Interdisciplinary engineering education

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JEE

RESEARCH REVIEW

Interdisciplinary engineering education: A review of vision, teaching, and support

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Abstract

Background: Societal challenges that call for a new type of engineer suggest the need for the implementation of interdisciplinary engineering education (IEE). The aim of IEE is to train engineering students to bring together expertise from different disciplines in a single context. This review synthesizes IEE research with a focus on characterizing vision, teaching practices, and support.

Purpose: We aim to show how IEE is conceptualized, implemented, and facilitated in higher engineering education at the levels of curricula and courses. This aim leads to two research questions:

What aspects of vision, teaching, and support have emerged as topics of interest in empirical studies of IEE?

What points of attention regarding vision, teaching, and support can be identified in empirical studies of IEE as supporting or challenging IEE?

Scope/Method: Ninety-nine studies published between 2005 and 2016 were included in a qualitative analysis across studies. The procedure included formulation of research questions, searching and screening of studies according to inclusion/exclusion criteria, description of study characteristics, appraisal, and synthesis of results.

Conclusions: Challenges exist for identifying clear learning goals and assessments for interdisciplinary education in engineering (vision). Most pedagogy for interdisciplinary learning is designed to promote collaborative teamwork requiring organization and team management. Our review suggests that developing interdisciplinary skills, knowledge, and values needs sound pedagogy and teaming experiences that provide students with authentic ways of engaging in interdisciplinary practice (teaching). Furthermore, there is a limited understanding of what resources hinder the development of engineering programs designed to support interdisciplinarity (support).

KEYWORDS
engineering curriculum, higher education, interdisciplinary, teaching and learning

1 | INTRODUCTION

Today's social, economic, environmental, and medical challenges are complex and often open ended and ill-defined (Gómez Puente, Van Eijck, & Jochems, 2013a). These challenges go beyond the traditional image of engineers' tasks and responsibilities (Vojak, Price, & Griffin, 2010). They call for a type of engineer who is socially connected and who can work both within and outside the boundaries of his or her own discipline (Barut, Yildirim, & Kilic, 2006). As a result, future engineers need the ability to access, understand, evaluate, synthesize, and apply perspectives and knowledge from fields other than their own (Czerniak, 2007). This ability would help engineers consider a large range of environmental and social factors for approaching contemporary challenges (Lattuca, Knight, & Bergom, 2013).

In response to these demands, the implementation of interdisciplinary engineering education (IEE) is recommended (Lattuca, 2001) to train engineering students to bring together combinations of theories, concepts, and methods from different disciplines in a single context (Lattuca, Voight, & Fath, 2004). Previous review studies have shown that engineering education treats interdisciplinarity as a concrete capability in this respect (Gero, 2014; Lam, Walker, & Hills, 2014), which can and should be taught and acquired in educational settings (Barth & Michelsen, 2013; Czerniak, 2007). But these educational settings are often diverse in form and approach (Becerik-Gerber, Ku, & Jazizadeh, 2012). Given this diversity, it is important to align instructional design, learning goals, learning activities, and learning spaces specifically to support IEE (Gütl & Chang, 2008).

Based on a review of the research on the nature and structure of interdisciplinarity (Frodeman, Klein, & Mitcham, 2010) and on the practice of IEE, this study aims to analyze the empirical studies on current curriculum and course interventions in IEE. Earlier literature reviews have usually focused on subareas of IEE such as student barriers (Richter & Paretti, 2009) or educational programs (Becerik-Gerber et al., 2012; Lam et al., 2014). Other reviews have focused on general interdisciplinary programs broadly (Knight, Lattuca, Kimball, & Reason, 2013). As a result, these reviews have not given a comprehensive view of approaches; reported success factors and challenges in IEE; nor how educators and researchers can use this knowledge to develop, improve, and evaluate programs, courses, and assessments. We argue that, in addition and in response to the earlier review studies, the current state of the field is such that a comprehensive overview of local experiments and cases is needed (Borrego, Foster, & Froyd, 2014). Such an overview would contribute a level of awareness that will allow teachers and educational leadership to take the next step toward a more systematic and less diffuse approach to IEE.

1.1 | This review study

This review provides an analysis of studies exploring interdisciplinary courses and curricula in higher engineering education. We propose and apply a conceptual framework (see Section 1.3) to help organize and categorize the results of the studies included. We position and interpret the results through this conceptual framework to understand existing empirical descriptions of interdisciplinary engagement along with providing recommendations to synthesize what it means to engage in interdisciplinary teaching and learning. Thus, we aim to contribute to an understanding of the challenges of vision, teaching, and support, and their interrelations specifically for IEE. By doing so, this review helps give a structured overview of the current state of research, useful for drawing links between otherwise potentially disparate results and, in turn, identifying opportunities and potential requirements for future research to advance our knowledge of this topic effectively.

Our examination and analysis and the resulting implications for practice allow us to identify approaches and list reported success factors and challenges for the three levels of vision, teaching, and support of IEE. Such an analysis appears timely. Studies of IEE have both increased and diversified in numerous directions (Graham, 2012). Funding for interdisciplinary education and interest from administrators in interdisciplinarity have increased over the last 15 years (Jacobs & Frickel, 2009; National Academy of Sciences, 2006; National Science Foundation, 2008). Yet at the same time, the need for an integrated perspective on curriculum development and the professional development of teachers has been identified as a pressing issue (Meijers & Den Brok, 2013). Although many search for this integrated perspective as the holy grail of IEE, in practice interdisciplinarity in higher education is often implemented by mono-disciplinary people (Blizzard, Klotz, Pradhan, & Dukes, 2012). As such, the added value of this review consists of bringing together approaches and reported success factors and challenges from individual case studies that can serve as points of attention for teachers, curriculum designers, and researchers of IEE.

1.2 | Defining interdisciplinarity

One principal challenge of IEE research is defining or agreeing upon what skills, knowledge, and values are at play in effective interdisciplinary problem-solving and interactions. Any review of studies of IEE should be able to identify what counts as a contribution to interdisciplinary education. This ability depends upon having some concept of what interdisciplinary interactions are in the first place and how to distinguish them particularly from multidisciplinary and transdisciplinary interactions. However, it is not our intention to give a final definition of interdisciplinarity (cf. Frodeman et al., 2010), nor to give an historical account of the concept (cf. Czerniak, 2007), nor to dig deep into epistemological aspects of interdisciplinarity (cf. MacLeod, 2016). Because we want to do justice to the reality of the ambivalent and interchangeable use of interdisciplinarity and multidisciplinarity in educational practice, it suffices in our opinion to offer a working definition.

The working definition that studies of IEE seem to agree on is that interaction between fields of expertise requires some level of integration among those fields to count as interdisciplinary (Huutoniemi, Klein, Bruun, & Hukkinen, 2010; Klein, 2010). By contrast, multidisciplinary interactions are less likely to employ integrative processes, and the individuals involved do not necessarily learn from other disciplinary perspectives (Borrego & Newswander, 2010). Multidisciplinarity can be characterized as a combination of disciplinary components, whereas interdisciplinarity requires methodological or conceptual synthesis with the aim of deepening knowledge and skills (English, 2016). Transdisciplinarity takes this synthesis a step further by starting from two or more disciplines and applying their knowledge and skills to real-world problems or projects in collaboration with stakeholders outside the university, thus aiming to enhance the learning experience (English, 2016). Individuals in interdisciplinary teams learn from others' perspectives and produce work in an integrative process that would not have been possible in a mono-disciplinary setting (McNair, Newswander, Boden, & Borrego, 2011). The result, at least in theory, is that participants emerge from such interactions speaking "one language."

The progression from multidisciplinarity to interdisciplinarity and transdisciplinarity could be considered as an increase in the complexity of the integrative task facing participants (Klein, 2013). This increasing complexity, as a result, requires learning goals that are broader-reaching than those required for a domain-specific course, which, in turn, calls for specific competence and a specific attitude among teachers (Gresnigt, Taconis, Van Keulen, Gravemeijer, & Baartman, 2014). In this context, our working definition considers interdisciplinary interactions as attempts to address real-world cases and problems by integrating heterogeneous knowledge bases and knowledge-making practices, whether these are gathered under the institutional cover of a discipline or not (Krohn, 2010). This working definition offers space for those reports and case studies that strive for interdisciplinary goals with multidisciplinary teams of teachers or students as well as those that attempt to integrate knowledge and skill from external disciplines within an otherwise disciplinary program. Yet, this definition helps distinguish interdisciplinarity from transdisciplinarity by focusing less on entirely novel problem-driven methodological development or on collaboration with participants outside the university.

1.3 | Conceptual framework

Due to its relatively nascent state (Borrego et al., 2014), research on IEE attempts to tackle educational aspects across a wide range, from basic conceptual questions about interdisciplinary education to full-scale curricula implementations. We believe it is essential to provide a conceptual framework to guide the analysis of interdisciplinary learning and practices in higher education so that teachers and curriculum designers can make sense of the literature. Our conceptual framework builds on a basic why-how-what approach (Sinek, 2009), which supports thinking about educational strategies from the ground-up. These strategies result in interdisciplinary courses and curricula based on an institution's educational vision, which is operationalized into a specific pedagogical approach, resting on specific institutional support structures. Exploring interdisciplinary courses and curricula, therefore, needs to identify educational processes at three levels: vision, teaching, and support (Van den Akker, 2003; Figure 1). The boundaries of our review are defined by a focus on teaching and learning, with connections to the other two process layers.

Vision serves as a foundation for an interdisciplinary approach by describing the basic motivations and goals that are to govern an educational program. It, thus, refers to the why of an educational program (Hansen & Dohn, 2017). It ensures coherence across a program and frames, among other things, curriculum development (Marder, 2013), educational policy, and collaboration and knowledge sharing across scientific and educational faculties (Karal & Bahcekapili, 2010). For example, the vision that "graduating engineers should be able to Conceive-Design-Implement-Operate (CDIO) complex value-added engineering systems in a modern team-based environment" (Crawley, 2001, p. 4) is stipulated in the CDIO-initiative.

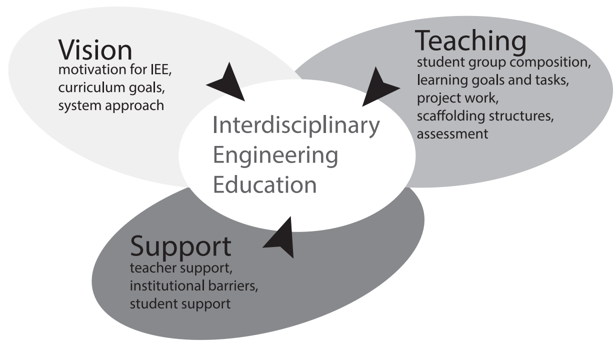

FIGURE 1 Interdisciplinary engineering education (IEE) educational processes and main themes at three key levels

Our reasons for singling out vision for assessing current studies of IEE are several. First, the use of interdisciplinarity as a concept in educational contexts is often ambiguous (see Section 1.2). Furthermore, since in engineering education motivations for interdisciplinarity might be questioned by both students and staff, they require clear articulation and justification. Finally, anyone engaging with IEE needs to be aware of the values underlying particular visions and the relations between different visions and chosen teaching approaches.

The primary processes, which we labelled as teaching, consist of instruction and curricular aspects such as learning goals (Larsen et al., 2009); competence indicators (Gómez Puente et al., 2013a); content, structure, and design of instruction (Aikenhead, 1992); assignments and assessment (Boix Mansilla, Duraisingh, Wolfe, & Haynes, 2009); student characteristics (Bächtold, 2013); and teacher characteristics. Teaching responds to the how and what questions by putting the governing vision into action (Hansen & Dohn, 2017).

Teaching processes depend on conditions and resources being in place that facilitate their development and operation, thus addressing the why, how, and what of IEE. Support consists of aspects such as infrastructure and institutional support, including available instruction rooms and laboratories, learning management systems, and other information and communication technologies (Larsen et al., 2009), tools and techniques, practice-based management, resources for developing teacher skills, incentives, and allocated time for curriculum development. Important reasons for singling out support as an issue in interdisciplinary contexts are the institutional constraints that make it difficult to work across disciplinary boundaries. For instance, while in many disciplinary educational contexts support and facilities are already in place and can be taken for granted, these resources might be insufficient or inappropriate for interdisciplinary undertakings. As such, our review focuses also on the degree to which current studies of curriculum and courses in IEE address aspects of support.

1.4 | Research questions

To do justice to the complex situation of factors and considerations related to interdisciplinarity in curricula and courses in higher engineering education, this literature review intends to synthesize existing research using the perspectives of vision, teaching, and support. Our aim to contribute to a more comprehensive understanding of the interrelated challenges of vision, teaching, and support specifically for IEE leads to the following research questions:

- What aspects of vision, teaching, and support have emerged as topics of interest in empirical studies of IEE?
- What points of attention regarding vision, teaching, and support can be identified in empirical studies of IEE as supporting or challenging IEE?

2 | METHOD

To find examples of interdisciplinarity in engineering education and empirical evidence on whether the suggested IEE approach worked, we followed a predefined procedure (Petticrew & Roberts, 2006; see also Borrego et al., 2014) that emphasizes the following steps: formulation of research questions, searching for and screening of studies according to inclusion/exclusion criteria, description of study characteristics, appraisal, and synthesis of results. In this study, the approach chosen was an aggregative synthesis of results (Dixon-Woods et al., 2006). Searching, selecting, and data extraction were done systematically (see also Petticrew & Roberts, 2006). As we started from the conceptual model, vision-teaching-support, we did not use a straight bottom-up approach (see also Thomas & Harden, 2008). Our aggregative synthesis combined both bottom-up and top-down approaches in an iterative manner. In contrast to a systematic review, which analyses a set of studies from a statistical perspective (Grant & Booth, 2009), our review is a qualitative analysis across studies (Dixon-Woods et al., 2006), which allows for identifying aspects and themes. This approach aligns with our aim of organizing and situating current results in IEE.

2.1 | Step 1: Searching for studies

Target articles were identified through the Web of Science and Scopus databases. These databases include scientific publications from all fields and from societies such as the Institute of Electrical and Electronics Engineers (IEEE) and the American Society for Engineering Education (ASEE). The ERIC database was used as well to include educational sources.

Queries were performed with the search terms "interdisciplinary" OR "multidisciplinary" OR "transdisciplinary" AND "engineering education." Additional queries with hyphenation were performed (i.e., "inter-disciplinary," "multi-disciplinary," and "trans-disciplinary") to account for differences in English language writing. The search terms were applied on the fields title, abstract, and keywords. Based on the aims and research questions, empirical studies with the document type article were selected. Articles published in international peer-reviewed journals were preferred over conference papers because they undergo rigorous review and to avoid additional criteria for evaluating the quality of potentially numerous papers. Because of our group's language proficiencies, only articles written in English were considered.

Initially, the search was conducted at the end of 2015. To better reflect the nascent state of the literature, a 10-year period was chosen. As the final search was conducted in November 2016, it was decided to include 2016 as well. This review, thus, covers articles published from 2005 up to and including 2016. The searches resulted in 996 unique abstracts (Figure 2). All search results were merged in a Microsoft Excel spreadsheet, including abstracts of all papers.

2.2 | Step 2: Surface level screening based on criteria for inclusion

Step 2 consisted of surface level screening by reading titles and abstracts and aimed to identify only relevant articles that met the following criteria for inclusion:

1. The article investigated curriculum or course-related aspects of IEE (e.g., curriculum analysis; curricular aspects such as goals, content, structure, and design of instruction; interdisciplinary student-projects; or courses within the context of interdisciplinary fields).
2. Interdisciplinarity in engineering education needed to be central to the case and/or argumentation; both interactions between engineering fields and between engineering and other scientific fields were considered.

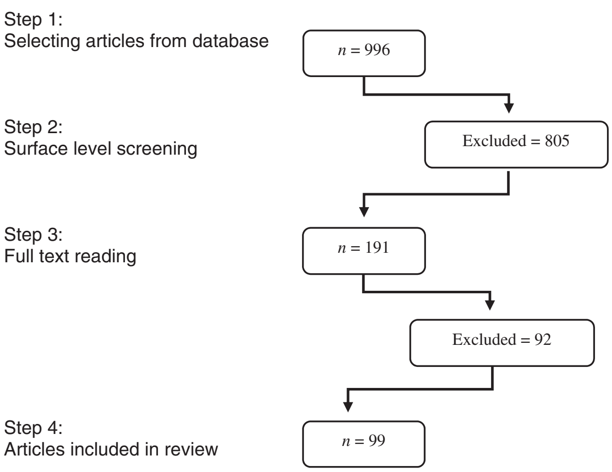

FIGURE 2 Flowchart of the article selection process

3. Participants were students or teachers in higher education.
4. The article discussed at least one of the three levels of vision, teaching, support, or elements thereof.
5. The article was published in an international peer-reviewed journal.
6. The article was published between 2005 and 2016 to capture the current state of the literature.
7. The article was published in English and available as a full-text version.

During reading of abstracts and of full texts, careful decisions about excluding articles were made. This resulted in the following exclusion criteria:

1. Articles that presented a mere course or program description without conclusions for IEE.
2. Articles that studied IEE itself.
3. Articles in which IEE was only illustratively used to support a non-IEE argument, in which interdisciplinarity was not central to the actual intervention, or in which the interdisciplinarity aspect was only mentioned without providing details.

During the process of surface level screening, two of the authors designed a coding table based on an initial set of literature. This coding table structured the criteria for inclusion and subsequent data extraction from the included articles. The coding table included the following sections:

1. General information: authors, title, publication source, publication year, abstract, and keywords.
2. Research design and population: qualitative or quantitative method, number of participants, and main academic discipline involved.
3. Vision: motivation for IEE, curriculum goals, orientation (e.g., design/research/problem-based), multi-, inter-, or transdisciplinary, system approach, and discipline/field.
4. Teaching: learning goals, group size, learning environment, scaffolding structures, student skills, assessment, and collaboration.
5. Support: organization, teacher support, and barriers.
6. Overall results: findings related to any of the subquestions defined for this review.

After this screening, 191 publications remained for full reading.

2.3 | Step 3: Reading full articles

Once the abstracts had been identified as potentially meeting the criteria and worthy of further exploration, full articles were accessed. Because of inclusion Criterion 7, seven articles were removed from the initial set. The available articles were scanned, after which a further selection was made based on criteria including the search terms discussed above. Moreover, 92 studies were excluded because of exclusion Criterion 3. Ultimately, a total of 99 studies were included in the review.

2.4 | Step 4: Synthesis of results

Each of the 99 studies were coded based on the coding table, which was further refined by the complete group of authors after it was applied to a small number of studies. A priori codes were used to categorize the articles after reading the full text. All authors participated in the coding team and read articles in accordance with individual expertise.

First, all papers were read to identify content relevant to our research questions. All coding decisions and notes were summarized in a rich data matrix in Microsoft Excel. In the second round of analysis, emergent themes in the included studies were identified. To increase the reliability of this literature review, the authors collaborated closely in the process. Points of debate and uncertainty were discussed until consensus was reached. This reliability check led to initial and follow-up meetings with the whole group of authors to discuss the coding scheme and the content of the matrix, and to implement minor changes to improve the matrix.

The remaining 99 papers were evaluated in terms of study quality. However, since we intended to situate and interpret current research, this evaluation was not used to exclude any of the papers. We reserve our comments on the quality of current research for the Discussion section.

3 | RESULTS

In this section, we first give methodological characteristics of the studies in our review. The descriptive results indicate that a majority of the included studies used a case study approach to investigate professional skills, problem-based learning (PBL), or interdisciplinary learning. The descriptive results are followed by a discussion of topics of interest surrounding vision, teaching, and support as they emerged from the included studies (see Section 3.2.1). For vision, we identified a variety of motivations for IEE. Topics of interest for teaching addressed characteristics of learning, instruction, and assessment. The main topics for support addressed institutional barriers and support for students and teachers. Finally, we focus on points of attention regarding vision, teaching, and support that were reported as success factors and challenges in individual cases. The reported success factors include taking a system approach, employing real-world problems as exemplars and tasks, involving reflective dialogue, and aspects of infrastructure and collaboration. Reported challenges address institutional barriers, complexity, and acquiring adequate levels of support.

3.1 | Methodological characteristics of existing interdisciplinary learning in higher education

3.1.1 | Methods and participants

Descriptive results of our review (Table 1) show a majority of empirical case studies, followed by perception research and curriculum analyses. Quantitative survey methods for measuring student or teacher perceptions of interdisciplinary projects or courses were applied more frequently than other methodological options ($n = 32$). Also, many used a combination of quantitative and qualitative approaches to help develop both a general and a deeper understanding of what happened in courses or programs. The nine studies reporting literature reviews, all applied qualitative methods. One of the eight studies reporting curriculum analysis applied quantitative methods and one mixed methods. A total of 64 studies reported the number of students involved, ranging from 4 to 5,249, with a median of 38 and two-third of these studies having 100 or fewer participants (see also the overview of the studies included in the Appendix). Methods sections usually did not report the participants' gender, age, or other demographics. Exceptions are, for instance, Barnard, Hassan, Dainty, and Bagilhole (2013), who reported gender division, and Barut et al. (2006), who reported country of origin of respondents.

TABLE 1 Characteristics of studies included and respondents

Code	Value		Number of studies
Method case study	Quantitative		24
	Qualitative		21
	Mixed-methods		37
		Total	82
Method curriculum analysis	Quantitative		1
	Qualitative		6
	Mixed-methods		1
		Total	8
Method literature review	Qualitative		9
		Total	9
Code	**Value**		**Number of respondents**
Respondents	Students		4–5,249
	Staff		2–52

3.1.2 | Conceptual framing

Approximately 20% ($n = 16$) of all case studies involved interdisciplinary learning within a single discipline with the aim of incorporating outside materials and nondisciplinary project goals. One example is a chemical engineering case study in which the main goal was to expose engineers to nonengineering knowledge for the development of their professional skills in a societal context (Abbas & Romagnoli, 2007). This example implies that authors do not always conceptualize cross-disciplinary collaboration as an essential aspect of interdisciplinarity or interdisciplinary learning. Sustainability issues often offered an educational context for cases ($n = 15$), while PBL or project-based learning (PjBL) appeared to be the dominant educational paradigms used in IEE.

One substantive conceptual framing for structuring and motivating IEE often drawn upon in our collection was a systems approach. In this context, engineering education and research perceive a system as a collection of components undergoing dynamic interaction with one another, often across disciplinary domains, and a system approach as the required set of skills needed to handle such systems (Gero, 2014). Such skills include metacognitive abilities such as systems-thinking and T-shape competencies, in which a core strength of disciplinary expertise (the vertical axis of the "T") is coupled with the ability to value and work with a broad range of people and situations (the horizontal axis of the "T") (Brown, 2005).

Systems thinking and T-shape learning were explicitly mentioned in 15 of the articles reviewed. However, many articles investigated a combination of skills and knowledge that we defined as systems thinking without referring directly to the concept. Most of these articles explicitly advocated that instruction should start by focusing on a single discipline. The horizontal axis of the T-shape was subsequently described as a capstone or a combination of knowledge from different disciplines or systems, or as a combination of professional skills, such as communication, project management, presentations, or the understanding of cultural differences. Twenty-five articles explicitly used the term "soft skills" to refer to these professional skills as part of the course or project.

We now focus on the levels vision, teaching, and support, of our framework, in an effort to identify main themes as topics of interest and reported factors that support or challenge IEE. Following our objective, we aimed for a synthesized review of results rather than an annotated bibliography. The references included serve as examples of studies that reported a particular result.

3.2 | Vision

Vision covers the motivations for interdisciplinary education—why it is advocated and what benefits are sought in the studies included here. Our results identified variation in the underlying motivations across the literature, ranging from (a) learning to solve complex real-world problems, (b) developing entrepreneurial competencies, and (c) developing socially aware engineers to the perceived need to improve existing disciplinary programs. Apart from some predominance of the first motivation, the studies reviewed were spread in terms of the motivations reported. Some studies focused on just one motivation, others on multiple motivations. Additionally, we identified support factors and challenges with respect to framing the goals of IEE.

3.2.1 | Emerging themes for IEE vision

Complex real-world problem-solving

The central reported motivation behind interdisciplinarity in engineering education in the included articles is that engineers are not yet being trained well to address complex real-world problems, which require interactions across disciplinary boundaries (Lansu, Boon, Sloep, & Van Dam-Mieras, 2013). This category includes motivations from new interdisciplinary research areas such as robotics (Do, 2013) and biomedical engineering (Lattuca, et al., 2013), which require solving complex interdisciplinary problems.

Entrepreneurial competencies

Today's economic pressure on engineers to be entrepreneurial motivated authors to stress the value of interdisciplinary team projects for better preparing engineering students to work in industry (Borrego, Karlin, McNair, & Beddoes, 2013) or even learning to start their own business (Klapper & Tegtmeier, 2010). This motivation appears to be guided by ideas about what future workplaces will look like and what industry demands from its employees (see also Cantillon-Murphy, McSweeney, Burgoyne, O'Tuathaigh, & O'Flynn, 2015; Cobb, Hey, Agogino, Beckman, & Kim, 2016).

Socially aware engineers

Articles that focus less specifically on industry engagement and collaboration often cite an imperative to produce engineers capable of shaping their professional work. For instance, many articles in which sustainability is seen as a common motivating factor (Apul & Philpott, 2011; Brundiers, Wiek, & Redman, 2010) concluded that interdisciplinary engineers need to be capable of handling and integrating environmental, social, and economical objectives into their work not only through engagement with social scientists or societal groups outside academia but also in terms of their own values (El-Adaway, Pierrakos, & Truax, 2015). Authors motivated by ecological sustainability stressed the need for awareness among engineers of social, political, economic, and environmental constraints (Apul & Philpott, 2011; Dewoolkar, George, Hayden, & Rizzo, 2009). They emphasized that IEE should promote this awareness through real-world, problem-solving scenarios and experiences instead of through disciplinary learning alone (Krohn, 2010). When the purpose of IEE is perceived as cultural, it can serve to reshape engineering attitudes and facilitate open-mindedness and improved cultural knowledge (Kabo & Baillie, 2009).

Improving disciplinary programs

Internal disciplinary benefits of interdisciplinarity were sometimes prioritized in articles that detail such benefits in terms of disciplinary knowledge and understanding, creativity or adaptability (Collier, Duran, & Ordys, 2013; Lattuca et al., 2004). From this point of view, included studies rationalize interdisciplinarity as a good source for training relevant professional skills (Hayden et al., 2011; Iyer & Wales, 2012) such as project management, working in teams, or making presentations (Aquere, Mesquita, Lima, Monteiro, & Zindel, 2012). Gardner et al. (2014) emphasize students learning the values and norms of outside disciplines with which a student is interacting, requiring a degree of socialization to interdisciplinarity among students and faculty alike.

Furthermore, when students are forced to think about their knowledge structures in a critical and relational way, interdisciplinarity both generates and relies on the development of meta-cognitive skills (Goddiksen & Andersen, 2014). These specific skills enable students not only to spot the limitations and capabilities of different disciplinary perspectives and to learn how to integrate them (Ivanitskaya, Clark, Montgomery, & Primeau, 2002) but also to develop knowledge of their own disciplinary structure. Several articles conceptualized the goal and motivation for IEE in these terms and studied empirically what engineers and others gain through interdisciplinary collaboration in terms of higher order cognitive skills (Ertas, Frias, Tate, & Back, 2015; Gardner et al., 2014; Gorbet, Schoner, & Taylor, 2008).

3.2.2 | Supporting and challenging factors for IEE vision

Supporting factors

Concepts and theory related to a systems approach as we described above provide a set of resources to help conceptualize interdisciplinarity in more concrete terms. They promote a contextual understanding of concepts and awareness of the contextual problems of related disciplines. A system approach to curriculum and courses integrates content-based teaching methods with PBL (Hayden et al., 2011; Rashid, 2015) and, thus, provides specific guidance knowledge and skill requirements, and learning goals for IEE.

Furthermore, one study reported that identifying vision and related demands can be supported by involving engineering professionals (Lansu et al., 2013). These professionals, it is suggested, can play a strong role in identifying the skills relevant for today's engineers to help define vision and design curricula that can meet professional demands.

Challenges

Institutional barriers, such as the disciplinary departmental structure of colleges and universities, are reported to appear particularly resistant to interdisciplinary programs (McNair et al., 2011). These barriers could impede clear conceptualizations of notions of interdisciplinarity and attendant goals governing course or curricula designs. As a result, there may be little attempt to integrate course subject-matter or assessment regimes. Two of our studies reported that without shared notions of interdisciplinarity, engineers will usually find it easier to avoid crossing institutional boundaries and confronting institutional conflicts such as scheduling and time-frame conflicts by maintaining a largely mono-disciplinary program (Bacon et al., 2011; Cantillon-Murphy et al., 2015).

Borrego and Newswander (2010) reported that the complexity and diversity of interdisciplinary engineering complicates the ability of teachers to conceptualize the goals of interdisciplinary learning in any concrete way. Many specifications of skills, such as communication and teamwork, reported in the articles included appear vague: "ability to list, give and receive feedback" or "acquire language skills to move comfortably across disciplinary boundaries" (Borrego & Newswander, 2010, p. 76). Vague conceptualizations from vision to teaching can, thus, lead to unclear learning goals, making it also difficult to translate these into concrete assessments that measure what they are supposed to.

3.3 | Teaching

The primary process of teaching includes, among other elements, learning goals, pedagogies, assignments, and assessment. The main themes emerging from our results address (a) student participation and group composition, (b) pedagogies and scaffolding applied, (c) assessment characteristics, and (d) procedures. Again, we also identified various supporting and challenging factors with respect to structuring teaching.

3.3.1 | Emerging themes for IEE teaching

Student participation and group composition

One of the course design aspects reported is whether and how to combine students from different disciplines collaboratively or whether to simply import knowledge and skills. It appeared that in 16 articles, IEE was organized within a single discipline by bringing in materials from other fields, for instance by bringing sustainability to a chemical engineering program (Abbas & Romagnoli, 2007) or system thinking skills to an engineering program (Gero, 2014; Rashid, 2015). This disciplinary approach is reported to encourage students to consider multiple perspectives, while a multidisciplinary teacher team supervises the course. Other programs ($n = 37$) organized interdisciplinary education by having students from different engineering disciplines in one course (Dewoolkar et al., 2009) or by combining engineering students with medical students (Cantillon-Murphy et al., 2015; Tafa, Rakocevic, Mihailovic, & Milutinovic, 2011) or with students from social sciences (Kabo & Baillie, 2009). Learning to work with specialists from other fields and learning to know and appreciate methods and vocabulary from these fields are, thus, included in the learning goals of these courses.

Pedagogies and scaffolding

PBL and PjBL are the most often applied educational formats in IEE settings in the studies included here. PBL aims to cover relevant content and procedures through careful selection of authentic problems that student teams have to study through an enquiry process (Barrows & Tamblyn, 1980). In PjBL student, teams are offered open and ill-defined real-world challenges and problems (Brundiers et al., 2010). Student teams collaborate over a long period of time, sometimes scaffolded by milestones to present their working plan, draft ideas, or prototype artefacts. Real problem owners were reported to be involved not only as stakeholders but also as reviewers of solutions (Dewoolkar et al., 2009; Redshaw & Frampton, 2014).

To avoid overly difficult problem tasks, research suggests that courses and projects should provide structures that scaffold students toward success (Borrego et al., 2013). Scaffolding structures useful for open-ended assignments and ill-defined problems (Gómez Puente et al., 2013a) include problems structured around goals that are achievable in one term and assignments defined according to levels of difficulty, with learning goals related to those levels (Do, 2013). Additionally, integration of introductory laboratory practicals was reported to help students tie concepts together (Rashid, 2015).

Assessment characteristics

Included studies suggest that assignments for interdisciplinary education need careful construction, balancing all involved disciplines and offering tasks that allow active engagement of all team members (Apul & Philpott, 2011). Assignments can include directions with respect to roles that student teams should divide among their members (Hamade & Ghaddar, 2011). Some included studies discussed how complex problem-solving skills are linked to real-world problems that often bring interdisciplinary settings and multiple stakeholders (Gomez-Puente et al., 2013a). Also, studies suggested how in courses focused on entrepreneurial skills, market research or business case tasks can be part of the assignments (Cobb et al., 2016; Klapper & Tegtmeier, 2010). Strategies such as CDIO (Crawley, 2001) and challenge-based learning (Kohn Rådberg, Lundqvist, Malmqvist & Hagvall Svensson, 2018) can be used to decide if and how each of these typical engineering phases will be addressed.

Assessment procedures

Assessment in general is considered underdeveloped and underdiscussed in interdisciplinary educational contexts (Boix Mansilla et al., 2009; Richter & Paretti, 2009). Only 11 of the articles in our review discussed aspects of assessment. Half of those presented a solid assessment strategy directly targeting interdisciplinary skills (Hasna, 2010). The others relied on a preexisting strategy for their otherwise interdisciplinary courses. Despite some attention to measuring levels of integration in student knowledge (Borrego, Newswander, McNair, McGinnis, & Paretti, 2009) or for assessment regimes (Cantillon-Murphy et al., 2015; Soares, Sepulveda, Monteiro, Lima, & Dinis-Carvalho, 2013), our set of articles and the extent to which they tackled assessment raised specific supporting aspects and challenges with respect to handling assessment in IEE (see next sections).

When interdisciplinarity is conceptualized in terms of professional skills, it appears that traditional means, such as reflective journals, meeting notes, or peer assessment, can be effective for measuring student learning in both interdisciplinary and disciplinary contexts (Kavanagh & Cokley, 2011). However, when assessing the quality of interdisciplinary student work, the different epistemic values, learning goals, and evaluation standards brought in by the disciplines involved appear to complicate the construction of assessment procedures for interdisciplinary courses (Borrego et al., 2009).

3.3.2 | Supporting and challenging factors for IEE teaching

Support factors

The use of interdisciplinary, real-world problems as a hook for projects was reported to increase student motivation (Brundiers et al., 2010; Guardiola, Dagli, & Corns, 2013). Students reported higher motivation if they feel the topic is directly related to practical needs. Students, thus, also learn to understand decision-making processes and the ambiguity and lack of information that can attend real projects. Related IEE supporting factors which were also reported included role-based learning within student teams or other supporting formats and exercises for teamwork (Hamade & Ghaddar, 2011). Additionally, Do (2013) reported the importance for students to have a good understanding of the content required to handle their project topic. One often identified point of attention was the importance of having students learn about the other disciplines involved in the course and learn to respect these disciplines (McNair et al., 2011), despite their different epistemologies.

Assessing students through a dialogue that stimulates reflection is reported as an alternative approach for measuring, monitoring, and promoting interdisciplinarity effectively, at least in the case of graduate students (Manathunga, Lant, & Mellick, 2006, 2007). Instead of perceiving interdisciplinarity as a matter of hitting interdisciplinary skill targets or assessment goals, this type of dialogue mediates the development of interdisciplinary attributes. In this approach, students assemble evidence of interdisciplinary and other learning (in what is called a Research Student Virtual Portfolio) and receive direct feedback from their supervisors on how to improve their learning. Such an approach is likely to be a fine-grained and contextually sensitive way to assess interdisciplinarity in a given case.

Challenges

Challenges reported with respect to teaching include a possible underestimation by curriculum designers of the level of support students need in interdisciplinary contexts (Soares et al., 2013). The project management and teamwork required for modern professional contexts need targeted instructional intervention and support based on effective group coordination models that help students to structure and manage their teams (Aquere et al., 2012). Students have been reported to view interdisciplinarity with ambivalence in general (Barnard et al., 2013). Some articles reviewed here argue that engineers can be highly resistant to interdisciplinary learning goals, such as improving their cultural, social, and political sensitivity (Kabo & Baillie, 2009).

Some authors argue that systems thinking is needed rather than integrated courses or projects, yet they notice a lack of dedicated courses dealing with systems thinking for beginner students (Frank & Elata, 2005). This lack might be caused by the absence of enough educational materials (Blizzard et al., 2012) as well as a lack of ideas on how systems thinking could be taught within the time constraints of current curricula (Blizzard et al., 2012). Another reported cause is the complexity of designing an interdisciplinary curriculum, such as deciding on an order of topics or describing content from different domains (Bächtold, 2013). Two frequently found lines of thinking can be distinguished regarding what students should learn first: single discipline knowledge (Bächtold, 2013) or broader skills (Borrego et al., 2013). By referring to constructivist theories, the single discipline approach argues that students need to develop in-depth knowledge of their chosen discipline first before they can construct knowledge together with others. The other approach prefers a broad overview of the field before students can understand the depth of their specific field. A third, less often encountered approach starts with a whole-systems design and subsequently works in iterative cycles going between disciplinary and broad learning (Blizzard et al., 2012; Iyer & Wales, 2012).

Various types of problems reported in other educational contexts for any group project setting, such as social loafing and lack of trust or shared mental models (Borrego et al., 2013), appear in interdisciplinary contexts as well. They raise the issue of the degree to which instructors need to actively scaffold and reinforce professional identities over institutional ones during an interdisciplinary program or project rather than leaving students to develop such identities themselves (McNair et al., 2011).

Open-ended problems might be thought to encourage interdisciplinary interaction and flexible thinking. However, Gómez Puente et al. (2013b) report that students, when asked, preferred a scenario with more detail and clearer signposts on what was required for a result that would be advanced enough for their educational level. Learning how to cope with the challenge of interdisciplinary work can be accomplished by starting with less open-ended, more structured problems, while working toward open-ended and ill-defined projects (Gómez Puente et al., 2013b).

Some of these results point to the importance of the constructive alignment between learning goals and assessment tools (Biggs, 1999), particularly in interdisciplinary learning contexts in which the expectations of students may seem less structured or clear. However, the paucity of articles addressing assessment suggests there are still challenges to be faced, particularly with respect to aligning learning goals of interdisciplinary courses and programs. Problems related to assessment and alignment can be avoided through the reflective dialectic process between students and their supervisors reported above (Manathunga et al., 2007). Students are supported through this communication and can adapt their research toward developing their own interdisciplinary skills. This approach may not yield any type of standardized results, but it does bring the assessment process into strong constructive alignment with skill development in a flexible way. The involvement of assessment specialists might help in constructing better tools for disciplinary experts to use such as rubrics, surveys, and interviews (Borrego & Cutler, 2010) or a press conference (Redshaw & Frampton, 2014). Similarly, including community partners (Dewoolkar et al., 2009) or industrial partners (Larsen et al., 2009) can help ensure that students acquire skill-development goals related to professional communication and communication with stakeholders.

3.4 | Support

Support of education covers the availability of, among other things, laboratories, instruction rooms, a learning management system, information and communication technologies, and infrastructure (Larsen et al., 2009). Coordination (Aquere et al., 2012) and institutional support for the development of teacher skills (Karlsson, Anderberg, Booth, Odenrick, & Christmansson, 2008) are also considered part of support. The general educational research literature has found that support of teacher professional learning (Jansen in de Wal, Den Brok, Hooijer, Martens, & Van den Beemt, 2014), social learning (Darling Hammond, Wei, Andree, Richardson, & Orphanos, 2009), and infrastructure (Becerik-Gerber et al., 2012) are essential for reaching desired quality standards in teaching and learning. We focus here on the main emerging themes (a) teacher support, (b) institutional barriers, and (c) student support. Subsequently, we identify support-related challenges although we note exploration of this topic is limited and insufficient for distinct support and challenges sections.

3.4.1 | Emerging themes for IEE support

Teacher support

Providing instructors with the right type of training and advice for preparing and educating students in interdisciplinary work appeared a large concern in the studies reviewed (Gardner et al., 2014). This concern included training teachers in the use of nontraditional or research-level problems (Ding, 2014), or in concepts of interdisciplinarity (Gardner et al., 2014), or showing teachers how to structure their role as supervisors who provide timely interaction with students during open-ended problem-solving (Gómez Puente et al., 2013b).

Strategies for enhancing interfaculty relationships to support interdisciplinary education were often discussed in the studies reviewed here (Ferrer-Balas et al., 2008). These strategies were reported to include creating the right external links to business partners and internal links among different university programs to generate viable interdisciplinary entrepreneurship programs (Lehman, 2013). In this context, a shortage of the all-important institutional support and resources for teachers to develop external relationships for collaborative PBL purposes was reported (Lantada, Bayo, & Sevillano, 2014). Some authors discussed support in terms of availability of laboratories (Rashid, 2015) or a dynamic infrastructure or classroom design (Bocconi, Kampylis, & Punie, 2012; Larsen et al., 2009) as a prerequisite for IEE.

Institutional barriers

Teachers who lack interdisciplinary experience themselves may also lack enthusiasm or willingness to invest in the development of interdisciplinary programs (Gardner et al., 2014). Dewoolkar et al. (2009), for instance, reported a shortage of institutional incentives on the instructor's behalf to put time into interdisciplinary course design. Nonetheless, some included studies suggested that teachers need more institutional training and support to play a role in their student's professional skills development (Lantada, et al. 2014) and interdisciplinary training (Gardner et al., 2014).

Student support

Redshaw and Frampton (2014) report that from a student's point of view, a student needs support to communicate, integrate disciplines, and utilize peer-related skills. This support can include the use of evidence-based group structures that best facilitate interdisciplinary teamwork (Borrego et al., 2013). A few authors argued for the use of information technology and computer software to encourage and facilitate the group interactions necessary for collaborative work and interactive learning (Klein, 2013; Makrakis & Kostoulas-Makrakis, 2012). Students in interdisciplinary contexts are reported to have explicitly asked for access to experts (Redshaw & Frampton, 2014) and to connect with ideas, interests and people (Bocconi et al., 2012). Nonetheless, a face-to-face learning environment was not explicitly designed nor analyzed in most of the reviewed articles.

3.4.2 | Supporting and challenging factors for IEE support

Institutional practices and standards tend to hinder IEE because funding, tenure, and review processes are oriented along disciplinary lines (McNair et al., 2011; Hasna, 2010). In this context, the "siloed nature" of academia was referred to using various phrases (Borrego & Newswander, 2010; McNair et al., 2011). Apart from the availability of laboratories and related infrastructure (Rashid, 2015), these results suggest teachers need institutional support to collaborate on course building. Hence, there is a reported overall need for educational management to cultivate interdisciplinarity as a legitimate institutional identity and goal (McNair et al., 2011).

4 | DISCUSSION

This review applied a conceptual framework of vision, teaching, and support to synthesize and categorize current results and emerging themes in IEE. These aspects are interrelated because vision (the why) needs to be translated into teaching (how and what), which, in turn, requires support. Conversely, teaching should aim to meet a guiding vision, and support should be applied to remove barriers for students and teachers. Our work in this review intended to support or facilitate practice related to IEE, in which the interrelated challenges of vision, teaching, and support are all at play, by collecting and organizing current results based on these elements. In what follows, we discuss the limitations of our review, the implications of both the results and this study in general for IEE implementation, and suggestions for future research.

4.1 | Limitations

Our Results section outlined the results from the set of studies reviewed here. Many of these results were often derived from only a few studies based on specific cases. Furthermore, as we suggest below, there is a lack of conceptual consistency across studies. As a consequence, there is uncertainty about the generalizability of these case results. We have avoided for the most part drawing generalizations about what may or may not work extensively across all IEE contexts in favor of those reporting findings as individual results, and we would caution against applying these results without due attention to the details of the case reported. We would also note that some of our suggestions stemming from the limited attention we report on aspects of both vision and support may be somewhat influenced by our study selection. For instance, confining ourselves to engineering education papers alone means that papers in more general educational literature covering support and vision aspects extensively or at a theoretical level were not included, giving the impression that there is little relevant literature on these themes. Of course, such general material may be relevant to engineering education as well as to other areas. A further limitation likely arises from the search terms used to identify studies. Our focus on inter-, multi-, and transdisciplinary work left out possibly relevant work using "cross-disciplinarity" or "cross-disciplinary" as its central terms for interdisciplinary interaction. Finally, the inclusion criteria of full-text available studies might have caused a bias in our results.

4.2 | Implications

While the recommendations derived from our results represent a core of findings educators and researchers can draw on, we believe the scope and limits of these results suggest opportunities and directions for future research in IEE and for improving IEE design. In the rest of this Discussion section, we concentrate on providing some directions, with the overall goal of improving our understanding of the challenges facing IEE and best practices for handling them.

4.2.1 | Development of vision

Despite our identification of several overlapping and distinct visions underlying contemporary research, there remains some lack of concreteness with respect to how IEE is conceptualized and motivated in the studies included here. The primary motivation for IEE is found in the perceived complex nature of modern engineering practice (Gómez Puente et al., 2013a; Vojak et al., 2010), and the main advice is to organize education by means of real-world, problem-solving scenarios and experiences (Bacon et al., 2011; Barut et al., 2006; Brundiers et al., 2010; Hasna, 2010; Larsen et al., 2009). However, as some of our results show, visions of interdisciplinarity constructed around metaphorical or abstract concepts such as integration and communication render it difficult for interdisciplinarity to be translated into procedural skills and abilities (see Sections 3.1 and 3.2, particularly on assessment). As a result, it appears challenging to define clear learning goals and, in turn, concrete assessment formats. Many of the challenges of IEE may ultimately, we think, have their root in the difficulties of conceptualizing interdisciplinarity in terms of skills and learning goals, and the predominance of professional skill-based learning goals in our set of articles may owe something to this difficulty. More research seems to be required on translating IEE into sets of deeper cognitive and concrete procedural skills for this reason.

4.2.2 | Creating shared visions to help compare results

Current diverse or loose conceptualizations may contribute to difficulties drawing comparisons between results. This can prevent researchers and educators from setting standards on what counts as a good educational result in IEE. On our advice, defining clearer skills would help give a clearer set of learning or cognitive goals against which different IEE teaching strategies could be effectively identified and evaluated. T-shape learning is perhaps one of the clearest concepts to serve in this role in current IEE research (Hayden et al., 2011; Rashid, 2015). However, this approach calls for making clear to students that what they learn at university is actually of some use (Lantada et al., 2014) and to ensure that students learn how to link both axes of the T-shape model (Rashid, 2015). What we have tried to do here is at least identify the types of motivations guiding interdisciplinary education (see Section 3.2.1), each of which can be developed further into fully rationalized and articulated positions and then linked to specific learning goals. In this regard, system thinking and the CDIO framework (Crawley, 2001) as well as T-shape learning offer valuable starting points. The field should welcome research which takes up this task.

4.2.3 | Factoring in teacher experience

Third, interdisciplinarity seems highly desirable in course design, especially problem or project design. However, in our view there remains a lack of investigation into how to facilitate this process or what kinds of features problems or projects need for interdisciplinary learning goals to be reached, despite the preponderance of papers advocating PBL as the central educational framework for IEE. Hence, while it is accepted that problems need to be collaboratively constructed by teams of teachers from distinct disciplines (Abbas & Romagnoli, 2007; Gardner et al., 2014), interdisciplinarity still appears a relatively unfamiliar activity for many teachers.

Managing student team dynamics in interdisciplinary contexts needs its own investigation and management. It has been recommended, for instance, that teachers avoid social loafing and conflict while building trust among team members to ensure equal effort (Borrego et al., 2013). Indeed, a recent study suggests the need to define explicit discussion items for teams, including interaction rules, mutual expectations of one another's contributions and providing rules and methods for how to deal with conflict (Sortland, 2019).

4.2.4 | Putting more attention on assessment

As mentioned previously, in general the results show relatively infrequent attention to assessment (only 15% of papers in our review) such that it is not always clear in what sense interdisciplinary education should be measured as effective. In addition, more attention could be paid to effective pedagogies and the actual process of teaching. The current focus of results appears to be primarily on students and their learning processes, with less literature critically discussing pedagogies and assessment in IEE (Richter & Paretti, 2009). A we have noted, however, generating constructive alignment between interdisciplinary learning goals and assessment procedures raises significant challenges (Borrego & Cutler, 2010; Borrego et al., 2009), and common practices for assessing professional skills may need to be updated for interdisciplinary purposes (Borrego et al., 2009; Cantillon-Murphy et al., 2015; Soares et al., 2013). That said, measuring the interdisciplinarity of a project or course result is likely to be a major challenge. We note that integration remains a vague notion which is rarely defined, making it difficult to measure in a concrete way (MacLeod & Nagatsu, 2018).

Lastly, assessment procedures should, in theory, rely on techniques that can evaluate a body of interdisciplinary work and learning as a whole. However, educational practice shows that evaluators defer to others' expertise rather than seeking genuinely common standards (Borrego et al., 2009). Even when integration is specified as an explicit learning goal, assessing and evaluating (individual) performance within teams may still be difficult (Becerik-Gerber et al., 2012).

As such, while we think employing assessors from the different fields represented in an interdisciplinary project might not be ideal, it could be the start of increased sensitivity toward interdisciplinarity among the staff involved. Not all teachers involved can be expected to be interdisciplinary experts, especially in young domains. We think there is, thus, room for investigation of a teacher team approach, guided by a course coordinator who has experience with interdisciplinary projects (Gast, Schildkamp, & Van der Veen, 2017). Such an approach might help limit teachers from deferring to their colleagues on how to grade the aspects not part of their expertise and support them in learning to recognize what good integration looks like.

4.2.5 | Incorporating studies of scaffolding strategies

Two-thirds of papers in this review constructed their study around a PBL or PjBL scenario. While we accept there are good reasons for treating PjBL as a canonical platform for interdisciplinary learning, we would caution against investigating only pure PjBL scenarios, and not alternatives such as course-work designs or combinations which apply both PBL and structured coursework. Indeed, given the added difficulty of handling open-ended problems when collaborators come from different fields, one would hypothesize a beneficial role to forms of scaffolding which, for instance, might give students relevant methodological tools or theoretical concepts useful for integration or indeed background preparation on the challenges of interdisciplinarity. We would, thus, suggest research in IEE not restrict itself too narrowly to PBL in this context and put time and energy into the investigation of more structured educational alternatives and scaffolding methods.

4.2.6 | More study of support aspects

This review found a need for further research. In approximately 20% of papers, support aspects are raised but primarily with respect to a specific teaching strategy. As mentioned, part of the reason why little research on support emerged in our review may have something to do with our focus on engineering education. Research on support may in general transcend specific disciplinary contexts and may have been studied as such. That said, leaving aside support issues in IEE may have consequences for the applicability of IEE results, and the study of support can help better gauge the generalizability of results. For instance, if we can better understand the constraints (institutional or cognitive) which inhibit the development of interdisciplinary programs and the background circumstances, including elements of facilitation, important for a program's success, we may be better able to transfer educational strategies that are successful in one context to another or at least describe the conditions under which a program design might be most effective.

4.2.7 | Improving the quality of current studies

This review is limited to the data that could be extracted from the articles reviewed. In general, these studies, even if they presented an IEE intervention, did not necessarily present clear implications for practice or research. If implications were formulated, we found they were often not drawn from the empirical results of the study. Furthermore, case descriptions of courses or programs often do not describe the study limitations. In this review, we give an overall impression of the important research over the decade 2005 to 2016 and how authors approach IEE. What this review cannot do is make a reliable judgement as to the precise effectiveness of certain approaches in IEE, for instance in terms of increased average scores, student satisfaction, or student numbers. No such statistical analysis has yet been attempted. Additionally, this review does not criticize the idea that interdisciplinarity is usually approached in a strongly normative rather noncritical manner.

As suggested previously, future reviews could show more awareness of support aspects and their critical role, which did not appear frequently in the studies reviewed. Studies of IEE often operate on the implicit assumption that everything is well organized in terms of teacher support, classroom organization, or scheduling, or at least that interdisciplinary courses do not differ from disciplinary ones in the extent to which these are problems. However, Lattuca et al. (2017) have investigated and identified the influence of support factors, including the potential of engineering students to gain interdisciplinary skills through cocurricular activities, the role of faculty beliefs about interdisciplinary learning, and the value of promoting interdisciplinary learning in the curriculum. Their research makes a case for specific interdisciplinary engineering programs guided by interdisciplinary teaching teams (Lattuca, Knight, Kyoung Ro & Novoselich, 2017).

4.3 | Future work

Based on our study, we raise a couple of hypotheses for future investigation. First, teachers with experience in interdisciplinary research or practice with their own interdisciplinary examples are likely to be better at designing courses and conveying interdisciplinary skills than teachers without these experiences (see also Gardner et al., 2014). We expect that educators do try to structure a course design process as a collaborative process, but this requires more interaction (Gast et al., 2017) and is accordingly more time-consuming and subject to the kinds of conflict researchers often face trying to work across disciplinary boundaries.

Second, although the literature suggests that all teachers need to be interdisciplinary, we would further hypothesize that challenges regarding teachers' mindsets and beliefs might be tackled by building a course-team around one teacher with interdisciplinary skills and knowledge, supplemented with discipline-oriented teachers.

5 | CONCLUSION

In this review, we analyzed 99 articles to capture the current state in research of IEE, and summarize and organize the information available for the benefit of educators and researchers. To do so, we developed and applied an analytical framework of vision, teaching, and support, which we believe captures the main issues governing the implementation of IEE. The result of this work is an expansive picture of what has been investigated since 2005, and the specific results that have been drawn from these investigations under the categories of vision, teaching, and support. Based on these results, we have identified areas where we think future research is warranted and how such research might be structured. Furthermore, we explored the role of having such a framework in IEE for providing structure, orientation, and ultimately generalizability. As such we have tried to both map current results and sketch the beginnings of a roadmap for enhancing our knowledge of IEE.

Current results that reported success factors and challenges with respect to teaching promote the value of T-shape learning and the importance of both constructive alignment and more tailored assessment strategies to meet this alignment in interdisciplinary learning contexts. Our framework in this respect helps single out the importance of shared visions to the ability of IEE researchers and instructors to generate relevant and effective teaching resources and design relevant forms of institutional support. Within the topic of support, some studies have raised the need for institutional incentives, better teacher training and the application of technology to support cross-boundary interaction among students. Support remains, however, the least investigated of our themes.

Based on this review, it can be concluded that interdisciplinarity has typically been interpreted as connecting different engineering domains, with only a few examples of broader collaborations with medical sciences or social sciences thus far. Explorations of new fruitful ways to integrate interdisciplinarity into engineering education are often impeded by the historically discipline-oriented nature of academia. Overcoming this impediment can open up new opportunities if we want our students to acquire interdisciplinary skills for their future professions and professional development. Such a step when guided by educational design based on a coherent vision and supported by university management will bring us closer to the holy grail of truly IEE.

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APPENDIX. INCLUDED STUDIES ON INTERDISCIPLINARY ENGINEERING EDUCATION (IEE)

Author (year)	Discipline	Kind of study	Method	*N*	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Abbas and Romagnoli (2007)	Chemical engineering	Case study	Quantitative	20	Students	x	x		Curriculum integration. Success factors: elimination of poorly coordinated units of study, contextual understanding of concepts, development of professional skills, allow students to see application of knowledge/skills from one unit to another, allowing for the construction of knowledge or skills applicable in real-world situations. Challenges: more preparation work, potential loss of academic identity for teachers, time pressure.
Apul and Philpott (2011)	Civil and environmental	Case study	Qualitative	4 + 4	Students, staff		x		Success: outdoor problems as a hook for project. Challenge: project should contain meaningful tasks for all.
Aquere et al. (2012)	Production engineering	Case study	Mixed	28	Students		x	x	Success: increased understanding of interpersonal competencies. Challenge: internal organization and communication. Tutor important as (s)he is responsible for supporting the teams.
Bacon et al. (2011)	Environmental studies, engineering, sociology, education	Curriculum analysis	Qualitative			x	x	x	IEE trends: increasing specialization into narrowly defined academic disciplines, which separate STEM from human-environmental fields and complicates cross-disciplinary interactions. Challenges: institutional barriers, funding, different community and university time frames, providing faculty time to follow-up.
Baran et al. (2014)	Electrical engineering	Case study	Quantitative		Students		x		Both core technical courses as well as integrated courses for professional skills training are equally important and relevant.

(Continues)

Author (year)	Discipline	Kind of study	Method	*N*	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Barnard et al. (2013)	Civil engineering	Case study	Qualitative	24	Students		x		Challenge: students pay little attention to program content before embarking on their chosen degree; students view interdisciplinary content with ambivalence, usually ascribing its necessity in the preparation for post-university employment.
Barth and Michelsen (2013)	Sustainability	Review	Literature review				x	x	Educational science can contribute to individual action and behavior change, to organizational change and social learning, and to inter- and transdisciplinary collaboration.
Barut et al. (2006)	Decision sciences, industrial engineering	Case study	Quantitative	47	Students		x		Projects with intercultural student groups increased comfort with different cultures; teachers promote learning rather than teaching. Challenges: effective time horizon and management.
Becerik-Gerber et al. (2011)	Architecture	Case study	Quantitative		Staff	x	x		Call from industry to integrate more Building Information Modelling (BIM) tools. Concerns: engineering graduates need to have strong collaboration and teamwork skills; need to have a broader perspective of the issues that concern their profession such as social, environmental and economic; and need to know how to apply fundamental engineering science and computer skills in practice.
Becerik-Gerber et al. (2012)	Architecture	Case study	Mixed		Students		x		Virtual collaborative setting with education and industry allows instructors to design a course that incorporates the use of more realistic scenarios that better simulate real-world challenges. In role-playing students learn how different disciplines rely on one other for information, what type of information is needed, and when and how this information could be exchanged/shared.

Author (year)	Discipline	Kind of study	Method	*N*	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Ben-Zvi-Assaraf and Ayal (2010)	Sustainability	Case study	Quantitative	30	Students		x		Engineering students develop industrial-environmental awareness and make use of interdisciplinary knowledge beyond that strictly related to the realm of engineering. Students became more attentive to environmental aspects associated with building. Challenge: organization difficult due to strong emphasis on core curriculum and limited space available.
Benedetto et al. (2010)	Engineering, architecture and design	Curriculum analysis	Qualitative	150	Students		x	x	Challenges: selecting the right problems for the point of view of multidisciplinarity and innovation potential, selecting the right student teams. Success: having a team of academic tutors with multidiscipinary competences, defining a coherent work plan for approaching the projects, asking students to manage projects “professionally” including the use of a limited budget.
Blizzard et al. (2012)	Whole-systems design	Case study	Mixed	165	Students	x	x		Cases in this course improved students’ consideration of essential whole-systems design concepts, strengthening student consideration of the clean sheet approach, integrative design, design for multiple benefits, optimization of the entire system, and the possibility of drastic efficiency increases with current technology. Challenge: siloed nature of academia.
Borrego et al. (2014)	Engineering	Review	Proposals review			x	x	x	Proposals for funded projects are most successful with strategies which address both policies and cultural norms.
Borrego and Cutler (2010)	Multiple engineering disciplines	Case study	Mixed				x	x	Desired student learning outcomes of evaluated programs: contributions to the technical area, broad perspective, teamwork, and interdisciplinary communication skills. Student requirements addressed these outcomes to some extent, but assessment sections generally targeted program level goals. This shows a lack of constructive alignment between curriculum components.

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Author (year)	Discipline	Kind of study	Method	*N*	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Borrego et al. (2013)	Engineering	Review	Literature review				x		Success factors: team projects lead to increased teamwork, communication, sustainability, and global/societal design context. Building trust among team members to ensure equal effort. Challenges: avoid social loafing and conflict. The issue of "free-riders," or team members who do not contribute their fair share to the project.
Borrego et al. (2009)	Biological systems engineering, materials science, industrial systems engineering, civil and environmental engineering, and engineering science and mechanics	Case study	Mixed	20	Students		x		Concept maps are powerful for representing complex knowledge networks, valuable tools for assessing students' interdisciplinary development. Challenge: lack of consensus about the structure and boundaries of disciplinary content.
Borrego and Newswander (2010)		Review	Proposals review				x		Categories of learning outcomes for ID education: disciplinary grounding, integration, teamwork, communication, critical awareness. Criteria for assessing ID work: disciplinary grounding, integrative quality, critical awareness.
Brundiers et al. (2010)	Sustainability	Review				x	x		A stepwise process of integrating real-world learning allows building competencies such as problem solving, linking knowledge to action, and collaborative work, while applying discipline concepts and methods. Real-world learning opportunities need to incorporate collaborative design, coordination, and integration in introductory courses.
Cantillon-Murphy et al. (2015)	Electrical, mechanical, civil/environmental engineers plus medical students	Case study	Qualitative	26	Students		x	x	Introducing real-world problems is key to interdisciplinary projects. Organizational issues arise as students come from different programs with other obligations and timeframes.

Author (year)	Discipline	Kind of study	Method	N	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Cardetti and Orgnero (2013)	English/math	Case study	Qualitative	2	Teachers		x		Professional development through dialogic reasoning, situated reflective learning. Extensive inquiry into the other person's disciplinary field and making sense of it through reflective activities. Professional development takes dedicated time and discipline, the will to create common understanding and to study the background of real-life problems.
Carmona-Murillo et al. (2014)	Telecommunication engineering	Case study	Quantitative		Students		x		Engineers must be trained in technical knowledge and in professional skills. Learning methodologies, such as project-based learning, support these skills. Projects are evaluated based on the ability to work in a multidisciplinary team, understanding of both professional and ethical responsibility, and the ability to communicate effectively.
Cezeaux et al. (2008)	Biomedical and industrial engineering	Curriculum analysis	Qualitative				x	x	Collegiality and available facilities are supportive for long-term development of multidisciplinary design experience.
Chan and Sher (2014)	Architecture, engineering, construction	Case study	Quantitative	621	Students		x	x	Collaborative learning supports building academic knowledge and generic skills. Collaboration skills necessary for employability and multidisciplinary working skills. Focus on taking away barriers to collaborative learning and stimulating collaboration.
Chin and Yue (2011)	Mechatronics (mechanics, computer, electrical engineering)	Case study	Mixed		Students	x	x		Vertical stream curricula model (VSCAM) for enhancing student learning system design through integration of educational activities. PBL as effective pedagogical framework for teaching multidisciplinary subjects if guidance and support are given to staff and students. Combine vertical curriculum with horizontal projects/hands-on. Offer students clear assessment criteria.

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Author (year)	Discipline	Kind of study	Method	N	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Cobb et al. (2016)	MBA, engineering, industrial design, information	Case study	Mixed	19 of 160	Students		x		Multidisciplinary teamwork: engaging students in multidisciplinary design projects as a means for developing the skills needed. Best practices: strategic, long-term orientation; formal portfolio management process; formal discipline-supported process; conduct market research proactively; utilize multifunctional teams; and employ standardized criteria and metrics.
Collier et al. (2013)	Electronic, mechanical and software engineering	Case study	Qualitative				x		Teamwork and communication skills hard to develop in first-year students with low technical maturity.
De Werk and Kamp (2008)	Sustainability engineering education	Case study	Quantitative	291	Students		x		Two-thirds of students integrate sustainable development into graduation project; students feel that the certificate adds value to their graduation; and many find jobs within their discipline field.
Dederichs et al. (2011)	Civil engineering, architecture	Case study	Quantitative	32 + 7	Students, staff		x	x	Traditional role distribution disbanded and induced a flat team structure; decisions made by consensus. Challenge: coordination between professional teachers complicated, lack of multidisciplinary or interdiscplinary experience makes it more difficult. Reaching consensus takes time.
Delaine et al. (2010)	Engineering	Case study	Mixed	157	Students		x	x	Student-led international organization: introducing students to other cultures provides a comparative environment in which he/she can more clearly appreciate the benefits and analyze the shortcomings of education, lifestyle, and career choices. It allows students to learn about trends, issues and norms of various cultures.

Author (year)	Discipline	Kind of study	Method	*N*	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Dewoolkar et al. (2009)	Civil engineering and environmental engineering	Case study	Quantitative	146	Students		x		Projects provided ideal platforms for students to grasp systems concepts while accomplishing academic goals, civic engagement, and improving personal/interpersonal skills. Challenge: problems and learning goals need to connect; communicate learning goals so students know why they do things; and administration attitude toward innovation.
Ding (2014)	Physics, engineering	Case study	Mixed	16	Teachers	x	x	x	Most instructors valued and used traditional textbook problems. They valued nontraditional problems but seldom used them due to limited resources and experience, time constraints, student reactions, and personal preferences. Teachers showed great interest in collaborating with educational researchers on a more personal level to increase the use of nontraditional problems in teaching. Success factor: support for teachers implementing research-based problems. Challenge: paradigm does not fit with teacher beliefs.
Do (2013)	Mechatronics	Curriculum analysis	Qualitative				x		Managing projects is difficult for teachers because of different student levels of ability. Solution: arrange projects to have multiple small objectives with different difficulty levels, and each student selects one objective to be achieved. Every student can actively participate in the project, and the approach enables most students to produce successful results. Success factors: formulate assignments in levels of difficulty; connect learning goals to these levels, and let students choose their own level. Challenge: skills of communication and cooperative interaction with other members.

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Author (year)	Discipline	Kind of study	Method	*N*	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Douglas et al. (2010)	Engineering education	Review	Literature review			x	x	x	Argues for "epistemological diversity" in engineering education research: instead of the current focus on quantitative method also include qualitative methods, which enable "question-driven" driven research instead of research directed by the "gold standard" method. Requires researchers to better understand and value quantitative methods.
Du et al. (2013)	Sustainability	Case study	Mixed	60	Students		x	x	Sustainability curriculum can attract students' interests in mastering relevant knowledge and necessary skills and competencies. PBL can facilitate participative learning, critical reflection, systemic thinking, creativity, and cultural awareness. Challenge: how to change the existing grading system, how to provide both teaching staff and students with prior knowledge about the new PBL methods, how to gain institutional support, and how to change the broader societal and cultural values.
El-Adaway et al. (2015)	Sustainability in building and construction engineering	Case study	Mixed	23	Students		x		Principles of active learning lead to stronger learning outcomes and development for students. Through PBL students were engaged in a service-based assignment for a new on-campus building. Success factors: developing rubrics with lecturer, a reflection report by students and a student evaluation. Guest lecture involvement needed to be organized and an authentic assignment, teachers as PLB facilitators.
Ertas et al. (2015)	Engineering	Case study	Mixed	15	Students	x	x		The paper contrasts interdisciplinary and transdisciplinary approaches. The transdisciplinary process involves not only crossing disciplinary boundaries within engineering but also integrates engineering with the social sciences and natural sciences in a humanities setting.

Author (year)	Discipline	Kind of study	Method	*N*	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Ertas et al. (2011)		Case study	Quantitative	134	Students, staff		x		Bringing together graduate students, faculty, and researchers from diverse disciplines through integrative transdisciplinary courses, lectures, and seminars supported education objectives, in addition to preparing students for an increasingly transdisciplinary, collaborative, and global job market.
Farrell and Cavanagh (2014)	Chemistry/ sustainability	Case study	Mixed		Students		x		A series of laboratory investigations made students explore the engineering aspects of biodiesel production and purification, properties characterization, quality control, and performance testing. Multiple choice questions were used as a pre- and post-evaluation method to assess learning outcomes. Students gained significantly in learning outcomes related to the application of mathematics, science and engineering principles; designing and conducting experiments; analyzing and interpreting experimental data; and solving engineering problems.
Ferrer-Balas et al. (2008)	Sustainability	Case study	Qualitative			x	x		A systems transformation analysis of seven case studies based on the tridimensional Framework-Level-Actors (FLA) method. Success: the main drivers for change are the presence of “connectors” with society, the existence of coordination bodies and projects, and the availability of funding. Challenge: lack of incentive structure for promoting changes at the individual level.
Fielding et al. (2014)	Engineering and design	Case study	Qualitative			x	x		Success factor: involving students in real-life projects; “vertically integrated projects”—starting from simplified tools in the first year, followed by a progression onto more complex methods and strategies; distributed design teams; increased product complexity; design for extended product lifecycle. Challenge: how to encourage students to think critically.

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Author (year)	Discipline	Kind of study	Method	N	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Fuselier and Jackson (2010)	STEM	Case study	Quantitative	311	Students		x		Student attitudes toward gender equity, values, contribution of competition and collaboration to science, and understanding of multidisciplinary collaborations in science. Women more strongly supported gender equity, perceived science as more collaborative, identified a broader range of disciplines, including social sciences and humanities. Success: stressing collaborative nature of science, develop wider perspective on science, introduce students to gender issues in engineering profession. Challenge: prejudice against gender and racial equity.
Gardner et al. (2014)	Biophysical sciences, social sciences	Case study	Qualitative	18 + 35	Students, staff		x	x	Socialization into interdisciplinary thinking requires communication to obtain knowledge and skills, investment to develop professional identity, and involvement to participate in professional role.
Gebhardt (2005)	Engineering	Case study	Qualitative				x	x	Scholar-practitioner synthesis suggests that academic and professional barriers block entrance to entrepreneurial activity. A functionally entrepreneurial engineer is multidisciplinary. Challenge: addressing technological illiteracy in America, a phenomenon that threatens entrepreneurial engineers.
Gero (2014)	Electrical engineering	Case study	Mixed	25 + 30	Students	x	x		Systems thinking skills enhanced by course consisting of first half discipline knowledge and second half design project.
Gilbert et al. (2015)	Engineering, social work	Case study	Qualitative				x		Engineering combined with social work students to infuse strategies for community engagement in designing and implementing student-led global engineering development projects. Collaborating in interdisciplinary teamwork can help engineering students increased awareness of sustainability and effective community engagement. While engineering education prepares students to design appropriate technologies to solve global problems, social work brings the knowledge and skillset to build community.

Author (year)	Discipline	Kind of study	Method	N	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Gillette et al. (2014)	Engineering, liberal arts	Curriculum analysis	Quantitative	27	Students		x		Case combines liberal arts with traditional engineering study in a hybrid program. Success: facilitate funding, openness in narrative and mutual respect, and core courses stimulate hybrid thinking. Challenge: siloed nature of academia.
Gnaur et al. (2015)	Architecture	Case study	Mixed	51	Students	x	x		Dual effect of experiential learning in problem-based, interdisciplinary environments with regard to both actualizing core knowledge, skills, and competences through solving complex real-life problems and having to employ and thereby develop professional skills. Space for discursive and methodological negotiation to facilitate the creation of alliances between communities of practice without threatening participants' disciplinary identities.
Gómez Puente et al. (2015)	Mechanical engineering, electrical engineering	Case study	Qualitative	52	Staff		x	x	Professional intervention for course redesign. Staff introduced to theoretical framework to redesign course to design-based learning.
Gómez Puente et al. (2013a)	Engineering	Review	Literature review				x		DBL projects consist of open-ended, hands-on, authentic, and multidisciplinary design tasks resembling the community of engineering professionals. Teachers facilitate both the process of gaining domain-specific knowledge and the thinking activities relevant to propose innovative solutions. Teachers scaffold students in the development from novice to expert engineers. Assessment is characterized by formative and summative of both individual and team products and processes and by the use of a variety of assessment instruments. Finally, the social context of DBL projects includes peer-to-peer collaboration in which students work in teams.

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Author (year)	Discipline	Kind of study	Method	*N*	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Gómez Puente et al. (2013b)	Mechanical engineering, electrical engineering, built environment, and industrial design	Case study	Mixed	98	Students	x	x		Teachers and students recognized DBL characteristics as part of the instruction. Not all DBL characteristics are embedded in student projects. Working closely with industry and stakeholders, especially with regard to feedback and assessment, provides additional learning moments and motivation for students.
Gorbet et al. (2008)	Engineering, fine arts	Case study	Quantitative	7	Students		x		Quality of student work improved after collaboration; cross-disciplinary interests developed; create small groups and keep them together from project to project; provide shared space; emphasize the importance of shared time and working together and make clear early on the different expectations that students from different backgrounds bring to the course and projects.
Guardiola et al. (2013)	STEM	Case study	Quantitative	39	Students		x	x	Bringing real-world problems into the classroom gives students a view of real-world engineering. Students learn to understand decision-making processes and the ambiguity and lack of information that can attend real projects. Challenge: means to train mentors to deal with student questions.
Haen et al. (2012)	Engineering	Case study	Mixed	38	Students		x		Intensive 10-week program teaches students laboratory research skills and immerses them in interdisciplinary academic environment. This led to increased discipline research knowledge and attitude change.
Hamade and Ghaddar (2011)	Mechanical engineering	Case study	Quantitative	204	Students		x		Up to 3 years later in their curriculum, students profit from the experience of multidisciplinary teams in which they performed one of the four possible roles of manager, systems engineer, analyst, or details designer.

Author (year)	Discipline	Kind of study	Method	*N*	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Hasna (2010)	Mechanical, civil, electrical engineering	Case study	Qualitative	14	Students		x		Student portfolios do not necessarily represent the learning progress. Individual reflective journals, design workbooks, progress presentations, self and peer assessment, and individual grade nominations together form portfolio evidence that represents this progress.
Hayden et al. (2011)	Civil engineering, environmental engineering	Case study	Mixed			x	x		Curriculum reform to have students learn and apply a systems approach to engineering problem solving. Assessment methods: student surveys, student focus groups, faculty interviews, and assessment of student work. Success factors: real-life problems, system approach as method for all projects. Challenges: problem should connect with the learning goals and have sufficient components for a group; staff continuity.
Hodgson et al. (2014)	Science	Case study	Quantitative	400	Students		x		Science student perceptions of their skills. Teaching activities developing the broadest number of skills were laboratory classes and tutorials. Lectures only effective for developing scientific knowledge.
Hotaling et al. (2012)	BME, mechanical engineering	Case study	Mixed	168	Students		x		Capstone design courses with multidisciplinary teams. All students who took the MCD course produced an engineering solution that was better than that of their monodisciplinary contemporaries. Success factors: employability; increased innovation, utility, analysis, proof of concept, and communication skills from multidisciplinary capstone course.

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Author (year)	Discipline	Kind of study	Method	*N*	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Ibn-E-Hassan et al. (2014)	Engineering	Case study	Mixed	102	Students		x		Describe team roles assumed by members of project teams. Pakistani engineers assumed the roles of implementer, coordinator, shaper, and team worker. Success: engineering curriculum incorporates activities which foster creativity among engineers, motivates students to innovate through collaboration in a PBL environment. Challenge: some typical roles seem to be missing in engineering education culture.
Iyer and Wales (2012)	Biotechnology	Case study	Mixed			x	x		Laboratory protocols use a guided inquiry method to teach techniques and skills and help students build a bridge between materials presented in courses and applications in real life. Students then apply these concepts and techniques in independently designed investigations. The modular nature of this curriculum makes it flexible for integration into a variety of courses and could serve as a model for interdisciplinary education. Lifecycle idea as a hook for running projects; guided inquiry approach; projects connected to research.
Jones et al. (2014)	Engineering	Case study	Quantitative	365	Students		x		Strong relationship between students' course perceptions, domain identification, motivational beliefs, effort, and academic outcomes. Although developing students' technical expertise remains a priority, just as important are perceptions of the learning environment, understanding of engineering as a career, and meaningful identification with the profession.
Joyce (2012)	Mechanical engineering	Case study	Mixed	34	Students		x		Combining the positive learning benefits of non-hierarchal, small-group and peer-to-peer learning with innovative and novel teaching aids quickly and effectively enhanced the student learning experience. Engineering students have a bias toward active, visual and sensory learning.

Author (year)	Discipline	Kind of study	Method	N	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Kabo and Baillie (2009)	Engineering, social sciences	Case study	Qualitative	13	Students		x		Cross-disciplinary course on engineering and social justice. Success: awareness of social justice issues to produce more responsible and aware engineers. Challenge: moving engineers from simplistic to more transformative and critical concepts of social justice.
Kanigolla et al. (2013)	Engineering	Case study	Quantitative	54/34	Students		x		Impact of PBL on students' knowledge. Hands-on collaborative projects conducted with local companies had a positive impact on students' knowledge in learning course concepts and the students were able to apply theoretical knowledge to solve real-world problems.
Karlsson et al. (2008)	Psychology, business economics, sociology, technology, medicine, and chemistry	Case study	Qualitative	13	Staff	x	x	x	Academics from different disciplines, in collaboration with practitioners, showed five categories of learning: deepened awareness of perspectives and concepts, practical development, new awareness of one's competences and professional learning process, flexible professionalism and practical usefulness, and insights into research and development processes. Challenges: trust and open dialogue, organized time and space for sharing and reflection.
Kavanagh and Cokley (2011)	Engineering	Case study	Mixed	118	Students		x		Design and communication of engineering students can be enhanced by interdisciplinary collaboration with journalism students. Success: appreciation of other discipline, change to practices, inclusion of other field's practices in own, colearning. Challenge: gender disparities between two groups, fear and unwillingness to engage, hard to get ongoing professional relationships, getting to use and apply methods of another field—in summary achieving any significant ID.

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Author (year)	Discipline	Kind of study	Method	*N*	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Keraminiyage (2013)	Construction	Case study	Mixed	350	Students	x	x		Industry engagement is necessary for vocational degree programs. Ensure the program content is up to date and in line with the respective industry demands. Group work encourages deep-learning and student autonomy. Challenge: free-riding among students often relates to language problems.
Khosa and Volet (2013)	Veterinary science	Case study	Mixed	116	Students		x		The intervention introduced students to a metacognitive strategy aimed at enhancing learning through meaning making in group interactions and high-level questioning. The intervention led to increased time spent on case content-discussion, but not at the desired deep level. Success factors: increase the amount of time students spend discussing and explaining the case rather than simply managing, organizing and delegating tasks.
Kirkup and Bonfiglioli (2011)	Science majors	Case study	Quantitative	56/60	Students		x		Audio and video interviews made with senior science researchers, early career researchers, post-doctoral fellows and PhD students connect students to research. The activity was found to be a positive learning experience, and academics whose research is highlighted valued the opportunity to explain their work to beginning students.
Klapper and Tegtmeier (2010)	Entrepreneurship	Case study	Qualitative				x		Innovative teaching approaches in entrepreneurship highlight the importance of personal development of students by empowering them to be proactive. The practice firm concept aims to break down the start-up process into small digestible chunks.

Author (year)	Discipline	Kind of study	Method	*N*	Type	Vision	Teaching	Support	Main outcome regarding vision, teaching, and support
Knight et al. (2013)	Liberal arts	Case study	Mixed			x	x		Interdisciplinary programs can be ordered based on such curriculum content and organizational features as whether the director had an appointment within the discipline and the percentage of the faculty holding an appointment within the interdisciplinary program. Strong interdisciplinary programs have director and faculty appointments in the interdisciplinary field and require a higher number of total credits for the major.
Kyprianidou et al. (2012)	Informatics students and learning technology (using the ADDIE model for online instructional design on informatics)	Case study	Mixed	50	Students		x		Exploration of the impact of teacher-led heterogeneous group formation on students' teamwork based on students' learning styles. Evaluation data revealed that students gradually overcame their initial reservations for the innovative group formation method. The adoption of learning styles theories in practice can be facilitated by systems for automated group formation and supportive group facilitation meetings. Heterogeneous teams realize more creative/innovative results.
Lam et al. (2014)	Sustainability	Review	Literature review				x		Analysis of the characteristics of interdisciplinary sustainability studies (ISSs). ISS is largely based upon attempts to integrate aspects of different disciplines. Focus is on resource management studies, have a practical orientation, with often addressing policy-making issues, and people's participation in decision-making. Sustainability is best understood and analyzed from interdisciplinary perspectives and approaches. The process of integrating disciplines challenges prevailing methodologies.

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Lansu et al. (2013)	Sustainability	Case study	Quantitative	32	Staff	x	x		Analysis of the role of universities in the social network of an increasingly knowledge-based society. Proposed is a design process based on open curriculum development in interaction with the workfield. Challenges: acquisition of transboundary competence; competence development should be holistic and adaptive; and competence should meet people expectations; professional experience of faculty should be incorporated to extract learning outcomes from professional demands.
Lantada et al. (2014)	Engineering	Case study	Quantitative				x	x	Methodical analysis of main strategies to promote professional skills. Success: improving student motivation and their perception that what they learn at the university "is actually of some use," promoting professional skills helps teachers become more involved in their relationship with students. Challenges: type of activities to be considered, assessment of students' performance, promoting student motivation, decrease of administrative tasks for staff, and additional support and funding.
Lantada et al. (2013)	Mechanical engineering	Case study	Quantitative	8	Teachers		x		Analysis of factors that influence PBL. Challenge: planning projects, application of knowledge to real problems, project coordination, critical analysis of problems, searching for solutions, setting up and conducting assessment, and professor skills.
Larsen et al. (2009)	Mechanical engineering, electronics engineering, software engineering, industrial design, human technology	Case study	Mixed	28	Students		x		Summer school program to overcome difficulties students face when working in multidisciplinary teams at the beginning of their career. Success: intensity of summer school, interact and discuss problems and solutions. Challenge: team spirit and motivating lectures.

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Lattuca et al. (2013)	Biomedical/ bioengineering, chemical, civil, electrical, general, industrial, mechanical	Case study	Mixed	5,249	Students		x		Eight dimensions of interdisciplinary competence: (a) awareness of disciplinarity, (b) appreciation of disciplinary perspectives, (c) appreciation of nondisciplinary perspectives, (d) recognition of disciplinary limitations, (e) interdisciplinary evaluation, (f) ability to find common ground, (g) reflexivity, and (h) integrative skill.
Lehman (2013)	Entrepreneurship	Curriculum analysis	Mixed				x		Evaluation of entrepreneurship programs: identification of institutional champions, communication with members of the “student supply chain,” and offering both noncredit, experience-based opportunities and dynamic for-credit courses. Implementing a strategy that includes faculty partnerships, designated advisory boards, and refined bootstrapping skills helps to ensure that robust human and capital resources are available for program delivery, growth, and sustainability
Litzinger et al. (2011)	Engineering	Review	Literature review			x	x		Future changes in engineering education should be guided by research on expertise and the learning processes that support its development. Engineering education should encompass a set of learning experiences that allow students to construct deep conceptual knowledge, to develop the ability to apply key technical and professional skills fluently, and to engage in a number of authentic engineering projects. Engineering curricula and teaching methods are often not well aligned with these goals. Curriculum-level instructional design processes should be used to design and implement changes that will improve alignment. The academic culture in engineering may discourage development and implementation of experiences that promote the use of deep approaches to learning.

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Liu et al. (2011)	Science, non-science	Case study	Mixed	177	Students		x		Relationships between scientific epistemological views (SEVs) and reasoning processes in socioscientific decision-making. Students who held changing and tentative beliefs about scientific knowledge were more likely to recognize the complexity, take multiple perspectives, and question omniscient authority in the decision-making process. Many students make decisions based on a single disciplinary perspective. Educational programs should encourage students to actively participate in issue investigation and decision making by utilizing multiple reasoning modes and interdisciplinary thinking.
Makrakis and Kostoulas-Makrakis (2012)	Sustainability	Case study	Mixed	37	Students	x	x		Learning activities were designed to offer the chance for students to interact asynchronously and synchronously, negotiate meaning and reflect on their learning and viewpoints through collaborative problem solving. Using a participatory curriculum development approach ensures that all the groups and individuals who have a real interest in the program are actively involved in some way in the project during various stages. Through this approach contextualized teaching and learning become more feasible as those involved bring their own experiences to the learning process. A rich learning environment encourages shared meaning and shared inquiry as well as multiple learning styles and multiple representations of knowledge.

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Manathunga et al. (2006)	Health, biotechnology, environment	Curriculum analysis	Qualitative				x		University research higher degree programs continue to be largely disciplinary-based. Few research students gain exposure to interdisciplinary research processes. Success: scaffolding and peer groups. Challenge: different supervisor opinions can hinder interdisciplinarity.
McNair et al. (2011)	Interdiscplinary design course	Case study	Mixed	21 + 3	Students, staff		x		Teaching interdisciplinarity requires faculty and students to navigate structures of engineering programs that do not accommodate interdisciplinary work. A pedagogical approach of self-managed teaming can promote interdisciplinary identities if (a) faculty model institutional identities as interdisciplinary researchers and instructors, (b) students are encouraged to perform as decision-makers in groups constructed through affinity identities, and (c) faculty provide scaffolding for self-managed teams and encourage valuing of different disciplinary perspectives.
Nagel et al. (2016)	Engineering	Case study	Qualitative	15	Students	x	x		Analysis of a Content-Knowledge theory inspired approach. C-K theory applied to bio-inspired design fosters the following competencies of the 21st century engineer: holistic, critical thinking; creativity; self-regulated learning; and complex, multidisciplinary problem solving.
Nielsen et al. (2010)	Engineering, computer science, electrical engineering,	Case study	Mixed	25	Students		x	x	How to prepare engineering students for the increasing complexity of their professional lives and how to help them acquire skills of collaboration, management and innovation as well as awareness of knowledge creation. Challenges: communication and culture; lack of local support at home university; management in the context of cross-disciplinary knowledge; assessment and quality control remain little discussed; and project work in teams remains a new experience for many students.

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Rangel et al. (2016)	Civil engineering	Case study	Mixed				x		Implementation of integrated project delivery (IPD) methodology to PBL. Success: understanding relation between the design process and the convergence of all engineering disciplines that work together with architecture design practice, improvement in "ability to acquire knowledge," student's motivation for developing extra homework improves due to their initiative and commitment.
Rashid (2015)	Computer engineering education	Case study	Mixed	30	Students	x	x		Capstone design course offers opportunities for students to acquire technical and soft skills in the context of a design project. Features of the proposed methodology include system model of the curriculum, coherent delivery of the course contents, systematic laboratory practical, and development of technical and soft skills through problem-based learning. The system model of the curriculum is constructed using Y-chart methodology.
Redshaw and Frampton (2014)	Medicine, environment	Case study	Qualitative	16	Students		x		PBL's popularity is expected to grow and influence instructional approaches in many disciplines. Acknowledging, accepting, and overcoming conflicts based upon prior experience that influences epistemological and ontological beliefs may be key to the development of effective PBL in interdisciplinary and multidisciplinary program. Horizontal and vertical integration of the laboratory practical helps students to tie concepts together.
Richter and Paretti (2009)	Sustainability	Case study	Mixed	30	Students		x	x	Educators lack research about learning barriers, outcomes, and concrete interventions to support interdisciplinary development. Students (a) lack the ability to connect interdisciplinary subjects to their own more narrowly defined fields of expertise and (b) fail to identify and value the contributions of multiple fields to complex problems.

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Robinson et al. (2013)	Engineering	Case study	Mixed	535	Students	x	x		Established engineering faculty makes the successful step change transition toward the delivery of CDIO objectives. Main success factor: practitioner lecturers with many years of experience in implementation and operation of major projects. These skills were essential to the scoping, design, planning, and implementation of the project as well as giving the backdrop of best practice from industry.
Shyr (2012)	Mechatronics	Case study	Mixed	20 + 10	Students, staff		x		Group project-based approach to teaching mechatronics. The complexity of student projects can make administration of mechatronics courses extremely difficult. PBL group work using a diversity of assessment types increased academic outcomes and enthusiasm.
Silva et al. (2015)	Mechanical engineering	Case study	Qualitative		Students		x		Any answer to an ill-defined problem can never be completely right or absolutely wrong. Inability of recently graduated engineers to work in problems where the boundaries are not well defined, are interdisciplinary, require the use of effective communication and integrate non-technical issues. Design project that is tackled in a sequence of conventional courses with a focus that depends on the course objectives and disciplinary domain.
Soares et al. (2013)	Mechanical, industrial electronics and computers, polymer, industrial management	Case study	Qualitative		Students		x		Innovation and Entrepreneurship Integrated Project (IEIP). Through cooperation between the students of the various courses, success is attainable. Students' technical skills are improved, and they acquire multidisciplinary knowledge. Soft skills like project management, teamwork, communication ability and personal development, all of which are valuable requisites for their future employers, improved. The participating industries also take advantage of the project. Challenge: teacher support, project management and interpersonal relationship.

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Sochacka et al. (2016)	STEAM	Case study	Qualitative	2	Teachers	x	x		Expanded view of how STEAM might enrich engineering education. Autoethnography between educators in environmental engineering and art education. The study is grounded in learning as an active, collaborative search for meaning, "wide-awakeness," and social change. Provide students and educators with opportunities to explore personally relevant connections between materials, design, society, and the natural environment and to critically engage with implicit and explicit facets of disciplinary identity
Tafa et al. (2011)	Computer science, electrical and biomedical engineering, medicine	Case study	Mixed	84	Students	x	x		The need for a multidisciplinary educational approach is becoming more and more important. In development and implementation of technology-driven applications, multidisciplinary issues should be properly addressed in the academic sense. CMMI-levels introduce a systematic approach; different angles of designing a tele-medicine device automatically bring into focus the different disciplinary angles via software, hardware and medical application.
Telenko et al. (2016)	Engineering	Case study	Quantitative	321	Students		x		Designettes and design challenges are rapid and creative learning tools that enable educators to integrate design learning. Two or more courses joining in a designette results in a multidisciplinary learning activity; multiple subjects are integrated and applied to open-ended problems and grand challenges. This practice helps foster a culture of design and enables the introduction of multidisciplinary design challenges. Designettes are found to increase students' understanding of engineering concepts.

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Winberg (2008)	Engineering	Case study	Qualitative	4	Teachers	x	x		Ways in which lecturers in engineering negotiate their academic identities. Academic identities, even within a single engineering discipline, are flexible, multilayered, and susceptible to different degrees of change. Despite these differences, all participants experienced similar stages in the process of shifting from engineering to engineering educator identities. The development of pedagogical engineering knowledge is a long-term interdisciplinary project.
Žavbi et al. (2010)	Mechanical engineering	Case study	Quantitative	3 + 5	Students, staff		x		Product development processes develop increasingly systematic approaches. No specific prior knowledge was necessary for this method; team work stimulated the search and extraction of data and information, and recognition of opportunities. Students were convinced that they could not have acquired knowledge in any other way, while employees were less sure.