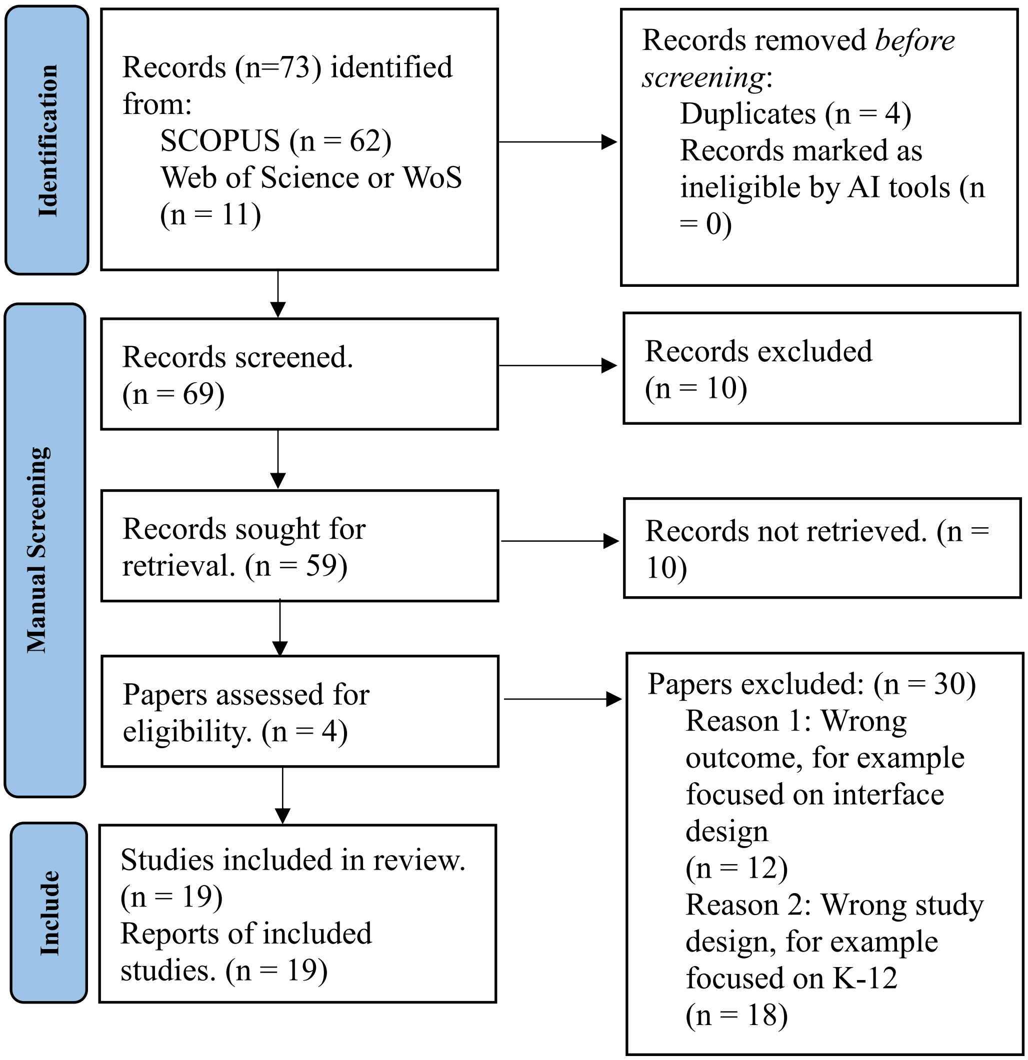
"Integrated Engineering" AND ("model" OR "theory" OR "theories" OR "framework" OR "concept" OR "competency" OR "competencies" OR "learning outcome" OR "learning objective" OR "objective" OR "skill" OR "graduate attribute" OR "ABET" OR "the Accreditation Board for Engineering and Technology") AND ("higher education" or "university") AND "Engineering Education"

We sought to include all studies that mentioned one or a synonym term. Hence, we used the OR operator. Since the focus is on Integrated Engineering in higher education settings, we include these terms via the AND operant. An overview of the inclusion and exclusion criteria can be found in Table 1, and the search process is summarized in the PRISMA chart shown in Figure 3. A total of 73 articles (11 from WOS, 62 from SCOPUS) were included. A total of 4 duplicates were removed. Our initial screening examined the titles and abstracts of papers and removed those that were not focused on Integrated Engineering. A total of 10 studies were not retrieved as they either had no online copy available or were missing key data pieces from the databases, such as the article name. Our secondary screening examined the remaining articles and selected those focused on Integrated Engineering in university or higher education contexts. This led to a total of 41 studies remaining for review.

Table 1
Inclusion and Exclusion Criteria

Criteria	Inclusion criteria	Exclusion criteria
Initial	Studies shared in English	Studies not written in English
	Article and conference proceedings	Grey literature
	Peer-reviewed	Not peer-reviewed
	Focused on Integrated Engineering	Not focused on or including Integrated Engineering
Secondary	Focused on higher education	Not focused on higher education
	Focused on Integrated Engineering curricula and concepts	Focused on mathematics, interface design, or areas not related to the Integrated Engineering curriculum and concepts

Figure 3
PRISMA chart



2.2 Codification and Analysis Process

Our protocol included the following steps:

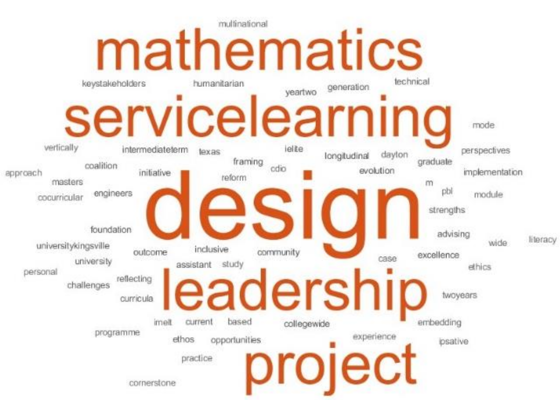
- Use the input string to search in both SCOPUS and WoS databases to download full records.
- Upload the full records to Covidence to identify and remove duplicate studies.
- Review each article and decide via consensus whether it is relevant.
- Gather the full records of studies selected for review.
- Code RQ1 with accompanying text/evidence from each reviewed article (see Appendix) RQ1. What models are associated with Integrated Engineering in the literature? 1. Acculturation: knowledge, language competencies, human capital; 2. Interaction: Social relations, communication, network position, social capital; 3. Identification: Values and norms, subjective feeling of belonging; 4. Placement: rights, positions, economic capital.

- Code RQ2 with accompanying text/evidence from each reviewed article (see Appendix). Coded RQ2. What competencies are associated with Integrated Engineering in the literature? 1. Knowledge; 2. Skills: 3. Attitudes.
- Use MATLAB to conduct qualitative analysis and follow MATLAB best practices to transform to lowercase, tokenize, erase punctuations, remove stop words, develop a word graph, bar graph, and scatter line summary of coded information.
- Code the exclusion of words, numbers, years and topics that were too general and provided little insight for the analysis, they were: "IE", "IEP", "integrating", "integrated", "Integrated Engineering", "engineering", "program", "assessment", "teaching", "curriculum", "year", "training", "development", "model", "framework", "skills", "outcomes", "competencies", "competency", "develop", "required", "courses", "students", "faculty", "ability", "years", "throughout", "evaluation", "assessment", "education", "Engineering Education", "2014", "1", "2", "3", "4", "5", "6", "7", "include", "increased", "added", "course", "three", "two", “appreciate", "understands", "awareness", "effective", "specific", "new", "first", "learning", "knowledge", "staff", "disciplines", "discipline", "connections"
- Synthesize future work areas and challenges.

3. Results

As described in the previous section, 19 articles were identified for review. First, we will present a demographic summary of the reviewed articles. Figure 4 presents a word cloud summary of the titles (a) and abstracts (b) of the reviewed articles. The word frequency analysis image in Figure 4a shows a heavy focus on design, project-based learning, leadership, service learning, and mathematics. The abstract image in Figure 4b frequently mentions students, universities, papers, projects, and curricula, suggesting the concentration of Integrated Engineering studies. Both images concern concepts more representative of the complexities of engineering work in the real world (e.g., multidisciplinary, service-oriented, design-centered).

Figure 4
Word cloud summary of title (a) and abstract (b)



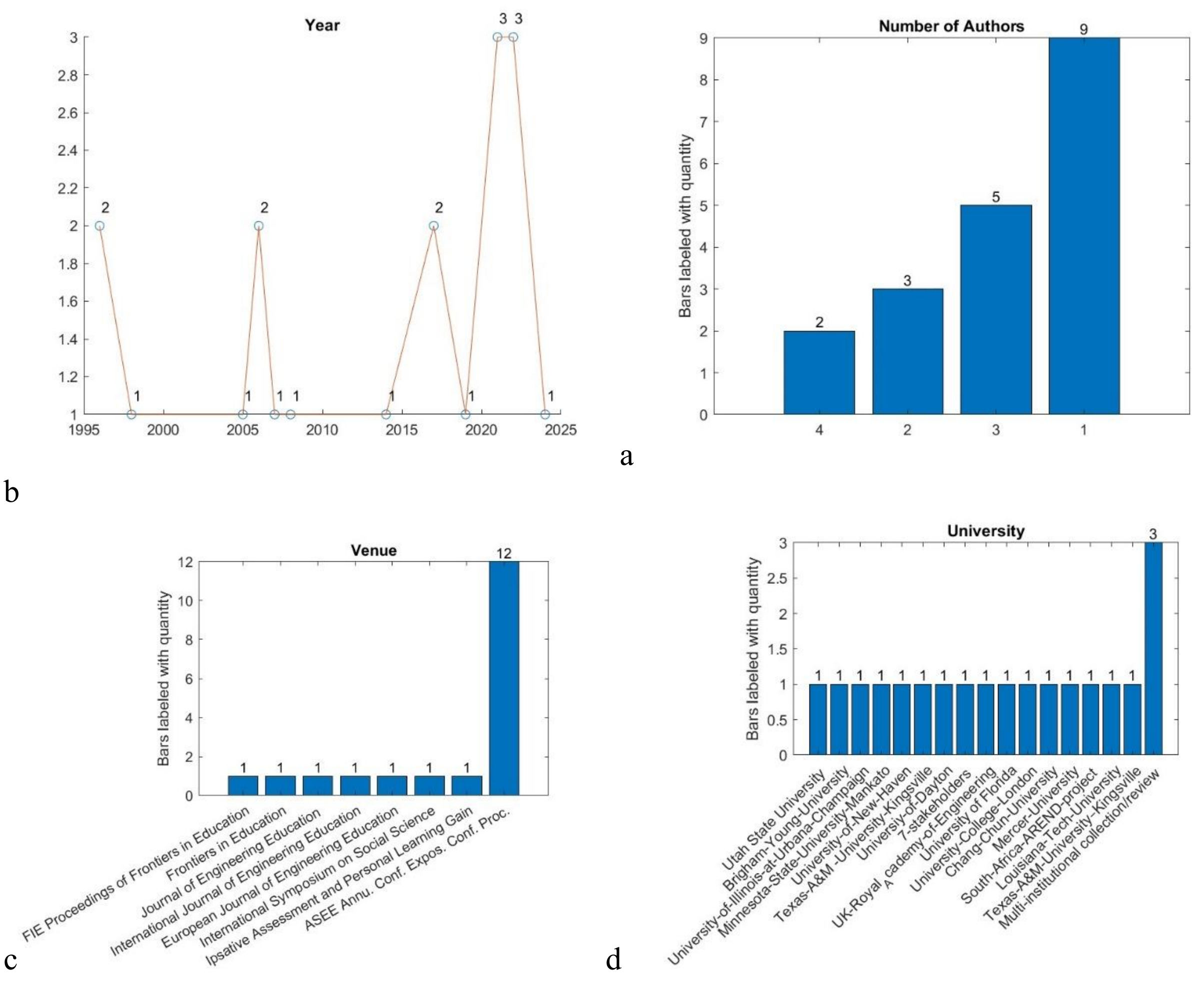
a

b

Figure 5 shows a scatter line summary of publications per year (a), a column bar summary of the number of authors (b), a column bar summary of the Venue of each published study (c), and a column bar summary of the University involved in the study. The number of publications across the years is inconsistent, spanning between 1996 and 2024 (refer to Figure 5a). This topic's existence since 1996 shows that this concept has existed for around 20 years. However, the work done on this topic is rather distributed and decentralized. This is evident from the frequent one-researcher publications (see Figure 5 b), done on a small scale at the conference venue (see Figure 5 c), and frequent deployment at one institution rather than multiple ones (refer to Figure 5 d)

Figure 5

Scatter line summary of publications per year (a), Column bar summary of the number of authors (b), Column bar summary of the Venue of each published study (c), and Column bar summary of the University involved in the study



This section summarizes the review's findings against the two research questions. A summary of references and findings is shown in Table 2, and a detailed version with accompanying text can be found in the Appendix.

Table 2
Summary of reviewed studies

RQ1. What models are associated with Integrated Engineering in the literature? **1. Acculturation: knowledge, language competencies, human capital** **2. Interaction: Social relations, communication, network position, social capital** **3. Identification: Values and norms, subjective feeling of belonging** **4. Placement: Rights, positions, economic capital**	**RQ2. What competencies are associated with Integrated Engineering in the literature?** **1. Knowledge** **2. Skills** **3. Attitudes**	**Example Reference**
12	23	[14]
12	12	[15]
124	123	[16]
23	23	[17]
2	123	[18]
1	2	[19]
13	1	[20]
3	2	[21]
13	23	[22]
24	2	[4]
23	12	[23]
13	N/A	[24]
14	12	[25]
2	12	[26]
13	123	[27]
12	23	[28]
23	123	[29]
13	12	[30]
21	123	[31]

3.1 What are the models associated with Integrated Engineering in the literature?

Our first research question explores the models associated with Integrated Engineering across the 19 reviewed studies. The dimensions of integrated assessment are adapted from [1] and comprises:

1. Acculturation: knowledge, language competencies, human capital
2. Interaction: Social relations, communication, network position, social capital
3. Identification: Values and norms, subjective feeling of belonging
4. Placement: rights, positions, economic capital

Figure 6 presents a word cloud summary of terms associated with models used for Integrated Engineering (a) and a bar graph summary of the dimensions employed from [1] across the 19 reviewed studies (b). The textual overview of models employed (Figure 6a) may suggest the broadness of model explanations and how they are defined with holistic terms such as design, science, system, practice, process, etc. The codification overview of models employed (Figure 6b) suggests that the most frequent trends are:

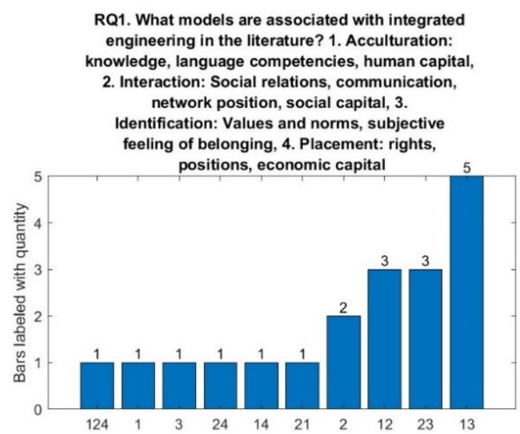
- 1. Accumulation of knowledge, language competencies, and human capital 3. Identification of values and norms and subjective feeling of belonging are studied the most (5/19, 26%), followed by
- 2. Interaction of social relations, communication, network position, and social capital 3. Identification of values and norms, subjective feeling of belonging (3/19, 16%), and
- 1. Accumulation of knowledge, language competencies, human capital, and 2. Interaction of social relations, communication, network position, and social capital (3/19, 16%)

The model of 4. Placement: rights, positions, and economic capital were not studied across the reviewed studies as a standalone model. These findings may suggest that 1. Acculturation, 2. Interaction, and 3. Identification models in a silo or combinations are more associated or explored with Integrated Engineering, and 4. Placement is less studied.

Figure 6

Word cloud summary of terms associated with models used for Integrated Engineering (a) and a bar graph summary of the dimensions employed from [1] Across the 19 reviewed studies (b).

a



b

3.2 What competencies are associated with Integrated Engineering in the literature?

Our second research question explores the competencies associated with Integrated Engineering across the reviewed 19 studies. The dimensions of competence are adapted from [2], [3] and shown in Figure 3 are comprised of:

1. Knowledge: Understanding and familiarity with information
2. Skills: Applied behavior
3. Attitudes: Feelings and beliefs

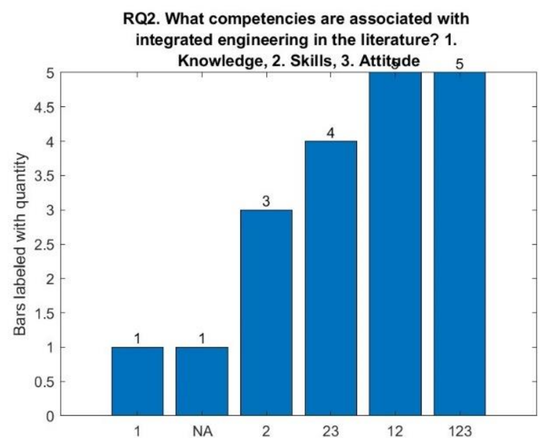
Figure 7 presents a word cloud summary of terms associated with competencies used for Integrated Engineering (a) and a bar graph summary of the dimensions adapted from [2], [3] across the 19 reviewed studies (b). The textual overview of competencies employed (Figure 7a) may suggest the socio-technical-cultural emphasis of competency explanations and how they are defined with holistic terms such as professional, global, ethical, etc. The codification overview of competencies employed (Figure 7 b) suggests that the most frequent trends are:

- 1. Knowledge: Understanding and familiarity with information 2. Skills: Applied behavior and 3. Attitudes: Feelings and beliefs are studied the most (5/19, 26%), along with
- 1. Knowledge: Understanding and familiarity with information, with Skills: Applied behavior is studied the most (5/19, 26%), followed by
- 2. Skills: Applied behavior with 3. Attitudes: Feelings and beliefs (4/19, 21%),

The competency of 3. Attitudes: Feelings and beliefs have not been studied across the reviewed studies as a standalone competency. These findings may suggest that Knowledge and Skill competencies in silo or combinations are more associated or explored with Integrated Engineering, and 3. Attitudes are less studied.

Figure 7
Word cloud summary of terms associated with competencies used for Integrated Engineering (a) and a bar graph summary of the dimensions adapted from [2], [3] *across the 19 reviewed studies (b).*

a



b

4. Discussion

This section shares a summary of findings and the synthesis of the reviewed studies with implications and suggestions on areas for future work. We conducted a systematic review of the literature on Integrated Engineering. After a review of 19 relevant studies, we realized that Integrated Engineering research, models, and competencies are rather broad and not well-focused and connected to higher education and Engineering Education literature.

4.1 Summary of demographic findings and areas for future work

Our demographic summary analysis of the reviewed articles emphasized design, project-based learning, leadership, service learning, and mathematics. Integrated Engineering research and curriculum intends to be more student-centered, contextualized at the university and not the university with the K-12 setting, and contain deliverables often in the form of projects and papers done individually and in teams. Future work may consider examining such broad terms in contextualized domains and reporting on the landscape of Integrated Engineering in practice more fully. Moreover, future work could consider pathway connections for Integrated Engineering at both K-12 and university undergraduate, graduate, and post-graduation levels, such that they are aligned and lead to K-16+ and life-long learning experiences.

We found inconsistencies in the number of publications across years, suggesting that this notion has received different amounts of attention across different years. Nevertheless, this topic has been around since 1996 (nearly 30 years at the time of this writing), suggesting its persistence and importance in the Engineering Education curriculum. However, the work on this topic is rather distributed and decentralized, with a limited number of researchers working on each study, venues of publications (often disseminated at the American Society for Engineering Education conference proceedings as opposed to Engineering Education journal venues), and limited multi-institutional efforts. Future work could benefit from more centralized, consistent, and aligned efforts, preferably with a larger pool of researchers, educators, and institutions involved, both at the national and international levels.

4.2 Summary of model findings and areas for future work

The first research question attempts to explore the models associated with Integrated Engineering across the reviewed 19 studies. The textual overview of models employed may suggest the broadness of model explanations and how they are defined with holistic terms such as design, science, system, practice, process, etc. Future work could focus on contextualizing and explaining Integrated Engineering models with theory and frameworks in cognitive and learning sciences and higher education theories to bridge the gap between Engineering Education practice and pedagogical theory. The codification overview of the models employed is adapted from [1] Moreover, it comprises: 1. Acculturation: knowledge, language competencies, human capital, 2. Interaction: Social relations, communication, network position, social capital, 3. Identification: Values and norms, subjective feeling of belonging, and Placement: rights, positions, and economic capital. Findings showed that the model of 4. Placement: rights, positions, and economic capital are not studied across the reviewed studies as a standalone model. These findings may suggest that 1. Acculturation, 2. Interaction, and 3. Identification models in silo or combinations are more associated or explored with Integrated Engineering and 4. Placement is less studied. Future work could benefit from acknowledging and scoping the role of Placement: rights, positions, and economic capital on the Integrated Engineering experience and outcomes.

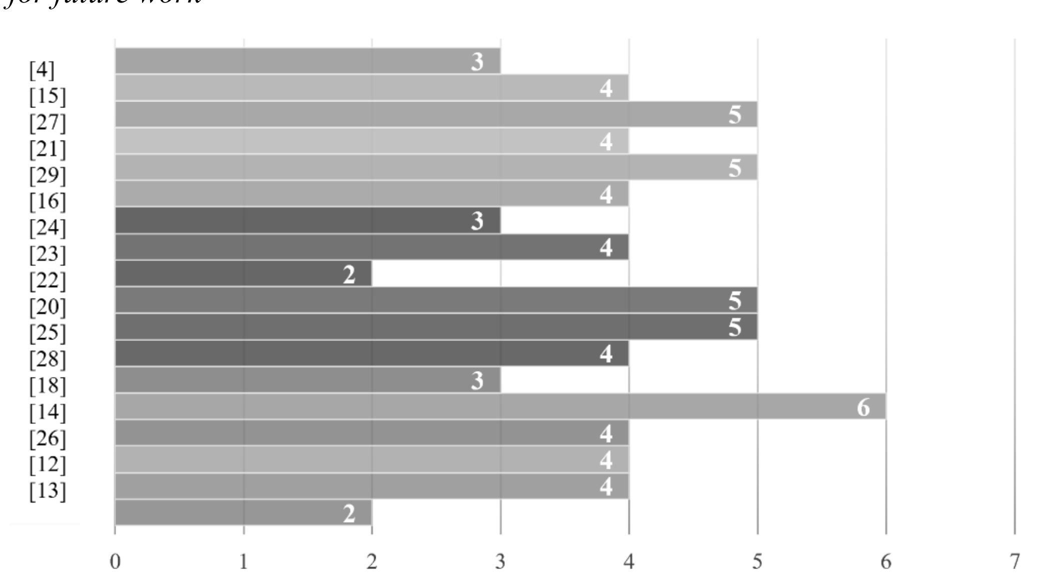
4.3 Summary of competency findings and areas for future work

The second research question explores the competencies associated with Integrated Engineering across the reviewed 19 studies. The textual overview of competencies employed may suggest the socio-technical-cultural emphasis of competency explanations and how they are defined with holistic terms such as professional, global, ethical, etc. Future work can examine what may constitute such competencies, especially in light of technological reforms with Artificial Intelligence or AI. The codification overview of competencies employed is adapted from [2], [3] and comprises: 1. Knowledge: Understanding and familiarity with information, 2. Skills: Applied behavior, and 3. Attitudes: Feelings and beliefs. Findings show that the competency of 3. Attitudes: Feelings and beliefs are not studied across the reviewed studies as a standalone competency. These findings may suggest that Knowledge and Skill competencies in silo or combinations are more associated or explored with Integrated Engineering and 3. Attitudes are less studied. Future work can examine what may constitute such competencies, especially in light of technological reforms with Artificial Intelligence or AI.

4.4 Suggested framework for Integrated Engineering model goals and competencies

In summary, we suggest that employing the dimensions of integrated assessment adapted from [1] and the dimensions of competence, adapted from [2], [3] could lead to an enhanced understanding of the state of Integrated Engineering for future work. Table 2 presents the state of the 19 reviewed literature against the backdrop of Integrated Engineering models and competencies. As shown, there is a significant variety in the type of models, skill categories, and combinations employed. Using the suggested framework of models and competencies may allow future research to chart the competencies needed for each model type, leading to a quality map conceptualization as shown in Figure 8. Each study's quality may then be examined by counting the dimensions in each model and the competency frameworks considered. Subsequently, their sum yields a quality map on Integrated Engineering models and competencies from the reviewed studies, which may be prescribed as shown in Figure 8. Note that the value for each study is derived from: the number of model dimension quality + the number of competencies dimension quality outlined in Table 3.

Figure 8
Quality map on conceptualization of Integrated Engineering models and competencies employed for future work



4.5 Limitations of the study

We find some limitations in this work. First, we only considered studies that had contextualized Integrated Engineering contexts and, as such, omitted including studies that may have explored Integrated Engineering in non-academic and Engineering Education areas. Also, we found many studies that touch upon Integrated Engineering models and competencies briefly, but do not define or examine them in detail, and in journal venues. This review and findings are generalizable to the 19 reviewed studies, predominantly from the American Society of Engineering Education conference proceedings.

5. Conclusion

This theory/methods paper seeks to expand and enhance the understanding of Integrated Engineering models and competencies. Following an interpretive and grounded theory approach, we reviewed the literature and charted and characterized the state of Integrated Engineering principles and learning competencies in each study. The contribution of this work is to engage readers to reflect on their views towards Integrated Engineering within Engineering Education literature, gain an understanding of models and competencies of Integrated Engineering often explored within Engineering Education literature, and inform content from the gathered data that is useful for teaching and learning Integrated Engineering.

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