INTERDISCIPLINARITY IN TOMORROW'S ENGINEERING EDUCATION

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ABSTRACT

Universities are embracing 'challenge-based learning' (CBL) to engage students in contributing to real-life societal challenges. In CBL learning takes places through identification, analysis and collaborative design of sustainable and responsive solutions to these challenges. One aspect of CBL is working in interdisciplinary student-teams. Hence, implementation of Interdisciplinary Engineering Education (IEE) is sought, with the aim to train students to bring together expertise from different disciplines in a single context. To support this implementation of IEE, this paper presents a review that synthesizes IEE research with a focus on characterizing vision, teaching practices, and support. We aim to show how IEE is conceptualized, implemented and facilitated in higher engineering education at the levels of curricula and courses. Ninety-nine studies were included for analysis. Results indicate challenges in identifying clear learning goals and assessments (Vision). Furthermore, developing interdisciplinary skills, knowledge, and values needs sound pedagogy and teaming experiences that provide students with authentic ways of engaging in interdisciplinary practice (Teaching). Finally, a limited understanding exists of barriers that hinder the development of engineering programs designed to support interdisciplinarity (Support). This review contributes a level of awareness that allows teachers and educational leadership to take the next step towards interdisciplinarity in CBL.

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1 INTRODUCTION

1.1 Interdisciplinary engineering education and challenge-based learning

Today's social, economic, environmental, and medical challenges are complex, and often open ended and ill-defined [1]. These challenges go beyond the traditional image of engineers' tasks and responsibilities [2]. 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 [3]. As a result, future engineers need the ability to access, understand, evaluate, synthesize, and apply perspectives and knowledge from fields other than their own. Or, at least be able to collaborate with those from other fields [4]. This ability would help engineers consider a broad range of environmental and social factors for approaching contemporary challenges [5].

One of the responses to these challenges and calls increasingly seen in higher engineering education is Challenge Based Learning (CBL) [6]. CBL is an interdisciplinary experience where learning takes place through identification, analysis, and collaborative design of a sustainable and responsive solution to a sociotechnical problem of which both the problem and outcomes are open [7]. CBL at least involves (1) open ended problems from real world practice that require working in interdisciplinary teams, (2) entrepreneurial acting and design thinking, (3) combining disciplines, and (4) linking curricular and extracurricular activities [7]. CBL both deepens disciplinary knowledge and stimulates 21st century skills such as self-awareness, self-leadership, teamwork, and an entrepreneurial mindset [8][7].

In our view CBL is an educational evolution, rather than a revolution, with working in interdisciplinary student-teams as a central characteristic. Hence, implementation of interdisciplinarity in engineering education is looked for, with the aim to train students to bring together expertise from different disciplines in the context of solving sociotechnical problems. The working definition for interdisciplinarity in education that studies of Interdisciplinary Engineering Education (IEE) seem to agree on is that interaction between fields of expertise requires some level of integration between those fields to count as "interdisciplinary" [9]. Interdisciplinary interactions can be considered as attempts to address societal challenges by integrating heterogeneous knowledge bases and knowledge-making practices, whether these are gathered under the institutional cover of a discipline or not. 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 [10].

This implementation of IEE makes it timely and relevant to explore how aspects of CBL can be found in studies of engineering education. The aim is an evidence-based grounding for developing CBL in engineering education, which would allow teachers and educational leadership to take the next step towards a more systematic less diffuse approach to interdisciplinarity and CBL.

This review builds on an earlier literature review of interdisciplinarity in engineering education [11]. Because of our aim of offering an evidence-based grounding for interdisciplinarity in CBL, for this paper we provide a secondary analysis of review results, filtering for CBL-relevant findings. As such, the added value of this review consists of bringing together approaches, reported success factors and challenges from individual case studies, that can serve as points of attention for teachers, curriculum designers, and researchers of IEE, and CBL in particular.

1.2 Characteristics of CBL

To characterize CBL, Malmqvist et al. [7] make a distinction between traditional engineering education, CDIO/Problem Based Learning (PBL), and CBL. This distinction leads to the following characteristics for CBL:

- Combination of engineering and entrepreneurship/business
- Emphasis on social context
- Combination of problem formulating and designing
- Combination of team and individual
- Value-driven, with a focus on transformation and integration, and short-term and long-term value creation [12]
- Competences in sustainability problem-solving; systems thinking, and anticipatory, normative, strategic, and interpersonal competence, and critical thinking [13]
- Based on a rigorous treatment of engineering fundamentals. Students accomplish high levels of specialized knowledge in their field of study

These characteristics together form an educational vision on CBL. Or, in other words, CBL in our view is an educational concept, rather than an educational method. However, this concept asks for a translation to practice to help curriculum designers or teachers in developing their courses and teaching, and formulating support requests.

1.3 Vision, teaching, and support

To explore interdisciplinary courses and curricula we identify educational processes at three levels: *vision, teaching,* and *support* [14]. 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. The primary processes, which we labelled *'Teaching'*, consist of instruction and curricular aspects such as learning goals, competence indicators, content, structure, and design of instruction, assignments and assessment, student characteristics, and teacher characteristics. *Teaching* puts the governing vision into action. *Support* consists of aspects such as infrastructure and institutional support, including available instruction rooms and laboratories, learning management systems and other tools and techniques, practice-based management, resources for developing teacher skills, incentives, and allocated time for curriculum development.

1.4 Research questions

Little is known about characteristics that really enable CBL-activities to succeed. Additionally, as challenges are inherently unpredictable, dealing with ‘emerging outcomes’ is an assessment challenge in itself. This paper presents a review that synthesizes IEE research with a focus on evidence for CBL characteristics that allow educators to translate visions into effective means of teaching and support. This aim leads to two research questions:
What aspects of Vision, Teaching, and Support have emerged as topics of interest for CBL 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 interdisciplinarity in CBL?

2 METHODOLOGY

To find examples of interdisciplinarity in engineering education and empirical evidence on whether the suggested IEE approach worked, we followed a pre-defined procedure [15] emphasizing 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 [16]. For a detailed description of the applied method, we refer to [11].

During the first step, searching for studies, target articles were identified through the Web of Science and Scopus databases. Queries were performed with the search terms “interdisciplinary” OR “multidisciplinary” OR “transdisciplinary” AND “engineering education.”

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
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
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
7. The article was published in English and available as a full-text version

The available articles were scanned in step 3, after which a further selection was made based on criteria including the search terms discussed above. Ultimately, a total of 99 studies were included in the review. Each of these 99 studies were coded based on a coding table. A priori codes were used to categorize the articles after reading the full text. This coding table structured the criteria for inclusion and subsequent data extraction from the included articles. The coding table included the following sections:

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

Because of the purpose of translating the educational concept of CBL to educational practice with a focus on interdisciplinarity, the results were analysed from the perspective of CBL characteristics. Therefore, no new codes were added to the coding table as designed in [11]. To increase the reliability of this literature review, the authors collaborated closely in the process of identifying emerging themes.

3 RESULTS

3.1 Emerging themes for IEE vision

Systems approach: Many articles in our review drew upon a “systems approach” to structure IEE. In this context, a system is perceived 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 [17]. 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’) [18]. Systems thinking and T-shape competencies thus refer to the CBL characteristics ‘Competences in sustainability problem-solving’ and ‘rigorous treatment of engineering fundamentals’ [7].

Most of the articles investigating systems thinking explicitly advocated that instruction should start by training knowledge of 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.

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 [19].

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 [20] or even for learning to start their own business [21]. This motivation appears to be guided by ideas about what future workplaces will look like and what industry demands from its employees [22][23].

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, articles with sustainability as a motivating factor [24][25], concluded that interdisciplinary engineers need to be capable of handling and integrating environmental, social and economic objectives into their work through engagement with social scientists or societal groups outside academia [26]. Authors motivated by ecological sustainability stressed the need for awareness amongst engineers of social, political, economic, and environmental constraints [24][27]. They emphasized that IEE should promote this awareness through real-world problem-solving scenarios and experiences, instead of through disciplinary learning alone [28].

Improving disciplinary competences: Internal disciplinary benefits of interdisciplinarity were sometimes prioritized in articles that spell out such benefits in terms of disciplinary knowledge and understanding, creativity or adaptability [29][30]. Because creativity and adaptability relate to skills such as project management, or working in teams, from this point of view, included studies rationalize interdisciplinarity as a useful source for training relevant professional skills [31][32][33].

These emerging themes show a natural development from traditional engineering education towards characteristics of CBL. However, where CBL emphasizes the combination of both entrepreneurship and social awareness, the included studies appeared to focus on these characteristics independently.

3.2 Emerging themes for IEE teaching

Student participation and group composition: 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 [34]. This disciplinary approach is reported to force 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 [27][22][35][36]. Learning to work with specialists from other fields and learning to know and appreciate methods and vocabulary from these fields is thus included in the learning goals of these courses.

Pedagogies and scaffolding: Problem-Based Learning (PBL) and Project-Based Learning (PjBL) are the most often applied educational formats in IEE settings in the included studies. PBL aims to cover relevant content and procedures through careful selection of authentic problems that student teams have to study through an enquiry process [37]. In PjBL student teams are offered open and ill-defined real-world challenges and problems [25]. Our results thus suggest that PjBL reflects some characteristics of CBL, however, scaffolding students in both problem formulating and design should be included as well [7].

Assessment characteristics and procedures: 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 [24]. Assessment in general is considered under-developed and under-discussed in interdisciplinary educational contexts [38][39]. Despite some attention to measuring levels of integration in student knowledge [40], or for assessment regimes [22][41], 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, especially section 3.4).

3.3 Emerging themes for IEE support

Teacher Support: Providing instructors with the right type of training and advice for preparing and educating students of interdisciplinary work appeared a large concern in the included studies [42]. This included training teachers in the use of non-traditional or research-level problems [43], or in concepts of interdisciplinarity [42], or showing teachers how to structure their role as supervisors to be able to provide timely interaction with students during open-ended problem-solving [1].

Strategies for enhancing interfaculty relationships to support interdisciplinary education were often discussed in the included studies [44]. These strategies were reported to include creating the right external links to business partners, and internal links amongst different university programs to generate viable interdisciplinary entrepreneurship programs [45]. Some authors discussed support in terms of availability of laboratories [46] or a dynamic infrastructure or classroom design [47][48], 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, often due to poor institutional incentives and rewards for engaging in it [42]. Nonetheless, some included studies suggested that teachers need more institutional training and support to play a role in their student's professional skills development [49] and interdisciplinary training [42].

Student support: Student support to communicate, integrate disciplines and utilize peer-related skills can include the use of evidence-based group structures that best facilitate interdisciplinary teamwork, including smaller teams or allowing students to self-select [20]. Students in interdisciplinary contexts are reported to have explicitly asked for access to asked for access to experts, stakeholders and relevant resources [47][50].

3.4 Supporting and challenging factors for interdisciplinarity in CBL

Supporting factors: Concepts and theory related to a *systems approach* provide a set of resources to help conceptualize interdisciplinarity in more concrete terms. Such an approach integrates content-based teaching methods with projects and problems [31][46], and thus provides specific guidance knowledge and skill requirements, and learning goals, for IEE. Further, involving *engineering professionals* [19] can play a strong role in identifying the skills that are relevant for today's engineers.

The use of *interdisciplinary, real-world problems* as a hook for projects was reported to increase student motivation [25]. 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 included *role-based learning* within student teams [51], and the importance for students to have a *good understanding of content* required to handle their project topic [52]. This relates directly to [7], who call for a rigorous treatment of engineering fundamentals in CBL. One often identified point of attention was the importance of having students learn about the other disciplines involved in the course and having them learn to *respect these disciplines* [53].

To avoid overly difficult problem tasks, research suggests that courses and projects should provide structures that *scaffold students toward success* [20]. Scaffolding structures 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 [52].

Challenging factors: *Institutional barriers*, such as the disciplinary departmental structure of colleges and universities, are reported to appear particularly resistant to interdisciplinary programs [53]. 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 sticking to a largely mono-disciplinary program [22].

Furthermore, specifications of skills, such as communication and teamwork, reported in the included articles, often appear vague: "ability to list, give and receive feedback" or "acquire language skills to move comfortably across disciplinary boundaries" [40]. This is a challenge for the CBL-characteristic 'competence in sustainability problem solving'. *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.

With respect to teaching, a possible underestimation by curriculum designers of the level of support students need in interdisciplinary contexts might be a challenge [41]. 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 [33].

Open-ended problems might be thought to encourage interdisciplinary interaction and flexible thinking. However [1] 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 towards open-ended and ill-defined projects (ibid.).

Institutional practices and standards tend to hinder IEE, because funding, tenure and review processes are oriented along disciplinary lines [53][54]. In this context, the 'siloed nature' of academia was mentioned, in several different wordings [53][40]. Apart from the availability of laboratories and related infrastructure [46], these results suggest teachers do need institutional support to collaborate on course building. Hence there is a reported overall need for educational management to cultivate the trait of interdisciplinarity as a legitimate institutional identity and goal [53].

In essence, these challenges represent a tension between the rigorous treatment of discipline fundamentals and competences in broader and professional skills such as sustainability problem-solving, systems thinking, and anticipatory, normative, strategic and interpersonal competence and critical thinking.

4 CONCLUSION

This review applied a conceptual framework of vision, teaching and support, to synthesize and categorize current results and emerging themes in IEE. Vision, teaching and support 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 interdisciplinarity in CBL by collecting and organizing current results in this way.

Limitations to this study concern uncertainty about the generalizability of included case results. Many of the results were often derived from only a few studies based on specific cases. Further, this uncertainty is caused by a lack of conceptual consistency across studies. We have avoided for the most part drawing generalizations about what may or may not work extensively across all IEE contexts in favor of these reporting findings as individual results, and we would caution against applying these results without due attention to the details of the case reported. 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.

Evident from this review is that both teachers and students need support and scaffolding to address real-world sociotechnical problems of which both the problem and outcomes are open. The CBL-characteristics as reported by [7] all appear with evidence for educational practice, apart from ‘value-driven’. This should be seen as a call for curriculum designers to make sure that CBL-assignments include attention for transformative and integrative values, and short-term and long-term value creation [12]. Furthermore, the tension between ‘sustainability problem-solving competences’ and ‘rigorous treatment of engineering fundamentals’ is apparent because there was no prevalence for either of these characteristics. This relates to two frequently found lines of thinking found in the literature regarding what students should learn first: single discipline knowledge [55] or broader skills [20]. 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 [32][56].

REFERENCES

[1] Gómez Puente, S. M., Van Eijck, M. W., & Jochems, W. M. G. (2013). A sampled literature review of design-based learning approaches: a search for key characteristics. *International Journal of Technology and Design Education, 23*(3), 717-732. https://doi.org/10.1007/s10798-012-9212-x

[2] Vojak, B., Price, R., & Griffin, A. (2010). Corporate innovation. In R. Frodeman, J. T. Klein, & C. Mitcham (Eds.), *The Oxford handbook of interdisciplinarity* (pp.546–560). Oxford, UK: Oxford University Press.

[3] Barut, M., Yildirim, M. B., & Kilic, K. (2006). Designing a global multi-disciplinary classroom: A learning experience in supply chain logistics management. *International Journal of Engineering Education*, *22*(5), 1105–1114.

[4] Czerniak, C. M. (2007). Interdisciplinary science teaching. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 537–559). Mahwah, NJ: Lawrence Erlbaum Associates.

[5] Lattuca, L. R., Knight, D., & Bergom, I. (2013). Developing a measure of interdisciplinary competence. *International Journal of Engineering Education*, *29*(3), 726–739.

[6] Tassone, V., O'Mahony, C., McKenna, E., Eppink, H., & Wals, A. (2017). (Re)designing higher education curricula in times of systemic disfunction: a responsible research and innovation perspective. *Higher Education*, published online. https://doi.org/10.1007/s10734-017-0211-4

[7] Malmqvist, J., Rådberg, K. K., and Lundqvist, U. (2015), Comparative analysis of challenge-based learning experiences. In CDIO (Ed.), Proceedings of the 11th International CDIO Conference. Chengdu, Sichuan, P.R. China: Chengdu University of Information Technology.

[8] Johnson, L. F., Smith, R. S., Smythe, J. T., Varon, R. K. (2009). *Challenge-Based Learning: An Approach for Our Time.* Austin, Texas: The New Media Consortium

[9] Klein, J. T. (2010). A taxonomy of interdisciplinarity. In R. Frodeman, J. T. Klein, & C. Mitcham (Eds.), *The Oxford handbook of interdisciplinarity* (pp. 15–30). Oxford, UK: Oxford University Press.

[10] McNair, L. D., Newswander, C., Boden, D., & Borrego, M. (2011). Student and faculty interdisciplinary identities in self-managed teams. *Journal of Engineering Education, 100*(2), 374–396. https://doi.org/10.1002/j.2168-9830.2011.tb00018.x

[11] Authors, 2020

[12] Larsson, J., and J. Holmberg. (2018). Learning While Creating Value for Sustainability Transitions: The Case of

Challenge Lab at Chalmers University of Technology. Journal of Cleaner Production, 172, 4411-4420

[13] Wiek, A., L. Withycombe, and C. Redman. (2011). Key Competencies in Sustainability: A Reference Framework for Academic Program Development. *Sustainability Science 6* (2): 203–218.

[14] Van den Akker, J. (2003). Curriculum perspectives: An introduction. In J. Van den Akker, W. Kuiper, & U. Hameyer (Eds.), *Curriculum landscapes and trends* (pp. 1–10). Dordrecht, The Netherlands: Kluwer.

[15] Petticrew, M., & Roberts, H. (2006). *Systematic reviews in the social sciences*. Oxford, UK: Blackwell. https://doi.org/ 10.1002/9780470754887

[16] Dixon-Woods, M., Agarwal, S., Annandale, E., Arthur, A., Harvey, J., Hsu, R., Katbamna, S., Olsen, R., Smith, L., Riley, R., & Sutton, A. (2006). Conducting a critical interpretive synthesis of the literature on access to healthcare by vulnerable groups. *BMC Medical Research Methodology, 6*(35). https://doi.org/10.1186/1471-2288-6-35

[17] Gero, A. (2014). Enhancing systems thinking skills of sophomore students: An introductory project in electrical engineering. *International Journal of Engineering Education, 30*(3), 738–745.

[18] Brown, T. (2005). Strategy by design. Retrieved from http://www.fastcompany.com/magazine/95/design-strategy.html

[19] Lansu, A., Boon, J., Sloep, P. B., & Van Dam-Mieras, R. (2013). Changing professional demands in sustainable regional development: A curriculum design process to meet transboundary competence. *Journal of Cleaner Production, 49*, 123–133. https://doi.org/10.1016/j.jclepro.2012.10.019

[20] Borrego, M., Karlin, J., McNair, L. D., & Beddoes, K. (2013). Team effectiveness theory from industrial and organizational psychology applied to engineering student project teams: A research review. *Journal of Engineering Education, 102*(4), 472–512. https://doi.org/10.1002/jee.20023

[21] Klapper, R. & Tegtmeier, S. (2010). Innovating entrepreneurial pedagogy: Examples from France and Germany. *Journal of Small Business and Enterprise Development*, 17(4), 552–568. https://doi.org/10.1108/14626001011088723

[22] Cantillon-Murphy, P., McSweeney, J., Burgoyne, L., O'Tuathaigh, C., & O'Flynn, S. (2015). Addressing biomedical problems through interdisciplinary learning: A feasibility study. *International Journal of Engineering Education, 31*(1), 282–291.

[23] Cobb, C., Hey, J., Agogino, A., Beckman, S., & Kim, S. (2016). What alumni value from new product development education: A longitudinal s-Study. *Advances in Engineering Education*, *5*(1).

[24] Apul, D. S., & Philpott, S. M. (2011). Use of outdoor living spaces and Fink's taxonomy of significant learning in sustainability engineering education. *Journal of Professional Issues in Engineering Education and Practice*, *137*(2), 69–77. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000051

[25] Brundiers, K., Wiek, A., & Redman, C. L. (2010). Real-world learning opportunities in sustainability: From classroom into the real world. *International Journal of Sustainability in Higher Education, 11*(4), 308–324. https://doi.org/10.1108/14676371011077540

[26] El-Adaway, I., Pierrakos, O., & Truax, D. (2015). Sustainable construction education using problem-based learning and service learning pedagogies. *Journal of Professional Issues in Engineering Education Practice*, *141*(1). http://dx.doi.org/10.1061/(ASCE)EI.1943-5541.0000208

[27] Dewoolkar, M. M., George, L., Hayden, N. J., & Rizzo, D. M. (2009). Vertical integration of service-learning into civil and environmental engineering curricula. *International Journal of Engineering Education*, *25*(6), 1257–1269.

[28] Krohn, W. (2010). Interdisciplinary cases and disciplinary knowledge. In R. Frodeman, J. T. Klein, & C. Mitcham (Eds.), *The Oxford handbook of interdisciplinarity* (pp. 31–49). Oxford, UK: Oxford University Press.

[29] Collier, G., Duran, O., & Ordys, A. (2013). Technology-centred teaching methods to introduce programming and robotic concepts. *International Journal of Technology, Knowledge and Society, 8*(6), 121–129.

[30] Lattuca, L. R., Voight, L., & Fath, K. (2004). Does interdisciplinarity promote learning? Theoretical support and researchable questions. *Review of Higher Education, 28*(1), 23–48. https://doi.org/10.1353/rhe.2004.0028

[31] Hayden, N. J., Rizzo, D. M., Dewoolkar, M. M., Neumann, M. D., Lathem, S., & Sadek, A. (2011). Incorporating a systems approach into civil and environmental engineering curricula: Effect on course redesign, and student and faculty attitudes. Advances in Engineering Education, 2(4), 1–27.

[32] Iyer, R. S., & Wales, M. E. (2012). Integrating interdisciplinary research-based experiences in biotechnology laboratories. Advances in Engineering Education, 3(1), 1–35.

[33] Aquere, A. L., Mesquita, D., Lima, R. M., Monteiro, S. B. S., & Zindel, M. (2012). Coordination of student teams focused on project management processes. International Journal of Engineering Education, 28(4), 859–870.

[34] Abbas, A., & Romagnoli, J. A. (2007). Curriculum intensification through integration of units of study in the chemical engineering degree programme. Education for Chemical Engineers, 2(1), 46–55. https://doi.org/10.1205/ece06030

[35] Tafa, Z., Rakocevic, G., Mihailovic, D., & Milutinovic, V. (2011). Effects of interdisciplinary education on technology-driven application design. IEEE Transactions on Education, 54(3), 462–470. https://doi.org/10.1109/TE.2010.2080359

[36] Kabo J., & Baillie, C. (2009). Seeing through the lens of social justice: A threshold for engineering. European Journal of Engineering Education, 43(4), 317–325. https://doi.org/10.1080/03043790902987410

[37] Barrows, H. S. & Tamblyn, R. M. (1980). Problem-based learning: An approach to medical education. New York, NY: Springer.

[38] Boix Mansilla, V., Duraisingh, E. D., Wolfe, C. R., & Haynes, C. (2009). Targeted assessment rubric: An empirically grounded rubric for interdisciplinary writing. The Journal of Higher Education, 80(3), 334–353. https://doi.org/10.1080/00221546.2009.11779016

[39] Richter, D., & Paretti, M. (2009). Identifying barriers to and outcomes of interdisciplinarity in the engineering classroom. European Journal of Engineering Education, 34(1), 29–45. https://doi.org/10.1080/03043790802710185

[40] Borrego, M., Newswander, C. B., McNair, L. D., McGinnis, S., & Paretti, M. C. (2009). Using concept maps to assess interdisciplinary integration of green engineering knowledge. Advances in Engineering Education, 1(3), 1–26.

[41] Soares, F. O., Sepulveda, M. J., Monteiro, S., Lima, R. M., & Dinis-Carvalho, J. (2013). An integrated project of entrepreneurship and innovation in engineering education. Mechatronics, 23(8), 987–996. https://doi.org/10.1016/j.mechatronics.2012.08.005

[42] Gardner, S. K., Jansujwicz, J. S., Hutchins, K., Cline, B., & Levesque, V. (2014). Socialization to interdisciplinarity: Faculty and student perspectives. Higher Education, 67(3), 255–271. https://doi.org/10.1007/s10734-013-9648-2

[43] Ding, L. (2014). Long live traditional textbook problems!? Constraints on faculty use of research-based problems in introductory courses. International Journal of Science and Mathematics Education, 12(1), 123–144. https://doi.org/10.1007/s10763-013-9400-5

[44] Ferrer-Balas, D., Adachi, J., Banas, S., Davidson, C., Hoshikoshi, A., Mishra, A., Motodoa, Y., Onga, M., & Ostwald, M. (2008). An international comparative analysis of sustainability transformation across seven universities. International Journal of Sustainability in Higher Education, 9(3), 295–316. https://doi.org/10.1108/14676370810885907

[45] Lehman, M. (2013). An insider's perspective on entrepreneurial program development at a small and a large institution. Annals of Biomedical Engineering, 41(9), 1889–1898. https://doi.org/10.1007/s10439-013-0778-6

[46] Rashid, M. (2015). System level approach for computer engineering education. International Journal of Engineering Education, 31(1), 141–153.

[47] Bocconi, S., Kampylis, P., & Punie, Y. (2012). Innovating teaching and learning practices: Key elements for developing creative classrooms in Europe. eLearning Papers, 30.

[48] Larsen, P., Fernandes, J., Habel, J., Lehrskov, H., Vos, R., Wallington, O., & Zidek, J. (2009). A multidisciplinary engineering summer school in an industrial setting. European Journal of Engineering Education, 34(6), 511–526. https://doi.org/10.1080/03043790903150687

[49] Lantada, A. D., Bayo, A. H., & Sevillano, J. D. J. M. (2014). Promotion of professional skills in engineering education: Strategies and challenges. International Journal of Engineering Education, 30(6), 1525–1538.

[50] Redshaw, C., & Frampton, I. (2014). Optimising inter-disciplinary problem-based learning in postgraduate environmental and science education: Recommendations from a case study. International Journal of Environmental and Science Education, 9(1), 97–110. https://doi.org/10.12973/ijese.2014.205a

[51] Hamade, R.F. & Ghaddar, N. (2011). Impact of team functions in an introductory design course on student performance in later design courses: A longitudinal study. International Journal of Engineering Education, 27(1), 101–113.

[52] Do, Y. (2013). Self-selective multi-objective robot vision projects for students of different capabilities. Mechatronics, 23, 974–986. https://doi.org/10.1016/j.mechatronics.2012.11.003

[53] McNair, L. D., Newswander, C., Boden, D., & Borrego, M. (2011). Student and faculty interdisciplinary identities in self-managed teams. Journal of Engineering Education, 100(2), 374–396. https://doi.org/10.1002/j.2168-9830.2011.tb00018.x

[54] Hasna, A. (2010). Multidisciplinary integrative learning in undergraduate design projects. International Journal of Continuing Engineering Education and Life-long Learning. 20(6), 495-516. https://doi.org/10.1504/IJCEELL.2010.037789

[55] Bächtold, M. (2013). What do students “construct” according to constructivism in science education? Research in Science Education, 43, 2477–2496. https://doi.org/10.1007/s11165-013-9369-7

[56] Blizzard, J., Klotz, L., Pradhan, A., & Dukes, M. (2012). Introducing whole-systems design to first-year engineering students with case studies. International Journal of Sustainability in Higher Education, 13(2), 177–196. https://doi.org/10.1108/14676371211211854