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# A Scoping Review of Concept Inventories in Engineering Education

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# WIP: A Scoping Review of Concept Inventories in Engineering Education


## Abstract

The present work in progress study synthesizes research evidence on Concept Inventories (CIs) in engineering education. We examined 25 studies conducted in various countries and different learning contexts in terms of study characteristics and methodology. The current study found that CIs have become prevalent tools in gauging students' understanding and identifying misconceptions in engineering field. The study identifies Statics concepts as the central theme, constituting 33.33% of the studies, and emphasizes the prevalence of quantitative research methods (61.54%). However, our analysis exposes a critical gap in the examination of its psychometric properties, as less than 30% of the studies assessed the reliability and validity of CIs. The findings emphasis the need for engineering education researchers should focus on psychometric properties of CIs in order to enhance the reliability and validity.



Keywords: Concept Inventories, Engineering Education, Misconceptions, scoping review


## Introduction

Assessing conceptual knowledge plays a crucial role in advancing engineering education [1]. Concept inventories have been used copiously in the extant research literature to assess knowledge misconception, conceptual understanding, and conceptual knowledge gain [2]. Concept inventories (CIs) are assessment instruments for gauging students' comprehension of fundamental engineering concepts and identifying misconceptions [2, 3]. Concept inventories facilitate scientific literacy, support teaching improvements, and foster curricular reform [4]. For example, by using CI, engineering instructors can tailor their teaching to address specific students' misconceptions that the CI identifies.

Previous studies have acknowledged the effectiveness of CIs in evaluating students' understanding of concepts, highlighting their role in assessing teaching methods and curricula [5, 6]. For example, *Almstrum* et al. *[3]* proposed the Discrete Math Concept Inventory (DMCI) to offer the computing education community a standardized tool for widespread use in research on computing education. They envisioned that the standard tool would serve as a reference point, enabling objective assessments of the relative performance of a chosen group of students across various applications of the inventory.

Furthermore, students' CIs performance may offer insights into various attributes such as problem-solving skills [4]. The assessment inventories can also play a crucial role in evaluating the efficacy of teaching techniques or pedagogy on student learning outcomes [5]. For example, in the study by Sands et. al. [6], force concept inventories (FCIs) were used to assess students' learning gains in teaching Newtonian mechanics through a 3-D visual programming environment.

While various CIs have been developed for measuring engineering concepts, there is a lack of comprehensive awareness of these instruments within the engineering education community. As instructors may be unaware of relevant CIs that could enhance their understanding of students' misconceptions and conceptual understanding of the concepts they teach in class. Neither would they understand the psychometric properties of such instruments. To address this gap, a scoping review and systematic evaluation of CIs in engineering education literature are urgently needed. Such a review can offer valuable insights for instructors and researchers, guiding them in selecting appropriate assessments for courses and enhancing overall teaching quality.

## Literature Review

*Misconceptions:* Students often hold misconceptions about the science and engineering concepts they encounter in their classes[7]. Researchers argued that students acquire such misconceptions while trying to make meaning of their daily experiences[8]. While misconceptions may have explanatory value, they  constitute hurdles to learning and the development of scientific knowledge [9], and do negatively impact learning performance [10].

Concept inventories can be traced to the 1980s with the development of assessment instruments such as the Force Concept Inventory (FCI) [6, 11]. The success and impact of the Force Concept Inventory led to increased interest in developing similar assessment tools in other disciplines. For example, concept inventories have been developed to identify common misconceptions and conceptual understanding in areas such as mechanics, thermodynamics, electrical circuits, chemicals, and materials science etc.

Concept inventories are mostly in the form of multiple-choice, and typically have been used for formative assessment. They are regarded as standard measurement tools for comparing the pedagogical efficacy between courses, academic sessions, and higher institutions of learning [6]. To establish students' conceptual understanding and identify firmly held misconceptions, distractors are built into the multiple-choice question as incorrect choices based on widespread student misconceptions [12]. Researchers and test developers often use various means such as pilot interviews, think-aloud sessions, and responses to open-ended questions to evaluate students' misconceptions and use those as distractors in the concept inventory [13]. Researchers can better comprehend students' thought processes and, occasionally, deeply held beliefs—by looking at the distractions that students select.

Several concept inventories have been developed and disseminated over the years. For instance, in the field of engineering graphics, the development of a concept inventory has been proposed to identify misconceptions and competencies [14]. Bursic [15] has developed a concept inventory for engineering economy, Ngothai [14] developed the Chemical Engineering Fundamentals Concept Inventory (CEFCI) among others.

Research has shown that concept inventories can effectively evaluate students' conceptual understanding in engineering courses and identify deep-seated misconceptions that students held from previous learnings. [14]

### *Rationale for current study*

Concept inventories play a vital role in assessing students' conceptual understanding, identifying misconceptions, and improving instructional strategies in engineering education. Several concept inventories have been developed in all STEM fields, including in engineering. With such proliferation of concept inventories however, there has been minimal effort to curate existing inventories. Hence, instructors and researchers who may need such inventories of engineering concepts are either unaware of their existence, or do not know how to locate them.
Hence, there is an urgent need in literature to curate all existing concept inventories for engineering subjects. Recognizing this gap, we propose conducting a scoping review to explore the extent of concept inventories in engineering education. Such a review will contribute to the broader understanding of the landscape of concept inventories in engineering and inform future research directions in this field.

## Research Methodology

A scoping review's primary aim is to synthesize a body of knowledge related to a particular area of research interest. Tait [16] advocated that a scoping review can adequately inform others about existing research questions within a field. However, there is no standard methodology for scoping reviews and continued debate and discussion about optimizing protocols to improve their usefulness and rigor are encouraged [17-19]. In this paper, we adopt the six-stage framework outlined by [20] in conducting systematic reviews: scoping, planning, searching, abstract screening, full-text sifting, extracting, and synthesizing information.

*Scoping:* The scoping stage is pivotal in stating the research questions, considering the wide spread use of Concept inventory in Engineering. Given the novelty of this research, as no prior review of CIs in engineering education exists and considering the widespread use of CIs, this scoping review aims to answer the following research questions:

1. What are the substantive features of the included studies, such as publication information and students' educational levels?
2. What are the methodological features of the included studies, such as the research methods employed and sample sizes?
3. What are the various concept inventories (CIs) developed and used in engineering education?
4. How have these CIs been used in the assessment of student learning?

*Planning:* During this phase, the inclusion and exclusion criteria were developed using the PICO framework (Population, Intervention, Comparison, and Outcome). This framework has been employed widely to develop search strategies for systematic reviews[21].

*Searching Strategy:* An extensive search of the academic databases available at the First Author Online University Library was conducted. The databases included ERIC, Science Direct, IEEE, GALE, Social Science, APA, Social Sciences Citation Index, Science Citation Index Expanded, APA PsycINFO, Education Research Complete, Academic Search Complete, IEEE Xplore Digital Library, Directory of Open Access Journals, MEDLINE with Full Text, ScienceDirect, Science & Technology Collection, and ACM. Prioritizing sensitivity, we included synonyms and related terms. The search string used was:

All the databases were simultaneously searched through the advanced online University Library, and in the initial search, 3,552 articles were identified. The subsequent search was refined with the following criteria:

**(Concept Invent* OR diagnostic) AND (Validity OR develop* OR psychometric) AND (Engineering)**

*Eligibility criteria:* To qualify for inclusion in this study, articles must have satisfied the followings inclusion criteria:

1. Publicly accessible peer reviewed Journal/conference papers in English language.
2. The article must be presented in English as we lack the resources to translate articles presented in other languages.

3. Engineering contents articles that focused on software engineering and computer science were excluded.

These refinements resulted in the identification of 93 articles for further review. We imported them into Rayyan AI, an online artificial intelligence platform for further reviews [22]. Rayyan AI detected 13 duplicates, resulting in 57 articles. Figure 1 shows overview of the selection process.

*Abstract screening:* For abstract screening phase, we read through the abstract of each article and identified 43 relevant papers that focused only on concept inventories in Engineering.

*Full Text sifting*: During the full text sifting phase, following Siddaway [20] recommendation to shift "emphasis from sensitivity to specificity", our focus centered on Concept Inventories in engineering. We gave particular attention to the development of concept inventories and their utilization in engineering. Work-in-progress concept inventories were excluded from this study. Through this approach, we identified 30 studies for inclusion in our review.

*Extracting and synthesizing relevant information:* The remaining 30 articles were divided into two with two authors coming together to develop a coding sheet using Microsoft excel. We extracted information about scope of study, Grade Level, Engineering Domain, Misconceptions identified, types of CIs used, was the CIs used or developed, and Reliability/Validity. We further excluded 5 articles that did not meet the inclusion criteria and analyzed the remaining 25 articles using the developed coding sheet.

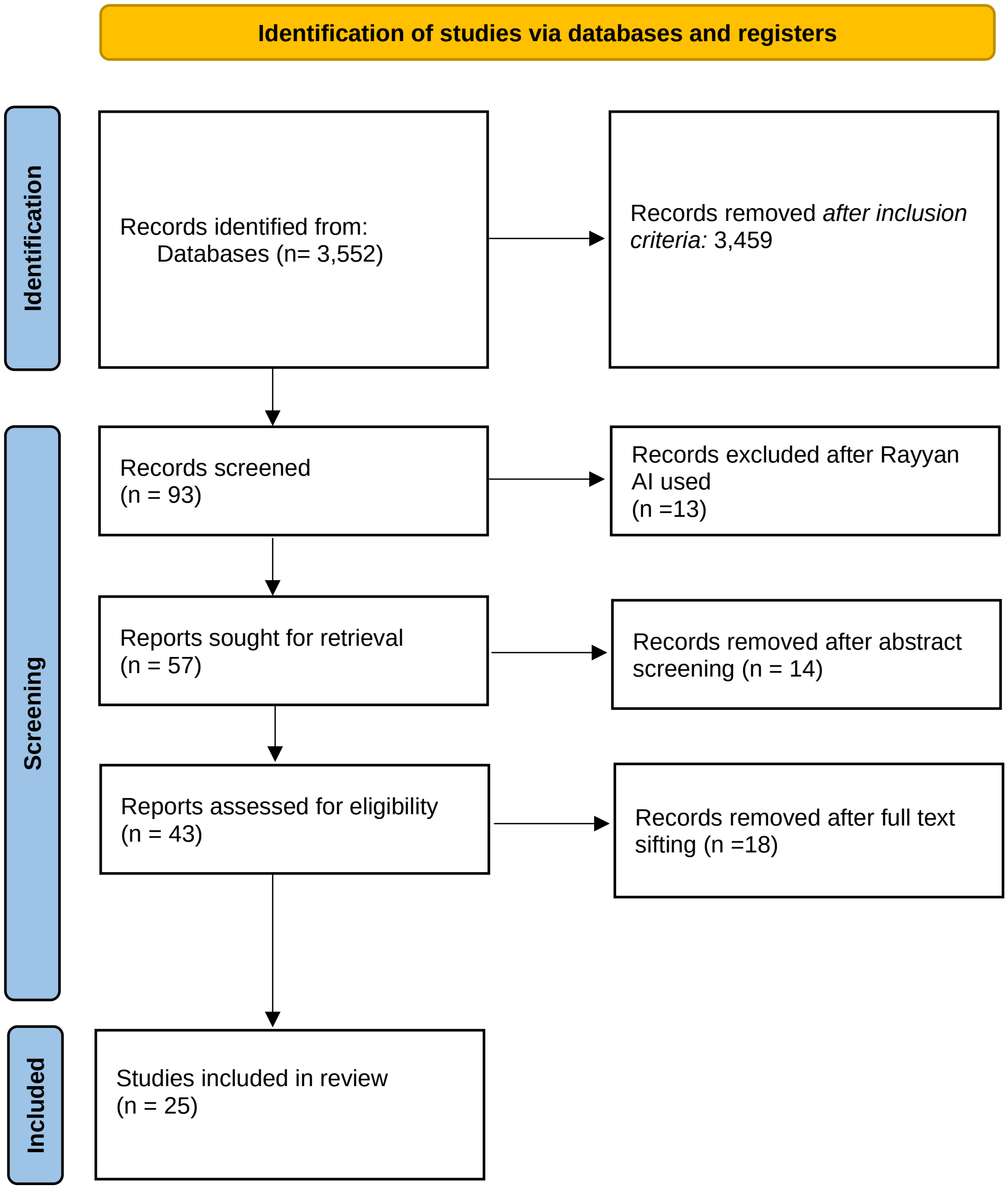


Fig 1: Overview of the selection process for the review

*Substantive features of the studies:* Substantive features of the studies included publication information, students' country, types of CIs, students' subject area or discipline, and education level. We coded the publication type as a journal article or conference paper. We analyzed the publication years, by doing so, we aimed to view the publication trends since the inception of the Force Concept Inventory in 1985. The education levels were all higher education (undergraduate and graduate level). We specifically group the undergraduate level into first year, sophomore, junior and senior.

*Methodological features of the studies*: Methodological characteristics of the studies include research methods and sample size. Research methods were categorized into three approaches: Quantitative (with statistical procedure), Qualitative (without statistical procedure) and mixed method, a combination of the two. We also coded the sample size within the included studies.

## Results and Discussion

### ***Findings about the substantive features of the studies***

*Publication information:* Out of the 25 articles that we reviewed 36% of the articles were published between 2008 and 2015. Figure 2 shows the percentage of articles published about concept inventory used in engineering between 1998 to 2023. The number of articles per journal and conferences included in the current scoping review is listed in Table 1.

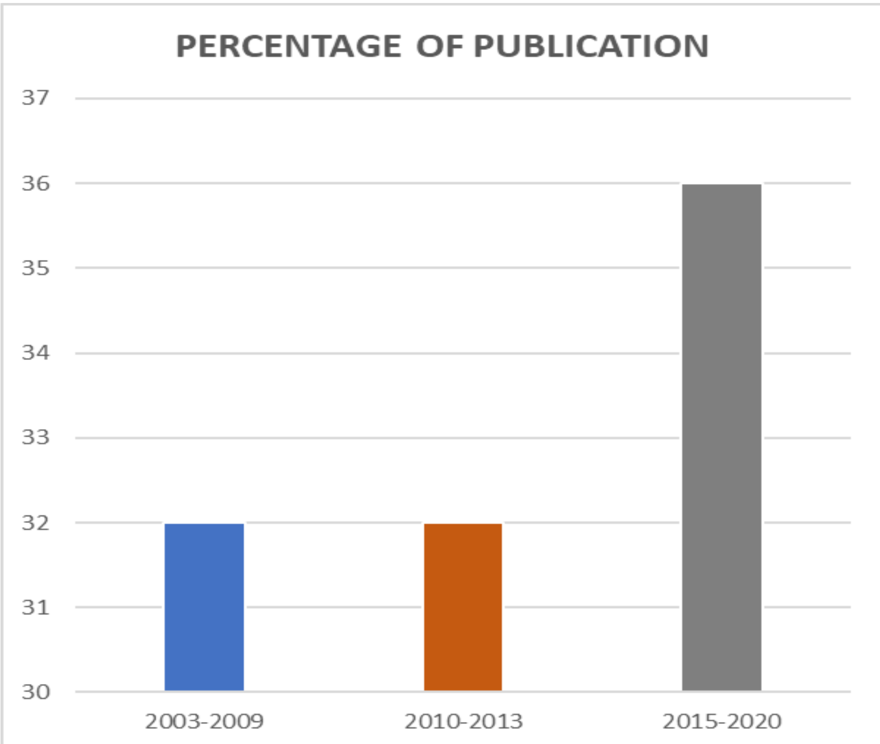


Figure 2. Number of publications by years

**Table 1**

**Journal and conference papers of included articles**

| Journal | Number of articles per Journal |
|---|---|
| International Journal of Science and Mathematics Education | 1 |
| European Journal of Engineering Education | 1 |
| America Journal of Physics | 1 |
| Journal devoted to the problems of capital investment | 1 |
| IEEE Transactions on education | 3 |
| Education for chemical engineers | 3 |
| ASEE | 3 |
| Journal of Engineering education | 4 |
| IEEE Frontiers in Education | 8 |

*Study Characteristics:* The distribution of studies reveals a predominant emphasis on the United States, comprising 16 studies, which corresponds to 66.67% of the total. Figure 3 shows the Geographic distribution of the included studies. This distribution aligns with existing research that highlights the predominant influence of the United States, particularly in the realm of engineering. The concentration of studies in the U.S. suggests its significant role in shaping policies and funding within these domains [23, 24] This dominance is further underscored by the heightened productivity of the U.S. in STEM education research [25].

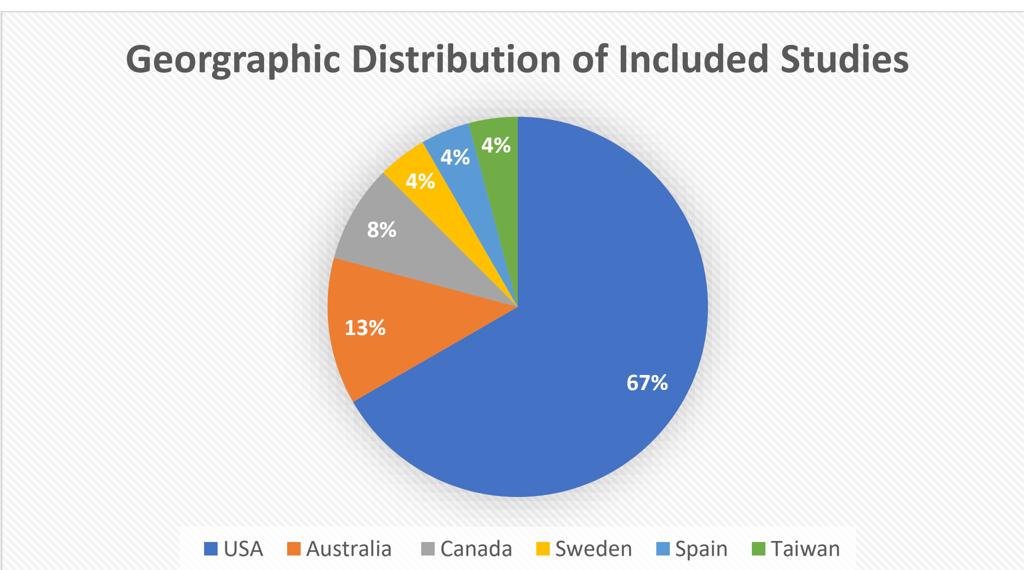


Figure 3: Geographic distribution of included studies

The predominant focus of Concept Inventories (CIs) lies in the undergraduate educational level, specifically targeting Freshmen, Sophomores, Juniors, and Seniors. Additionally, some studies adopted a cohort group approach. Figure 4 shows the distribution of concept inventory across educational level. A notable observation emerges when transitioning across educational levels, wherein the focus on misconceptions undergoes a discernible shift. These findings align with our expectations, emphasizing a noticeable gap in the attention given to misconceptions and their measurement as we move up the ladder in academic levels. However, there is a noticeable gap in the literature on the measurement and impact of misconceptions at the graduate level [26].

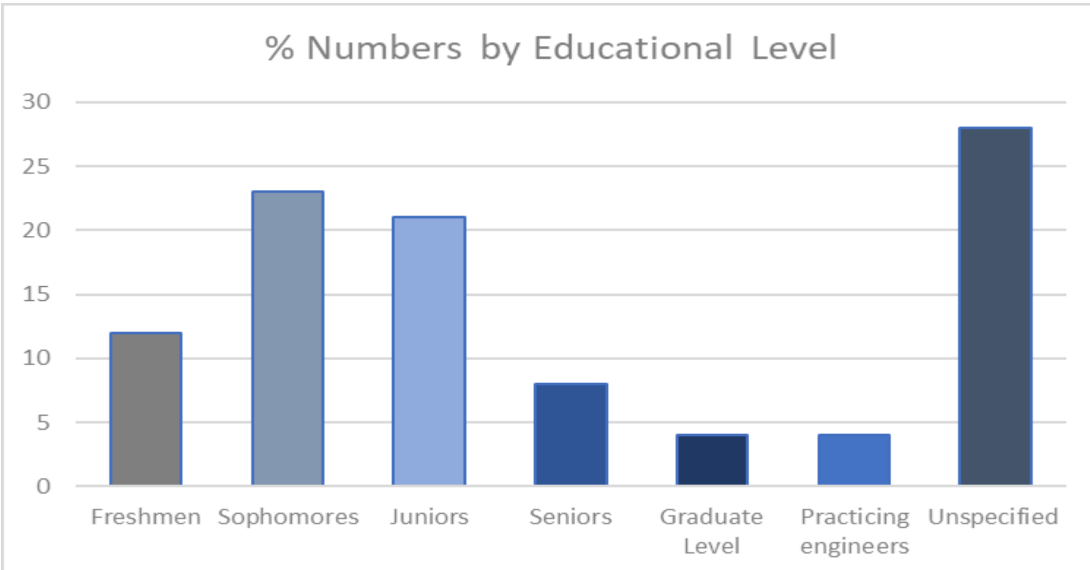

Figure 4: Distribution of Concept Inventory across educational level

Concerning students' subject areas, our analysis indicates a significant distribution across fundamental engineering concepts. Statics principles emerge as the most prominent, comprising 33.33% of the studies, highlighting the substantial focus on statics concepts in fundamental engineering education. Newtonian Mechanics, Dynamics, and Fluid follow closely at 22.22%, while Fundamentals Concepts in Signal, Control, and Power contribute 16.67%. Chemical Engineering Fundamentals, along with Engineering Graphics and Hydrology, and Heat and Energy Fundamental Concepts each comprise 11.11%, showcasing a well-distributed coverage. Material and Energy Balance, as well as Engineering Economy, constitute 5.56% of the studies.

**Findings about the methodical features of the studies**

*Research methods:* In our analysis, we categorized the research methods in each of the 25 included studies. The most prevalent approach among these studies was a quantitative methodology (n = 15, 61.54%), followed by mixed methods (n = 9, 34.62%), and a qualitative methodology (n = 1, 3.85%). This pattern aligns with the findings of *Xu et al*. [27] scoping review on digital game-based technology in English language learning, which highlighted the prevalence of quantitative methods. Given the nature of Concept Inventories (CIs) and their applications, it was expected that many studies would opt for quantitative methods. This trend has implications for the broader understanding and application of CIs in educational research. Figure 5 shows the distribution of research methods used in the articles reviewed.

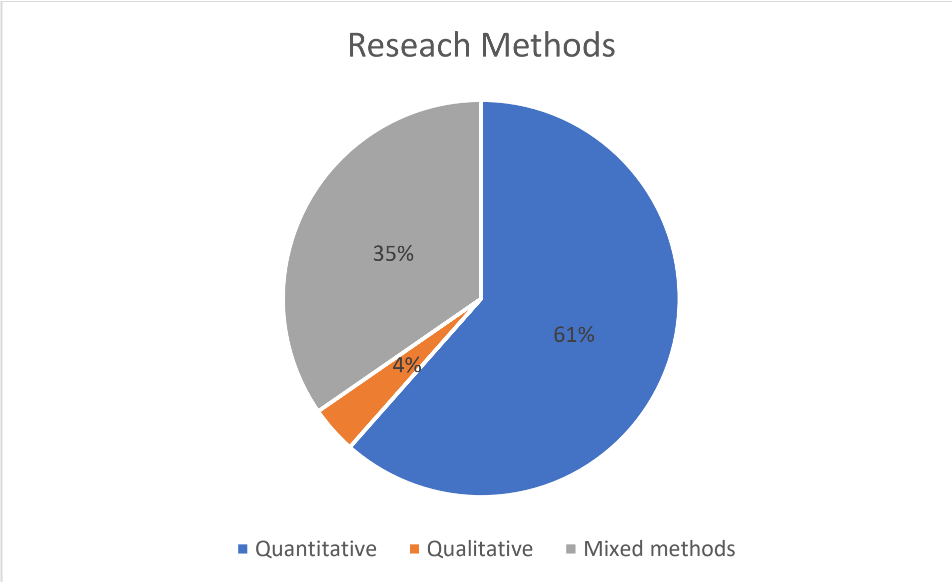


Figure 5. Types of Research Method.

*Sample Size:* According to *Slavin and smith* [28], studies with small sample sizes tend to report larger effect sizes, thus yielding potential bias. Therefore, reporting sample size information is important for critically evaluating studies. Since most of our included studies employed a quantitative methodology, we adhered to the commonly used quantitative research guidelines: studies with less than 100 participants were coded as small samples, studies between 100 and 250 were coded as medium, and studies with more than 250 participants were categorized as large samples[27-29].Among the 25 studies, 16% (n = 4) involved a small sample size, 28% were coded as medium sample size (n = 7), 24% qualified as having large sample size (n = 6) and 32% (n= 8) of the studies included do not specify their sample size.

*Types of Concept Inventory used in Engineering: In* our scoping review study, we observed distinct patterns regarding their utilization. Notably, Statics Concept Inventory (SCI) emerged as the most frequently employed CI in engineering, constituting approximately 30.77% of the included studies. Following closely is the Force Concept Inventory (FCI), utilized in approximately 23.08% of the studies. This distribution highlights the prevalence of SCI in engineering education, emphasizing its significance as a widely adopted assessment tool within the scope of our research.

*How have these CIs been used in the assessment of student learning?* Most Concept Inventories (CIs) served as both pre- and post-tests to assess conceptual gains following instructional interventions. Specifically, 15 studies adopted CIs in this manner to gauge students' comprehension before and after learning experiences. Existing literature underscores the importance of measuring conceptual change or students' prior knowledge. However, despite numerous studies highlighting shifts in conceptual gains post-test, there is a noticeable gap in the literature regarding the thorough examination of the reliability and validity of CIs utilized in the realm of engineering education.

**Conclusion and Future Study**

Although this is a work in progress review, we synthesized evidences from 25 articles that met our inclusion criteria. Our study has provided a comprehensive overview of substantive and methodological features of included studies. Particularly, the review encompasses study characteristics, sample characteristics, methods, publication source, and list of CIs used in engineering education. Our results revealed that CIs are applicable across engineering education disciplines and that sample sizes varied across studies, showing the contextual nuances of the included studies.

In addition, our review shows that the primary use of CIs in engineering education is to gauge students' understanding and to uncover any prevailing misconceptions. It also revealed that the predominant use of CIs is in undergraduate education, accounting for 90% of the studies examined. However, there is need for studies that examine the use of CIs to examine student conceptual understanding at graduate level as researchers have shown that students still have misconceptions even after graduation. For example, Maries and Li [30, 31] emphasize the critical need to examine the impact of misconceptions at the graduate level, recognizing that misconceptions persist at all educational levels. Furthermore, our review highlights a significant research gap in the studies reviewed as many of them did not report psychometric properties of the concept inventories used. Less than 30% of the studies in our review assessed the reliability and validity of the CIs used. It is important for researchers to examine the reliability and validity of instruments used for conducting their studies as this would affect the interpretation and the robustness of the findings.

In conclusion, our scoping review has provided useful insight into the usage of CIs in engineering education. By highlighting critical areas for further exploration, including the need to examine the psychometric properties of CIs used in engineering education, future research can be conducted with more rigor to identify and address engineering students’ misconceptions. As a next phase, we are embarking on a systematic review of CIs in engineering. This endeavor seeks to uncover more patterns regarding their usage and assess the overall reliability and validity of CIs in engineering field.

Appendix A: List of Concept Inventories developed and used in Engineering education within the included studies

| S/N | Author(s) | Name of CIs | Measurement Focus | Description |
|---|---|---|---|---|
| 1 | Y. Ngothai, M.C. Davis. (2012) | Chemical Engineering Concept Inventory (CECI) | Chemical Engineering | Assess understanding of chemical engineering concepts. |
| 2 | Buck, J. R., Wage, K. E., Hjalmarson, M. A., & Nelson, J. K. (2007)<br>Goncher et al., (2015) | Signal and Systems Concept Inventory (SSCI) | Aeronautical Engineering | Measures comprehension of signal and systems in aero engineering. |
| 3 | Steif, P. S., & Hansen, M. A. (2007). | Static Concept Inventory (SCI) | Engineering | Evaluates understanding of static concepts. |
| 4 | Hestenes, D., Wells, M., & Swackhamer, G. (1992).<br>Claudio Fazio, (2018) | Force Concept Inventory (FCI) | Engineering | Assesses knowledge of fundamental forces in engineering. |
| 5 | Wait, I. W., & Nelson, E. J. (2015). | Concept Inventory for Engineering Hydrology | Civil Engineering | Measures knowledge of engineering hydrology principles. |
| 6 | Martin, J., Mitchell, J., & Newell, T. (2003). | Fluid Mechanics Concept Inventory (FMCI) | Mechanical Engineering | Evaluates understanding of fluid mechanics principles. |
| 7 | Shallcross, D. C. (2010). | Material and Energy Balance Concept Inventory (MEBCI) | Chemical Engineering | Assesses knowledge of material and energy balance in engineering. |
| 8 | Bristow, M., et al. (2011). | Control Systems Concept Inventory (CSCI) | Electrical Engineering | Measures understanding of control systems concepts. |
| 9 | Jacobi, et al. (2003). | Concept Inventory for Heat Transfer (CIHT) | Mechanical Engineering | Examines comprehension of heat transfer concepts. |
| 10 | Goncher, A. M., Jayalath, D., & Boles, W. (2015). | Digital Technology-Signal Processing Concept Inventory (DT-SSCI) | Electrical Engineering | Evaluates knowledge of digital technology in signal processing. |
| 11 | Flynn, C. D., Davidson, C. I., & Dotger, S. (2018). | Rate and Accumulation Concept Inventory (RACI) | Chemical Engineering | Assesses understanding of rate and accumulation concepts. |

| | | | | |
|---|---|---|---|---|
| 12 | Nozaki, S., et al. (2016). | Concept Inventory for Engineering Graphics | Mechanical Engineering | Measures comprehension of engineering graphics concepts. |
| 13 | Ogunfunmi, T., et al. (2014). | Electric Circuit Concept Inventory | Electrical Engineering | Measures conceptual understanding of electric circuit |
| 14 | Gray, G., et al. (2005). | Dynamic Concept Inventory | Mechanical Engineering | Evaluating student understanding of fundamental concepts in dynamics, specifically in the context of 2D rigid body dynamics. |
| 15 | Richardson, J., et al. (2001). | Strength of Materials Concept Inventory | Civil Engineering | The concept inventory for Strength of Materials measures students' understanding of fundamental concepts in the field of Strength of Materials. |

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