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Evolving trends in student assessment in chemical engineering education

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ABSTRACT

Alongside innovation in teaching practice, student assessment in chemical engineering has seen significant changes in the recent past. This article undertakes a systematic review of the recent advances that have been reported in assessment practice in chemical engineering education. The main trends that emerge are: a shift towards authentic assessment methods, an increase in emphasis on peer-assessment and other approaches for group-based assignments, and a greater use of digital tools for the delivery of authentic assessments and improvement of marking and feedback practice. The analysis also examines the diversity of assessment methods used across the different chemical engineering subjects and how these map against assessment frameworks reported in the wider pedagogical literature. The emerging strand of research on synoptic and interdisciplinary assessment is used to develop an assessment framework for producing chemical engineering graduates who are also socially responsible and competent global citizens.

1. Introduction

Student assessment in higher education remains a topical subject (Ibarra-Sáiz et al., 2021; Medland, 2016; Slade et al., 2022). Evolving global challenges and employability requirements warrant appropriate assessment methods that enhance and evaluate desired competence in students. This is also true for the chemical engineering discipline, where desired skills have now broadened to encompass aspects of digitalisation and inclusive and sustainable design and innovation (IChemE, 2022). As a consequence, it is not just innovative teaching approaches aimed at improving the student learning experience that is important but also student assessment methods, both formative and summative, that need to be a good fit with the changing landscape (Gibbs, 2006).

Besides being the means to evaluate student accomplishment of intended learning outcomes, diligent consideration of assessment methods is important as they have a pronounced impact on the student learning process (Gibbs, 1999; Ibarra-Sáiz et al., 2021; Scouller, 1998) – for example, one such coupling of the assessment method to student learning that has been explored is the washback effect (Yi-Ching, 2009). Over the years, as the intertwining of learning and assessment tasks has become better understood (Dochy and McDowell, 1997), learner-centred authentic assessments have grown in prominence (Fook and Sidhu, 2010; Webber, 2012). This has shifted assessment practice from being a myopic evaluation of specific decontextualized knowledge to a broader evaluation of knowledge and skills expected of working professionals.

Authentic assessments assess students' ability to leverage technical expertise to solve problems mimicking real-world scenarios and challenges (Fook and Sidhu, 2010; Villarroel et al., 2018). Such assessments provide a more accurate reflection of a students' learning and foster skill development in higher education that is at par with professional practice (Segers and Dochy, 2001). Furthermore, in times of increasing digitalisation and access to artificial intelligence (AI) tools, this pivot towards alternate assessment methods that are more suited to assessing student insight and competence is highly desired (Alam, 2021). In this context, specifically within chemical engineering education, aspects of continuous assessment (Sanz-Pérez, 2019; Tuunila and Pulkkinen, 2015) and e-assessment (Perry et al., 2007; Sorensen, 2013) have garnered attention. Thereby, the objective of this article is to analyse the advances reported in student assessment in chemical engineering education over the recent past.

This is an opportune moment to review progress as the increased emphasis on authentic assessments coupled with the outbreak of the COVID-19 pandemic has prompted significant changes to assessment methods. The published literature lacks an analysis of the emergent trends and diversity of assessment approaches used for various chemical engineering subjects, which this article attempts to address. Through this analysis, this paper will answer the following questions:

i. What are the recent trends in student assessment in the chemical engineering discipline?

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ii. What is the diversity in assessment methods used for different chemical engineering subjects?
iii. How have advances in digitalisation, including that enforced by the COVID-19 pandemic, changed student assessment practice?
iv. What do the recent developments signify for the assessment landscape going forward?

The pedagogical basis used to support the analysis comprise the Quality Assessment Framework (QAF) developed by (Gore et al., 2009) and the conceptual model of authentic assessment developed by (Villarroel et al., 2018). The QAF identifies three core dimensions: intellectual rigour, significance and student support. These dimensions call for assessments to 'engage students in higher-order thinking', 'draw clear connections with students' prior knowledge and identities with contexts outside of the university,' and 'set high and explicit expectations for student work' respectively (Gore et al., 2009). Meanwhile the three dimensions of the authentic assessment model developed by (Villarroel et al., 2018) are realism, cognitive challenge and evaluative judgement. Realism in an assessment can either be incorporated by the presence of a 'real context' or through 'performance-based tasks'. Cognitive challenge requires learners to use higher-order cognitive skills for the assessment task while the evaluative judgement dimension addresses aspects of self-appraisal and reflection, whereby students develop the ability to judge quality and what a good performance in the assessment means (Villarroel et al., 2018).

2. Methodology

The analysis of literature in this review is guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach (Rethlefsen et al., 2021; Udeozor et al., 2023; Xiao and Watson, 2019). The literature analysed in this article was curated from databases using the search phrase 'Chemical engineering student assessment'. Each of the four words (AND criterion) were required to appear in the title or in the main text of a publication. The following databases were used for this investigation: Web of Science, Scopus and IEEE Xplore. The selection of studies from databases was done through the standard identification-screening-inclusion process prescribed by PRISMA (Fig. 1).

The publication date range was set as between 1st January 2018–30 th June 2022. This time period is expected to cover advances in the field reported both pre- and post-COVID-19. Furthermore, this time period also shows a significant growth in the number of publications in this topic. A Web of Science search for the same key phrase in the preceding four year period (January 2014–December 2017) returns half the number of entries compared to the period under consideration in this article (n = 187 compared to n = 378). On performing preliminary screening of these results based on titles and abstracts, the increased rate of relevant publications is clearly evident (n = 121 compared to n = 235).

A cumulative total of 689 records were identified from the databases used for the literature search (Fig. 1). The screening process started with identification of duplicates. Several entries returned by the databases were not relevant to chemical engineering or student assessment at all. These were screened out in the first stage through a quick analysis of titles and abstracts. The remaining papers were considered for inclusion in the study after full text screening by applying the set of exclusion criteria mentioned below:

- Retracted papers
- Review papers
- Papers addressing pre-University or school students
- Papers in a language other than English
- Papers not related to student assessment
- Non-engineering subjects taught to non-engineering student cohorts

While student assessment did not have to be the focal point of a paper for it to be included in this literature survey, sufficient information needed to be present on the assessment methods used or postulated. This required diligent full-text analysis carried out manually. Papers reporting novel teaching methodologies for student satisfaction and engagement with no information of student assessment were not considered to fall within this article's remit.

With regards to the final exclusion criterion, this was applied to

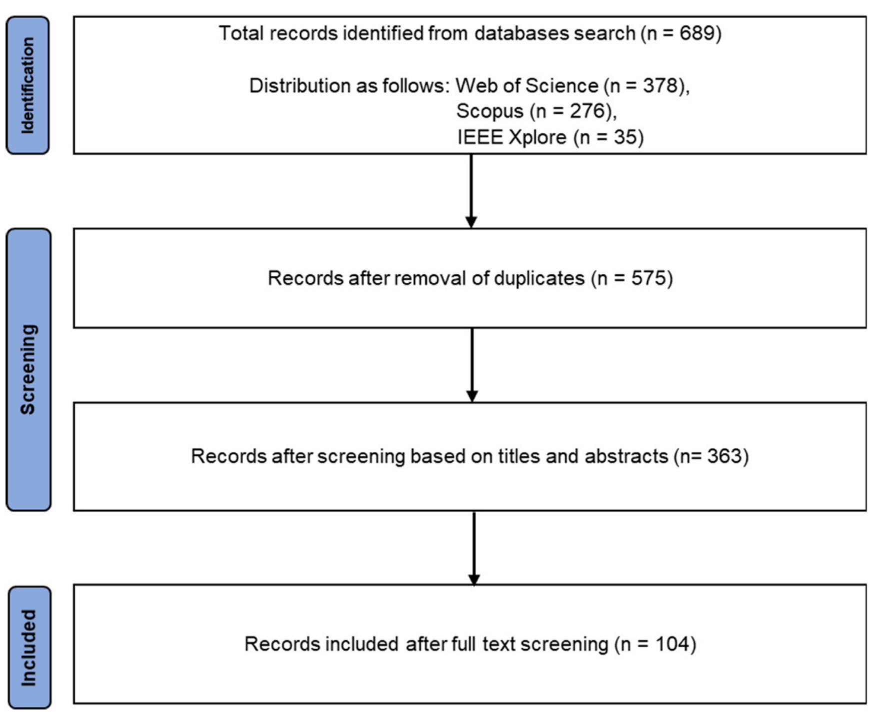

Fig. 1. PRISMA-type flowsheet describing the methodology of literature search.

narrow the focus on engineering education. This criterion does not exclude papers that discuss the delivery and assessment of chemistry topics to a chemical engineering student cohort but excludes papers dealing with chemical sciences education to a chemistry student cohort.

3. Overview of recent developments

Closed-book time-limited assessment has been the conventional approach for summative assessment in higher education. For convenience, this form of assessment is referred to as a 'standard exam' in this article. While 'standard exams' often require students to recall information, they aren't restricted in their scope to assess only the lower levels of the Bloom's taxonomy (Remember and Understanding) (Anderson and Sosniak, 1994), but can be used to assess higher levels too (Apply, Analyse and Evaluate). Furthermore, such exams can be used to improve estimation skills required to judge whether a computed value is realistic (Penn, 2018). If questions in a 'standard exam' are designed to provide context and assess higher cognitive levels of learning, the realism and cognitive challenge dimensions of authentic assessment may be partially addressed; however, this form of assessment seldom provides the time or the space for learners to engage in reflection and evaluative judgement (Villarroel et al., 2018). While 'standard exams' are still used, less than 30 % of the papers analysed in this review explicitly mention the use of a 'standard exam' as an assessment method. Furthermore, a vast majority of these publications refer to the use of such a 'standard exam' alongside one or more pieces of assessment that do not entail the student working in a closed-book setting. Although this is the trend in recent pedagogical literature, it would be incorrect to conclude that the use of 'standard exams' is in the minority in current educational practice. By focussing on the chemical engineering educational literature of the recent past, this analysis has an inherent bias towards newer assessment approaches since the lack of novelty with traditional modes of assessments would expectedly serve as a barrier to publication. Hence, the caveat to this analysis is that literature trends shouldn't be directly extrapolated to draw a broader perspective on the actual use of orthodox forms of assessment. However, what the literature analysis does reveal is a growing spotlight on authentic assessments, which is a ubiquitous trend in the higher education sector (Gibbs, 2006; Medland, 2016; Webber, 2012). Table 1 captures the wide variety of assessments identified in this literature review classifying them into different categories.

Table 2 presents a mapping of the references analysed herein in terms of the different types of assessment used for various chemical engineering subjects. While the spread of assessment types for different subjects vary, the collated data clearly reveals the use of diverse assessment methods. The diversity offered by oral, written and computational formats of assessments enables student competence to be assessed in more equitable ways than possible with a single or series of 'standard exams'. For example, the use of a portfolio-type assessment for thermodynamics offers students greater flexibility in format choice compared to a 'standard exam' (Vigeant, 2021). As reported therein, students felt a stronger 'sense of accomplishment' when submitting the portfolio over the 'standard exam', linking in strongly with the missing evaluative judgement dimension of authentic assessment highlighted earlier (Villarroel et al., 2018). To illustrate these differences, the last row in Table 2 shows a traffic light colour coding for each assessment type mapped against the three dimensions of the authentic assessment model (Villarroel et al., 2018): the three circles stand for realism, cognitive challenge and evaluative judgement in the same order. The possibility to embed each dimension is rated red (no to limited scope), amber (reasonable scope) or green (high scope) for each assessment type. It can be seen that assessment methods towards the right-end on the table score better on all dimensions of 'authenticity' as opposed to those on the left. As stated earlier, questions framed for 'standard exams' can be contextualised to a real-life context and test higher order cognitive skills, although this need not always be the case, resulting in an amber colour coding for realism and cognitive challenge for this assessment type in Table 2. Such closed-book time-limited assessments and multiple choice questions (MCQs) quizzes have very limited scope to engage students in reflection and evaluative judgement, which is depicted with a red colour code for these assessments in Table 2. On the other hand, project-based and hands-on assessments often mimic real-life tasks, require application of knowledge and analytical skills, and engage students in continuous reflection throughout the task – resulting in a green colour code on all three dimensions (Table 2).

Despite the emphasis on making assessments authentic, the space for MCQs and other similar forms of assessment still very much remains (Table 2). More than 15 % of the analysed papers report the use of MCQ-type assessment that enables automated grading and feedback, but these tend to be largely used for the purposes of formative student self-assessment. MCQ-type assessments are indeed a helpful tool to identify and correct student misconceptions and their use in this regard has a grounding in the wider pedagogical literature (Baleni, 2015; Gikandi et al., 2011; Yilmaz et al., 2020). The use of formative assessments within a classroom setting help improve student retention and progression in STEM degree programmes (Hempel et al., 2020).

Certain subjects in chemical engineering, such as, design, modeling and simulation, have predominantly been assessed through project work and report submissions, which naturally lend themselves well to the concept of authentic assessments. Building on this, using a troubleshooting exercise of a flawed or inefficient chemical process design as an assessment method is another way of embedding authentic problem solving in capstone design projects (Burkholder and Wieman, 2020). The predominance of project- and report-based assessments in the design domain is evident in Table 2 (Subject row: Design, modeling, simulation and research). However, the extension of these assessment types to other chemical engineering subjects now enables the delivery of authentic assessments across the entire chemical engineering curriculum. Such assessments are also a natural fit for course modules that engage students in experiential learning, which is a hands-on, active approach to learning that emphasizes practical application and real-world relevance. Amongst the papers explored herein, experiential learning has been adopted for course modules on engineering laboratories (Zhang et al., 2020), biotechnology (Bodnar et al., 2018) and materials chemistry (Clapson et al., 2020) for chemical engineers. Likewise, the use of project-based and hands-on student assessments have been extended for all chemical engineering topics (Table 2).

Table 2 places all oral assessments in the papers examined herein under the category 'Presentations and discussions'. In addition to conventional oral presentations, this form of assessment has now expanded to include structured debates (Gallego-Schmid et al., 2018), think-aloud interviews (Burkholder et al., 2019) and consultation meetings (Zhang

Table 1
Different types of assessment identified within the scope of this literature review.

Assessment category	Assessment information
Standard exam	Closed-book time-limited assessment; descriptive and numerical questions
MCQs & drag-and-drop questions	Closed-book multiple choice questions; standard questionnaires; drag-and-drop questions: pick, group, rank questions
Open-book tests	Open-book tests using problem-based questions; free response questions; worksheets; concept maps
Reports & posters	Lab reports; Written assignments; Posters
Presentations & discussions	Group and individual oral presentations; Structured debates; Think-aloud interviews; Consultation meetings
Project-based assessment	Design projects; Integrated project assessment; Portfolios; Case studies
Computational and hands-on assessment	Simulation files; Virtual lab assessments; Coding and troubleshooting; Do-it-yourself (DIY)/ makerspace models;

Table 2
A mapping of the literature analysed in this study in terms of types of assessments used against various chemical engineering subjects. The last row shows a traffic light colour coding of each assessment type against the authentic assessment model where the three dimensions colour coded for are realism, cognitive challenge and evaluative judgement respectively (Villarroel et al., 2018).

Assessment category Subject	Standard exam	MCQs & drag-and-drop questions	Open-book tests, worksheets & concept maps	Reports & posters	Presentations & discussions	Project-based assessment	Computational-based & hands-on assessment
Thermodynamics	(Sanz-Pérez, 2019)	(Caserta et al., 2021)		(Sanz-Pérez, 2019)		(Beneroso and Robinson, 2021; Vigeant, 2021)	
Unit operations/ Heat, momentum & mass transfer	(Lund, 2021; Sanz-Pérez, 2019; Sena-Esteves et al. 2018; Sena-Esteves et al., 2020;Valero et al., 2019;Ye and Zhong, 2021)	(Kaiphanliam et al., 2021)	(Kaiphanliam et al., 2021)	(Hu and Li, 2020; Ruslan et al., 2021; Sanz-Pérez, 2019; Zak et al., 2021)	(Hu and Li, 2020; Ye and Zhong, 2021; Zak et al., 2021)	(Ballesteros et al., 2021; Hu and Li, 2020; Ruslan et al., 2021)	(Ruslan et al., 2021; Sena-Esteves et al.; Sena-Esteves et al.;Valero et al., 2019;Ye and Zhong, 2021)
Mass & energy balances	(Sanz-Pérez, 2019)	(Ripoll et al., 2021)		(Sanz-Pérez, 2019)	(Ripoll et al., 2021)	(Beneroso and Robinson, 2021)	
Reaction & catalytic engineering	(Ravi et al., 2021; Sanz-Pérez, 2019)		(Ramírez et al., 2020; Ravi et al., 2021)	(Ravi et al., 2021; Sanz-Pérez, 2019)			(Koretsky, 2020; Koretsky et al., 2022; Ramírez et al., 2020)
Process control and safety	(Duedahl-Olesen et al., 2021; García-Fayos et al., 2019; Tighe et al., 2021; Udugama et al., 2020)	(Hassall et al., 2020; Viitaharju et al., 2021)		(Duedahl-Olesen et al., 2021; Fang et al., 2022; García-Fayos et al., 2019; Hassall et al., 2020; Hu and Li, 2020; Moodley, 2020)	(Duedahl-Olesen et al., 2021; Fang et al., 2022; García-Fayos et al., 2019; Hassall et al., 2020; Hassell, 2019; Hu and Li, 2020)	(Duedahl-Olesen et al., 2021; Hassall et al., 2020; Hassell, 2019; Hu and Li, 2020; Udugama et al., 2020)	(Fang et al., 2022; Moodley, 2020)
Chemistry / Chemical engineering labs	(Sancho et al., 2019)	(Moozeh et al., 2020; Moozeh et al., 2019; Viitaharju et al., 2021; Wu et al., 2021)	(Helgadottir et al., 2020; Ramírez et al., 2020)	(Carmel et al., 2019; Chen et al., 2019; Helgadottir et al., 2020; Piol et al., 2019; Rodgers et al., 2020; Russell, 2020;Sancho et al., 2019; Sanz-Pérez, 2019;Shah et al., 2020;Vasquez et al., 2020;Yang et al., 2021;Zhang et al., 2020)	(Carmel et al., 2019; Lau, 2020; Rodgers et al., 2020; Russell; Sancho et al., 2019; Shah et al., 2020; Vasquez et al., 2020; Yang et al., 2021; Zhang et al., 2020)	(Carmel et al., 2019; Piol et al., 2019; Sancho et al., 2019; Yang et al., 2021; Zhang et al., 2020)	(Ramírez et al., 2020)
Design, modeling, simulation and research	(Alique and Linares, 2019; Aranzabal et al., 2019; García-Fayos et al., 2019; Jamieson, 2020; Remón et al., 2020;Sancho et al., 2019;Udugama et al., 2020)	(Cifrian et al., 2020; Schwarzman and Buckley, 2019)	(Burkholder and Wieman, 2020; Burkholder et al., 2019; Šuligoj et al., 2020)	(Amini-Rankouhi and Huang, 2021; Aranzabal et al., 2019; Cifrian et al., 2020; Couturier and Bendrich, 2021; García-Fayos et al., 2019; Hu and Li, 2020; Jamieson, 2020; Jamieson and Shaw, 2020; Kiss and Webb, 2021; Lenihan et al., 2020; Moodley, 2020; Remón et al.;Sancho et al., 2019;Scholes, 2021;Schwarzman and Buckley, 2019;Sunarso et al., 2020;Yang et al., 2021;Zhang et al., 2020)	(Amini-Rankouhi and Huang, 2021; Burkholder et al., 2019; Cifrian et al., 2020; Couturier and Bendrich, 2021; Fornós and Cermak, 2021; Gallego-Schmid et al., 2018; García-Fayos et al., 2019; Hu and Li, 2020; Jamieson, 2020; Kiss and Webb, 2021; Lenihan et al., 2020; Saliceti-Piazza and Buxeda, 2018;Sancho et al., 2019; Schwarzman and Buckley, 2019;Sunarso et al., 2020;Yang et al., 2021;Zhang et al., 2020)	(Alique and Linares, 2019; Amiri et al., 2021; Cifrian et al., 2020; Couturier and Bendrich, 2021; Gallego-Schmid et al., 2018; Hu and Li, 2020; Jamieson, 2020; Jamieson and Shaw, 2020; Kiss and Webb, 2021; Lenihan et al., 2020; Sancho et al., 2019; Schwarzman and Buckley, 2019; Sunarso et al., 2020; Udugama et al., 2020; Yang et al., 2021; Zhang et al., 2020)	(Alique and Linares, 2019; Fornós and Cermak, 2021; Moodley, 2020; Rodgers, 2019; Sunarso et al., 2020)
Chemistry	(Chadha et al., 2022b; Dudek et al., 2022; Fischer et al., 2019; Lapierre and Flynn, 2020; Tan et al., 2019; Vyas et al., 2021)	(Müller et al., 2021; Tan et al., 2019; Vyas et al., 2021)	(Dudek et al., 2022; Fischer et al., 2019)				(da Silva Júnior et al., 2021)
Materials science and engineering	(Matinde, 2019; Rodríguez et al., 2019; Vahedi and Farnoud, 2019)	(Clapson et al., 2020; Roman et al., 2021)		(Rodríguez et al., 2019; Vahedi and Farnoud, 2019)	(Serrat et al., 2018; Vahedi and Farnoud, 2019)	(Serrat et al., 2018)	(Clapson et al., 2020; Rodríguez et al., 2019)

(*continued on next page*)

Table 2 (*continued*)

Assessment category Subject	Standard exam	MCQs & drag-and-drop questions	Open-book tests, worksheets & concept maps	Reports & posters	Presentations & discussions	Project-based assessment	Computational-based & hands-on assessment
Biotechnology/ environmental engineering	(Martín-Lara and Rico, 2020; Remón et al.)	(Martín-Lara and Rico, 2020; Ripoll et al., 2021)	(Bodnar et al., 2018)	(Peyton Brent and Skorupa Dana, 2021; Prado, 2021; Remón et al.; Rodríguez-Chueca et al., 2020)	(Geist et al., 2019; Margallo et al., 2019; Peyton Brent and Skorupa Dana, 2021; Prado, 2021; Ripoll et al., 2021; Rodríguez-Chueca et al., 2020)	(Geist et al., 2019; Margallo et al., 2019; Peyton Brent and Skorupa Dana, 2021; Prado, 2021)	(Geist et al., 2019)
Authentic assessment model mapping (Villarroel et al., 2018)	🟡 🟡 🔴	🔴 🟡 🔴	🟡 🟢 🟡	🟢 🟡 🟡	🟢 🟡 🟡	🟢 🟢 🟢	🟢 🟢 🟢

et al., 2020). These activities require students 'to produce an elaborate, sustained and coherent clarification of complex ideas', ranking them highly on the scale for 'substantive communication' in the 'intellectual rigour' dimension of the QAF (Gore et al., 2009). On the whole, Table 2 is also envisioned to be useful for educators of the corresponding topics to inspect progress in student assessment in their respective areas.

4. Group-based assessments

Alongside student assessment on an individual basis, assessment methods focusing on inclusive group-work are of considerable interest to the engineering pedagogical community. Close to 35 % of the articles investigated as part of this study refer to the use of team- or group-based assessments. Nearly half of these cited reports use group-work as part of design projects or course modules based on process design, modeling and simulation (Table 2). Although this skew is along expected lines – capstone design projects and design-based modules generally have a collaborative slant – it is important to highlight the proliferation of team-based assessments to other course modules including on unit operations and transport phenomena (Ballesteros et al., 2021; Ruslan et al., 2021; Russell; Sena-Esteves et al.; Zak et al., 2021), biotechnology and environmental engineering (Amini-Rankouhi and Huang, 2021; Geist et al., 2019; Peyton Brent and Skorupa Dana, 2021; Prado, 2021; Ripoll et al., 2021; Schwarzman and Buckley, 2019), and process control and safety (Hassall et al., 2020; Hassell, 2019). Novel approaches to group-based assessments in the chemical engineering domain include the collaborative student design of mass balance problems (Ripoll et al., 2021) and the concept of collaborative re-testing, in which students attempt an assessment individually followed by a collaborative attempt to potentially improve their grades (Nease et al., 2021). These approaches have been found to have a positive impact on students, both in terms of satisfaction as well as performance (Nease et al., 2021; Ripoll et al., 2021).

Being exposed to group work multiple times in the degree programme prepares students for the different careers they will embark on upon graduation. Training students for this reality, including through assessed group coursework, while being highly desirable has important implications from an assessment perspective. Assigning individual student marks on the basis of a group submission is a key area of interest. From the standpoint of fair assessments and accreditation requirements, this distils to two vital questions: (i) If a group's submission has met an intended learning outcome, can it be assured that all group members have individually met the learning outcome?, and (ii) How can individual marks be modulated to reflect their respective contributions to group work and the eventual output? In other words, while a group assessment task might appropriately address all dimensions of the QAF (Gore et al., 2009) or the authentic assessment framework (Villarroel et al., 2018), how does this filter down at the level of an individual student? In an endeavour to address these questions, student peer assessment methods are gaining traction. In its simplest form, peer assessment will require a student to rate the contribution of every group member. Multiple rounds of peer assessment may be held for coursework performed over long time periods with scores being averaged to determine a multiplication factor that can be used to compute individual marks for a group assessment. Peer assessment can be performed offline using standard evaluation forms (Vasquez et al., 2020) or using digital portals such as Google forms (Foong and Liew, 2020), TEAMMATES (Kiss and Webb, 2021), CATME (Vasquez et al., 2020), IPAC (Garcia-Souto, 2019a, 2019b) and ITPmetrics(Jamieson and Shaw, 2020). Having multiple rounds of peer assessment contributes to improving the reliability of the process and opens up the possibility for interim peer-to-peer feedback (Foong and Liew, 2020). Through this mechanism, students are empowered to take ownership of 'expectations' (Gore et al., 2009) and can be engaged in a feedforward practice of formulating criteria for efficient group work (Villarroel et al., 2018), all of which have been found to have a positive influence on self- and peer-assessment scores in subsequent assessment rounds (Foong and Liew, 2020). Alternate approaches that have been reported for evaluating individual performance as part of group work include the use of monitoring questionnaires comprising technical questions on key project milestones (Aranzabal et al., 2019) and rigorous three-part oral group examinations (Stenderup and Overby, 2016).

In addition to helping compute individual marks for group assessments, results of peer assessment can also be used to teach equality, diversity and inclusion (EDI) to the engineering student community and inform team formation strategies. Teams formed through a combination of student self-selection and instructor selection led to better outcomes than teams that were solely formulated on the basis of academic performance or self-selected student teams (Vasquez et al., 2020). Likewise, groups can also be formed in a way to explicitly account for international student diversity in the cohort (Sunarso et al., 2020). Furthermore, leveraging peer assessment in the context of cooperative problem-based learning is beneficial in terms of improving technical competence as well as empathy and other people skills (Ballesteros et al., 2021; Busu et al., 2020; Nease et al., 2021). Having been associated with low acceptance in the student community in the past (Pung and Farris, 2011), these more recent works on peer assessment demonstrate ways to increase the utility and patronage of this assessment approach.

5. Digitalisation in student assessments

Since the literature surveyed herein spans the 2018–2022 time period, there are several reports that discuss digitalisation approaches to student assessment both in the backdrop of COVID-19 and otherwise. With regards to the effect of the pandemic, the initial response of shifting existing forms of assessments online have been articulated in multiple publications (Bhute et al., 2020; Dietrich et al., 2020; Ghasem and Ghannam, 2021; Jamieson, 2020; Scholes, 2021). Trialling mock exams and offering homework-based assessments were some of the measures taken but addressing student collusion and satisfaction was challenging (Bhute et al., 2020; Dietrich et al., 2020). Students felt that online exams did not reflect real performance and competence (Ghasem and Ghannam, 2021).

While the pandemic forced this urgent action response, a more calibrated approach to digitalising student assessment is also apparent in the surveyed literature. One strand of this approach is the emphasis on gaming and formative assessments. MCQs and minute papers are widely used for formative assessment and offering them digitally facilitates the delivery of immediate automated feedback (Dua, 2021; Dudek et al., 2022; Müller et al., 2021; Roman et al., 2021). Likewise, the use of gaming apps for students to test and improve their understanding (Caserta et al., 2021; Chadha et al., 2022a), hybrid board games for students to review previously learned concepts (da Silva Júnior et al., 2021), and student-created game levels to demonstrate competence and creativity in process design (Fornós and Cermak, 2021), are recent attempts to tap into the gamification strategy to improve student motivation and thereby, the learning and assessment experience. Nevertheless, it is important to recognize that such assessments do not map well onto standard assessment frameworks, such as the QAF (Gore et al., 2009), and hence their consideration for use as summative assessments must be done with due caution.

The second strand focusses on technology-enabled authentic assessments that have positive ramifications for feedback. Offering detailed individualised feedback has always been an issue, especially with large student cohorts. Although the advent of digital formative assessments has improved the timing of feedback, this type of feedback is often not tailored to an individual. The possibility to provide tailored individual feedback using digital tools has now been demonstrated in chemical engineering education – examples being the use of a MS Excel tool for an assessment on mass and energy balances (Beneroso and Robinson, 2021) and the coding of questions and responses for a virtual lab assessment (Koretsky, 2020). Providing individual feedback for digital assessment submissions is also vital in the context of chemical engineering subjects with a strong computational element, such as design, modeling and simulation, where group-based assessments are more common(Koretsky et al., 2022). Hence, these developments on the digitalisation front enable coupling group-level feedback with actionable individual feedback.

Besides the positive outcomes on marking and feedback, technology-enabled assessments are well-suited for the delivery of next-generation authentic assessments, such as computer-based assessments engaging students in simulated or virtual lab environments (Koretsky, 2020; Ramírez et al., 2020). These add to the expanding use of digital approaches to assess design, modeling and simulation competence (Moodley, 2020), including the troubleshooting of process flowsheets on appropriate digital platforms (Burkholder and Wieman, 2020). By definition, the extension of the authentic assessment framework to topics like cybersecurity and automated process control necessitate the use of digital assessments (Villarroel et al., 2018). Likewise, competence in big data and machine learning cannot be trained or assessed authentically without appropriate digital tools. As a result, technology-enabled assessments are an important discussion point in curriculum review and redesign processes (Chadha et al., 2022a).

Besides the developments articulated above, fostering social responsibility and principles of social sustainability in students would have to be carefully considered in the context of digital assessments. For example, a recent study comparing virtual to in-person oral presentations assessment for a module on heat and mass transfer reveals that while virtual presentations enable students to be more creative and risk-tolerant, in-person presentations work better for awareness of social responsibility and outreach (Zak et al., 2021). This is where the 'significance' dimension of the QAF is important – 'to what degree is the cultural knowledge of diverse social groupings incorporated and valued in the task?' (Gore et al., 2009) Hence, although a pivot towards digital assessments in chemical engineering education is warranted, degree programmes must ensure that assessment methods sufficiently address the social dimension of student development.

6. The horizon

Student assessment in chemical engineering education continues to evolve with changing trends and demands. As detailed herein, there is an increasing emphasis on assessments being authentic with the inclusion of digital assessments where appropriate. Alongside changes at a subject- or module-level, the student assessment landscape has the emergence of synoptic and interdisciplinary assessments in the horizon. Synoptic assessments require students to integrate the knowledge gained from several subject modules in a single assessment (Constantinou, 2020; Lees, 2015; Southall and Wason, 2016). This form of assessment builds on systems thinking skills required to see interconnections between concepts (Orgill et al., 2019) and embraces the element of 'knowledge integration' as prescribed in the QAF (Gore et al., 2009). Within the chemical engineering curriculum, the capstone design project is where students pull together and apply core chemical engineering expertise acquired over a degree programme. Hence, design projects are a form of synoptic assessments. However, not all synoptic assessments need to take the form of a capstone project.

From the literature examined in this study, there are several reports that demonstrate the cross-cutting nature of assessments in chemical engineering education. While these assessments are not explicitly labelled as 'synoptic', they illustrate the potential of cross-module assessments for students to synthesize their learning from multiple modules without having to wait for a capstone design project at the end of the degree programme to do so. Table 3 maps the different chemical engineering topics that have been combined in assessments reported in these studies. As would be expected, the overlap of chemical engineering design with other core topic areas is prominent (Table 3). As an example, the interface of topics like fluid mechanics, reactive mass and energy balances and gas properties (thermodynamics) can be assessed through hands-on project-based assessments, such as a Do-It-Yourself (DIY) hydraulic jack (Table 3, (Ruslan et al., 2021)). Another example is the design of a Chem-E-car that requires integration of competence in thermodynamics, chemical reactions and control (Table 3, (Dominguez-Ramos et al., 2019)).

As synoptic assessments become more prevalent, it is important to carefully consider their implications on teaching and learning methods. It follows from the principle of constructive alignment that learning objectives, teaching and learning activities, and assessment methods need to be aligned for an ideal student learning experience (Biggs, 1996). At the level of a subject module, module-specific learning outcomes dictate the teaching and learning activities and assessment methods used within the module. The step up to synoptic assessments is an elegant way to address programme-level learning outcomes considered as part of outcome-based education (OBE) models (Chan et al., 2022); however, this also means students have to be provided opportunities to engage with synoptic learning activities before being assessed through synoptic assessments. Conventional capstone design projects work on an iterative approach wherein multiple instructor feedback cycles tend to shape a group or individual's final submission. Hence, the design process that students engage in constitutes a synoptic learning activity in itself, but what remains to be explored, are synoptic learning activities that can be used for the training of chemical engineering competence beyond design.

While module-level assessments often map onto learning outcomes related to core chemical engineering principles, broader programme-level learning outcomes addressing aspects of chemical engineering design, team work and professional practice require evaluation of skills beyond core technical ability, expanding to systems thinking and

Table 3
A mapping of literature analysed in this study that report cross-topic or synoptic assessments.

Safety	Safety						
Control		Control					
Unit operations	(Hu and Li, 2020)		Unit operations				
Mass & energy balance				Mass & energy balance			
Thermodynamics & reactions		(Dominguez-Ramos et al., 2019)		(Ruslan et al., 2021)	Thermodynamics & reactions		
Transport phenomena	(Hu and Li, 2020)		(Ballesteros et al., 2021; Hu and Li, 2020)	(Ruslan et al., 2021)	(Ruslan et al., 2021)	Transport phenomena	
Design	(García-Fayos et al., 2019; Hu and Li, 2020)	(Dominguez-Ramos et al., 2019; Udugama et al., 2020)	(Hu and Li, 2020)		(Dominguez-Ramos et al., 2019)	(Hu and Li, 2020)	Design

(Dominguez-Ramos et al., 2019, Ruslan et al., 2021, Hu and Li, 2020, Ballesteros et al., 2021; Hu and Li, 2020, Ruslan et al., 2021, Ruslan et al., 2021, García-Fayos et al., 2019; Hu and Li, 2020, Dominguez-Ramos et al., 2019; Udugama et al., 2020, Hu and Li, 2020Dominguez-Ramos et al., 2019Hu and Li, 2020)

metacognition and reflective thinking (Fig. 2). Tools and methods for assessment of systems thinking have been broadly described for STEM education (York et al., 2019) and also contextualized to catalysis and catalytic reaction engineering (Ravi et al., 2021). With regards to metacognitive and reflective thinking skills, the assessments methods that have been reported in the analysed literature herein include a reflective journal as part of project work (Lenihan et al., 2020), formative assessments to integrate metacognition in systems engineering and sustainability,(Tuzun, 2020) and homework reflection wrappers on kinetic data analysis (Lund).

Also on the horizon is the use of interdisciplinary assessments, which represents the pinnacle of professional formation provided by an academic degree programme. The ultimate objective of any degree programme, not just one in chemical engineering, is to produce technically competent and socially responsible global citizens. In the chemical engineering context, this would mean producing graduates who can help address global challenges embodied by the United Nations Sustainable Development Goals (UNSDGs). This is why interdisciplinary work, which fosters the ability to work collegiately and creatively to design solutions for a better world, is a salient higher-order feature of an educational curriculum. Since creativity is an important aspect of interdisciplinary assessments, developments on assessing and rewarding creativity are particularly interesting. Assessment criteria for innovation and creativity have been developed for chemical engineering design (Jamieson and Shaw, 2020; Šuligoj et al., 2020) as well as laboratory practice (Shah et al., 2020). Furthermore, working in a cooperative environment as a project team enhances feelings of empathy within the student group (Busu et al., 2020). Hence, interdisciplinary assessments are also an authentic way of assessing for EDI and other ethical principles. Like synoptic assessments, interdisciplinary assessments score highly on several QAF components across all dimensions - problematic knowledge and higher order thinking under intellectual rigor, knowledge integration and connectedness under significance, and high expectations and student direction under student support (Gore et al., 2009). Because this is often a challenge to replicate at the scale of module-level assessments, synoptic and interdisciplinary assessments are valuable features of a diverse assessment portfolio.

Within the body of literature surveyed herein, the nexus of chemical engineering with other engineering disciplines (civil, electrical, mechanical and software) (Couturier and Bendrich, 2021; Hassell, 2019; Piol et al., 2019; Schwarzman and Buckley, 2019), chemistry (Remón et al. 2020; Schwarzman and Buckley, 2019) and nursing (Geist et al., 2019) have all been reported in an assessment context. Each of the aforementioned interdisciplinary assessments embrace the concept of inclusive innovation, where chemical engineering students leverage their core competence to co-design an innovative solution through a process that requires basic understanding of the cross-cutting disciplines, an awareness of socio-economic and ethical considerations, and

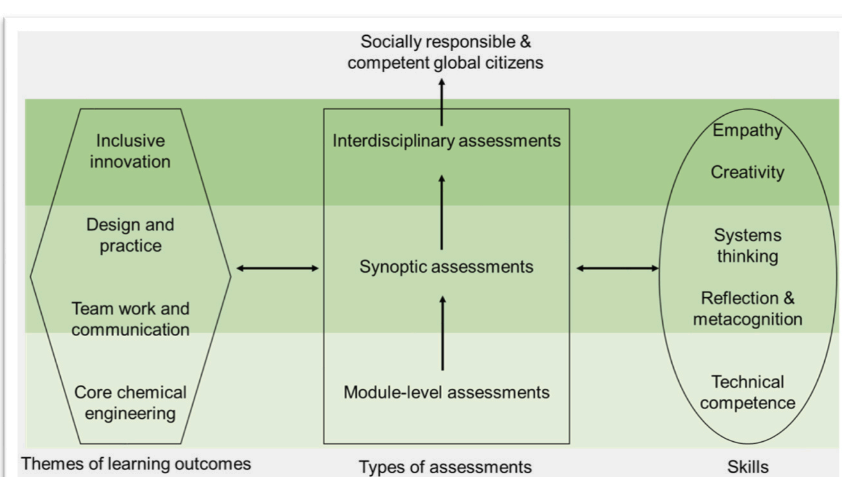

Fig. 2. A framework presenting the cascading of three types of student assessment aligned against the required skills and corresponding learning outcomes.

efficient teamwork.

7. Conclusions

This article examined the advances in student assessment methods reported in chemical engineering education in the recent past (January 2018–June 2022). While the use of closed-book time-limited summative assessments has not ceased altogether, they are frequently being employed in conjunction with a range of other assessment methods. A mapping of various assessment methods used for the different chemical engineering subjects reveals the increasing use of open-book and other forms of assessments that address core dimensions of the authentic assessment framework: realism, cognitive challenge and evaluative judgement. This is particularly found to be the case for assessing competence in design, modeling and simulation. However, there is an increasing inclination towards using such assessment methods for other chemical engineering subjects too.

The proliferation of digital tools and their importance in the chemical engineering profession, necessitates skill development that can be authentically assessed using digital methods. The digitalization strategy has been found to improve individualisation of feedback and efficiency of marking for staff. Going forward, digitalisation approaches can help provide individual data sets for assessments and embed generative AI technologies. In addition to enabling authentic assessments, the extension of the digitalisation strategy for formative assessment, gamification approaches and peer assessment were also identified. With regards to the latter, this paper highlighted the widespread use of team- or group-based assessments, which are not just limited to design projects where group work has conventionally been the norm, but is finding more novel applications through ideas such as collaborative re-testing and problem formulation. Furthermore, different approaches to implement peer assessment and using peer assessment results to inform EDI practice and group formation were also discussed.

Finally, the emergence of synoptic and interdisciplinary assessments in the chemical engineering educational space were described to develop a cascading assessment framework. Synoptic and interdisciplinary assessments address broader learning outcomes than possible at a module-level; specifically, around inclusive innovation, design and teamwork, which require systems thinking and people skills in addition to core technical competence. While only a relatively small fraction of the literature examined here addressed cross-topic and cross-discipline assessments, the emphasis on student assessment to produce socially responsible and competent global citizens is expected to drive further research in this direction in the near future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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