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# Pedagogical Framework to Fulfill and Improve the Understanding of Capstone Design Engineering Among STEM Graduates – A Mini Review

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***ABSTRAK***

*Dalam persekitaran pembelajaran abad ke-21 yang mencabar, terdapat keperluan yang semakin meningkat untuk memastikan seorang jurutera boleh menyelesaikan cabaran kejuruteraan yang baharu dan sukar. Maka penting untuk mengemas kini pendidikan kejuruteraan bagi melahirkan jurutera yang boleh menyelesaikan masalah dan bekerja dalam persekitaran hari ini. Masalah yang mendasari penyelidikan ini adalah wujudnya kelemahan dalam pembelajaran kursus projek reka bentuk atau kursus kejuruteraan reka bentuk bersepadu dalam kejuruteraan kimia dan adalah sangat penting untuk memberikan tumpuan terhadap pemahaman pelajar serta pencapaian hasil program. Kajian ini bertujuan untuk mereka bentuk, membangun dan menilai model pengajaran dan pembelajaran projek reka bentuk kejuruteraan kimia dengan meneroka pedagogi pengajaran. Penyelidikan ini merupakan penyelidikan asas yang menggunakan pendekatan reka bentuk dan pembangunan berlandaskan model ADDIE. Oleh yang demikian, adalah sangat diharapkan agar penyelidikan ini dapat memberikan input tentang model pembelajaran yang lebih efektif. Populasi kajian ini adalah pelajar tahun akhir di Fakultas Kejuruteraan Kimia & Teknologi, dan 9 tenaga pengajar pakar dari kebanyakan universiti di seluruh negara. Kesimpulannya, penerapan model ini diharapkan dapat memberi peluang dan panduan kepada pihak berkepentingan termasuk pensyarah, pengajar, dan pelajar untuk meningkatkan kemahiran dan kebolehan mereka dalam menyelesaikan masalah kejuruteraan yang kompleks dalam kursus projek reka bentuk pada masa hadapan.*

**ABSTRACT**

In the challenging 21st century learning environment, there is an increasing need to ensure that engineers can solve new and difficult engineering challenges. So it is important to update engineering education to produce engineers who can solve problems and work in today's environment. The problem underlying this research is the existence of weaknesses in the learning of design project courses or integrated design engineering courses in chemical engineering and it is very important to provide support for student understanding and achievement of program outcomes. This study aims to shape, build and assess teaching and learning models for chemical engineering design projects by exploring teaching pedagogy. This research is a basic research that uses a design and development approach based on the ADDIE model. Therefore, it is highly hoped that this investigation can provide input on more effective learning models. The population of this study was final year students at the Faculty of Chemical Engineering & Technology, and 9 expert teaching staff from most universities throughout the country. In conclusion, the application of this model is expected to provide opportunities and guidance to interested parties including lecturers, teachers and students to improve their skills and abilities in solving complex engineering problems in design project courses in the future.



## 1. INTRODUCTION

This challenging global world requires a variety of engineers with competent skills and diverse attributes and it is the responsibility of engineering educators to shape the landscape of engineering education. Besides, they must use their problem-solving expertise to educate future engineers about modern technological advancements. In addition, engineering education in the 21st century requires students who are prepared to face the demands of dynamic and complex work environments (Cole & Feng, 2015; Yu et al., 2021). Therefore, they need to engage in experiences that comprise the complexity, innovation, and application of knowledge in the chemical engineering curriculum. Previous study eviewed that studies need to be conducted to determine the specific factors of graduate employability (Bridgstock et al., 2019). Graduates need to understand the skills and characteristics employers are looking for to meet job requirements. Employers have highlighted the issue of graduates which is the lack of

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generic skills such as problem-solving skills. Furthermore, all industry leaders and bodies such as the National Academy of Engineers (NAE) recognize the need to develop engineers who act as design thinkers because of their ability to deal with complex, open-ended, and ambiguous real-world problems (Karaca-Atik et al., 2023; Mazumder et al., 2020). As a result, the Washington Accord's (WA) Graduate Attributes (GA) have been refined over more than a decade and in 2013 were adopted by the signatories as an example. A defining feature of engineering professionals is the ability to work with complexity and uncertainty and focus on complex engineering problem-solving. In recent years, industry leaders, academics, and Accreditation Board for Engineering and Technology (ABET) standards have expressed a renewed interest in teaching engineers to solve real-world and open-ended problems through design education (Liu, 2020; Nesbit & Li, 2004). Engineering students should be able to produce design solutions to complex engineering problems that meet specific requirements with appropriate consideration for constraints (Alexa Ray Fernando, 2022; Arthur et al., 2020).

The development of capstone design courses is an effort to bring the practical side of engineering back to the engineering curriculum. Additionally, it has been influenced by many sources including the ABET, engineering educators, and numerous industrial companies (Aristawati & Budiyanto, 2017; Bosica et al., 2021). The capstone design project is a key component of undergraduate engineering education that integrates and reflects knowledge gained in preparatory years and is a culmination of the overall chemical engineering curriculum. It is the heart and purpose of the Institution of Chemical Engineers (IChemE) accredited chemical engineering degree. According to previous study various authors discuss the development of capstone project with applications to laboratories or process control courses which involve design, instrumentation, simulation, and control (Ocampo-López et al., 2022). However, the capstone project carried out in most Chemical Engineering faculties in Malaysia includes the integration of process design, process control, and process engineering laboratories. Process design and control are applied to complete chemical plants and not to single unit operations. In the engineering curriculum setting, complex engineering problem are embedded in the capstone design project of the final year. Unfortunately, students often face well-constrained problems but are expected to graduate with the ability to solve complex problems. On the other hand, studies show that learning through solving real-world problems can provide context, thus it promotes deep and meaningful learning, in addition to enabling students to retain and transfer or use knowledge in other situations (Kamaruzaman et al., 2018). It is important to ensure that the university's output is in line with current demand, and real-life practice as engineers for graduates to be able to work after graduation.

The future of engineering education, states employers think that engineering graduates have the lowest competence in problem identification, formulation, solution and the highest in theoretical engineering. Perhaps this indicates that students manage to fully understand the theory but have trouble applying the theory practically, especially to solve complex engineering problems through capstone design projects (Abban, 2012; Adzobu, N, 2014). Furthermore, different interpretations or expectations from universities and industries make it more difficult to include complex engineering problems in capstone design projects. Industry trainers should allow enough time for students to develop alternative solutions for the projects to challenge students' thinking skills in capstone design (Artiyasa et al., 2020; Donovan et al., 2013). As industry, engineering professional organizations and accreditation bodies put more emphasis on solving complex engineering problems, it is a priority for students to know how to identify and define that the engineering problems they face require complex problems (Lyon et al., 2021; Moreira et al., 2023; Ocampo-López et al., 2022). In addition, educators have also used a pedagogical framework to improve student understanding through the approach and finally, their level of acceptance of this new technique is assessed. This pedagogical framework can be visualized as a teaching method or teaching system consisting of elements such as program objectives (POs), course learning outcomes (COs), learning approach (pedagogy), theory, reflective practice, student-centered assessment, and standard teaching plan. Previous study has supported this by stating that the pedagogical framework in its general form is a teaching system that consists of four elements such as philosophy, pedagogy, teaching strategies, and tactics (Goodyear, 1999). Although some research uses capstone design as the only sample course, it is possible that future research could assess how complex engineering problems are conceptualized by students in lower-year engineering professional courses that involve design (Alexa Ray Fernando, 2022; Saputra & Sujarwanta, 2021).

A successful teaching process depends on the development of appropriate and effective teaching methods, techniques, and strategies. Previous study introduced constructivism as a learning theory that supports the development of engineers' competencies for engineering practice and through graduate education (McHenry et al., 2005). As far as concerned, the teaching and learning approach of engineering education at the undergraduate level is focused on the development of specific factual knowledge when intellectually combined, it enables the understanding of engineering principles, scientific laws, and mathematics applications required to conceptualize and execute solutions to problems with a particular focus on design. Cognitivism is a learning theory that supports this approach (Hendy, 2020; Khoiriyah & Murni, 2021). Engineering education based on cognitive processes is adequate as a primary method for preparing engineering graduates as long as engineers apply their knowledge to real-world life. Therefore, educators need to apply this theoretical constructivist learning approach because it will be able to challenge or encourage students' metacognitive and cognitive thinking skills in solving complex

engineering problems through cornerstone design projects. Furthermore, through this approach, students will reflect on their own experiences to build their understanding of the world. This means they will generate their rules and mental models to understand their own experiences.

This process model shows that constructivism promotes the mental construction of the student's reality (experiences) and this experience causes the student to generate new understanding through the mental processing of each new experience with existing understanding. In addition, constructivism impacts the learning process through curriculum, instruction, and assessment. A framework is used to manage and evaluate capstone design projects. How People Learn (HPL) is an example of an educational framework. Capstone students as learner-centered will use their skills and knowledge to do capstone design projects according to the course content. The assessment centered is the design project implementation while the community in this framework refers to the faculty involvement, educators, industry involvement, and the tools. Therefore this study aims to shape, build and assess teaching and learning models for chemical engineering design projects by exploring teaching pedagogy. The novelty of this research lies in its attempt to address a critical gap in the education of STEM graduates by providing a focused pedagogical framework for Capstone Design Engineering.

## 2. METHOD

This research aims to overcome challenges in 21st century engineering education, where engineers need to be able to solve engineering problems that are increasingly complicated and complex. Technological developments and new engineering problems require an engineering education system that is capable of producing graduates who are competent in solving problems. One of the main issues identified in this study is weaknesses in the learning of design project courses in the field of chemical engineering, where student understanding and achievement of program outcomes are not optimal. This research uses a design and development approach based on the ADDIE model to design and assess an effective learning model in a chemical engineering design project course (Branch, 2009). This model is designed to improve existing teaching methods by focusing on innovative and relevant teaching pedagogy. This research involved final year students at the Faculty of Chemical Engineering & Technology as well as 9 expert teaching staff from various universities throughout the country as the study population, to evaluate the effectiveness of the model developed. The conclusion of this study shows that the application of this new learning model has great potential to help lecturers, teachers and students improve their abilities in solving more complex engineering problems. With this model, it is hoped that all interested parties in engineering education can be better prepared to face future challenges and prepare engineers who are able to work in an increasingly competitive and dynamic work environment.

## 3. RESULT AND DISCUSSION

### Result

#### *Trends and Challenges in Engineering Education for Industry 4.0*

New labor market demands, shaped by advances in the Industry 4.0 era require a shift in engineering education. According to previous study UNESCO's concern is to educate engineers to meet the demands of modern labor in the labor market (M. Krsmanovic, 2019). This shows that STEM jobs have grown significantly over the past few years. Concerning the current situation and future trends, this study is conducted to develop engineers who can solve the big problems of the time needed towards real life. Engineering education must enforce transferable skills and allow STEM graduates to develop cross-capacity in a time of rapid globalization, thus making them more employable and flexible in their working environment. Furthermore, because tertiary education as a public value creates a high level of trust with both graduates and businesses, there is a need to introduce a more holistic approach to engineering education with the concept of possibly reorganizing current practices in the curriculum to better prepare engineers for future challenges.

#### *Learning Theory and Methods Recommend forWorking with Generation Z*

Generation Z students are considered to be risk-adverse, unique, and universities must be prepared to face the challenge of instructing this new generation (Moore et al., 2017; Seemiller & Grace, 2017). Engineering educators are being challenged to adapt to the speed of technological change in particular. Previous study have defined a generation as a group of individuals born in the same period who experience the same cultural context and in turn, create that culture (Campbell et al., 2015). This leads us to believe that the time in which we are born and the events we experience shape us and our culture and this seems to form a strong bond between members of a generation. Therefore, new educational techniques need to introduced because it is also only based on good pedagogy. The teaching and learning environment are an interactive process that requires the involvement of both instructors and students in an effort to achieve results. However, this study will introduce an interactive learning approach for engineering design courses where a student-centeredness is suggested. Active learning is rooted in

constructivist theory and collaborative learning (Case & Light, 2011; Mills J.E., and Treagust, 2003). Constructivism is the most efficient learning theory and process in the development of professional competence. The main idea of this theory is that knowledge is not transmitted from teacher to student, but is an active process of construction. This is very important in the context of engineering practical knowledge built on theoretical foundations (Kurniawan et al., 2020; Taajamaa & Holvitie, 2018). On the other hand, previous study stated that active learning and problem-based learning have been shown to improve performance in STEM classes and develop skills in solving complex problems (Freeman et al., 2014). This is a key factor in developing successful engineers. Sequentially, problem-based learning and project-based learning are already been established in senior design classes. They involve collaborative work and interaction between members of a group when doing capstone design. According to other study they state that the project-based learning methodology has its foundation in constructivist learning theory, which claims that learning is focused on interpreting and constructing meaning (Gomez-del Rio & Rodriguez, 2022). In addition, this technique is likely to help in developing student creativity and engagement. It is a good suggestion to integrate it throughout the curriculum. This study is carried out to examine the students' understanding in chemical engineering design and this also means that researcher want to improve their achievement in this field.

There are many opportunities to integrate current technology into project-based classes. As an educator, it is very important to teach students to integrate information to form solutions to complex problems. This means that problem-solving strategy needs to be adopted, taught to student, and reinforced throughout the curriculum. Students need to understand the entire content related to the design in engineering. On the other hand, design-based learning has been discussed as an educational approach to support students in gathering and applying knowledge in open-ended assignments (Koesoemadinata, 2022; Ma & Li, 2021). According to previous study state this approach has become a practice among electrical engineering students (Puente & Jansen, 2017). The organization of the project has gone through different modifications and iterations in three consecutive years regarding the organization and supervision of the students. The result of this study shows that the open-ended character of the project has a positive influence on the designs especially regarding efficiency criteria. According to this educational principle, learning takes place in a group-based process is an excellent environment for students especially when they complete their engineering design in their final year degree. Furthermore, this teaching method encourage students to solve problems interacting each other, practicing interpersonal skills, and regular self-assessment of team functioning. Project-based learning is one of the common active learning methods in chemical engineering education. In Project-based learning within that framework, students went through their capstone engineering design. They apply knowledge while designing creative and innovative practical solutions representing the real world. They also can develop and practice twenty-first-century skills and collaborative teamwork. In doing so, design-based learning projects are incorporated into the curriculum to support students in achieving academic outcomes and industry expectations.

***Capstone Design Project And Students' Understanding In Chemical Engineering Design***

Capstone design projects were used to fulfill the ABET's requirement for a major culminating design experience. This is where all the knowledge and skills gained in previous coursework culminates in combing appropriate engineering standards and a variety of realistic constraints. Previous study states that capstone design projects provide a rich learning experience for engineering students to solve complex engineering problems (Alexa Ray Fernando, 2022). However, the current situation shows that in most cases, capstone design students immediately jump to solutions and idea without going through the proper design process. In the instrument created by other study to assess and improve design skills, he emphasized that the basic skills in design are the identification and definition of problems that comprise the phases of design problems (Jin et al., 2015). It is in this phase that knowledge and skills in complex engineering problems are required from students. Therefore, students undertaking capstone design projects must begin by recognizing and defining their own complex engineering complex. It is therefore important to identify their understanding because it will determine their awareness and willingness to do capstone design projects.

***Student-Centered Pedagogical Framework***

Educational innovators have attempted to address this challenge by developing disruptive pedagogical framework learning techniques such as inquiry learning, collaborative learning, flipped classroom, project-oriented problem-based learning, team-teaching, and digital environments for education. Most of these approaches are student-centered, while lecturers play a facilitative role in encouraging student interaction with knowledge and peers. The rapidly changing job market is now looking for engineering graduates with a more comprehensive collection of skills due to the need to address complex and multiparametric challenges (Ballesteros et al., 2021; Migliore et al., 2021). It is found that the traditional engineering education approach has provided an incomplete collection of competencies because it focuses solely on the development of technical skills. As a result, educational innovators have begun to address this important barrier by implementing an active-learning pedagogical

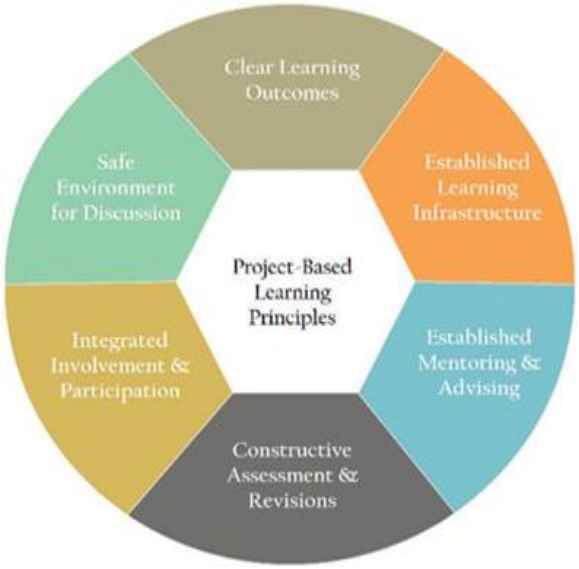
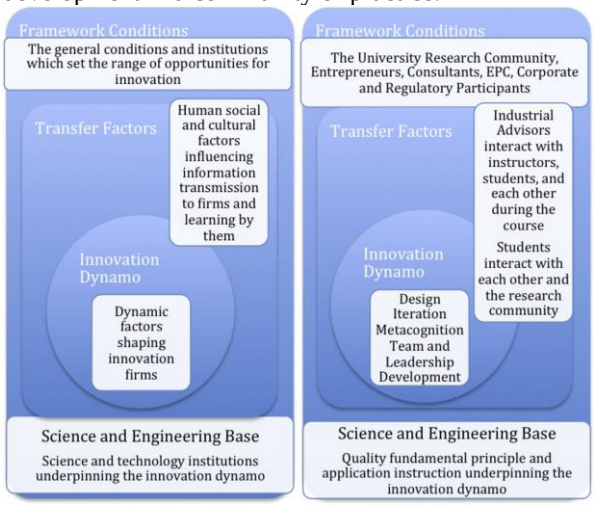
framework where the student is at the center of the experience. Similar studies in different fields have shown that students' progress towards more complex reasoning and expert concepts when they master tools in a technologically mediated environment (Reilly et al., 2019). However, engagement increases over time during that period, perhaps as a response to the complexity or increased understanding of that particular knowledge. This research hopes that with this emerging framework, engineering curricula worldwide have a profound transformation toward developing teamwork and the ability to operate in technology-enabled environments. Furthermore, capstone students will successfully understand to do engineering design project throughout twelve graduate attributes (WA). Table 1 and Table 2 summarizes the literature review on capstone design course and learning framework.

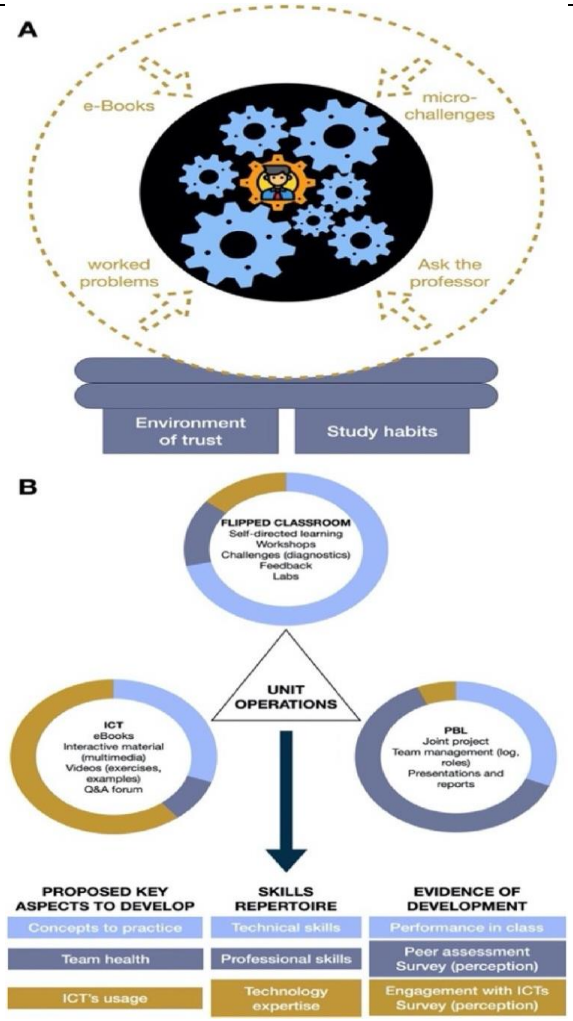
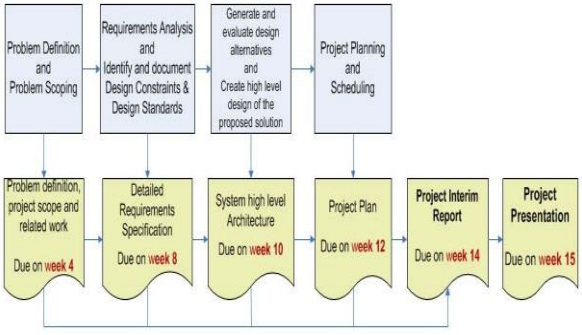
**Table 1**. Literature Review on Capstone Design Project: Issues and Solutions

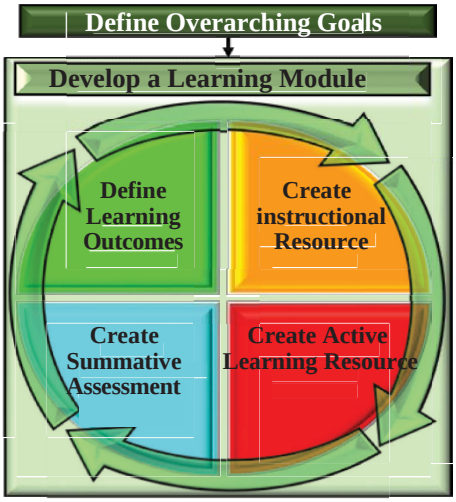
| No | Author/year | Country | Issues | Solution |
|---|---|---|---|---|
| 1. | (Alexa Ray Fernando, 2022) | Philippines | Design process starts with the problem phase where students are expected to recognize and define the problem. | Students doing capstone design projects must begin with recognizing and defining their own complex engineering problem. |
| 2. | (Qattawi et al., 2021) | USA | Gaps between the skills of engineering graduates and the qualifications or skills needed in the industry. | A design-based learning (DBL) educational approach is implemented for capstone design course to meet the multidisciplinary design needs and meet the skills' requirement. |
| 3. | (Ballesteros et al., 2021) | Colombia | To increase in the students' perception of the development of teamwork and people-related skills. | Course redesign to strengthen technical skills and technology expertise. |
| 4. | (Sawang et al., 2013) | Canada | How a community of practice contributes to student development, the achievement of the Canadian Engineering Accreditation Board (CEAB) graduate attributes, and the development of an innovation ecosystem. | Provide targeted direction to industrial participants in a process design course community of practice, therefore the focus of the community and their motivation for participation can be shifted over time from benchmarking competence to innovation competence that also supports student innovation and leadership capacity development. |
| 5. | (Howe & Goldberg, 2019) | USA | Discussed on the current practices and successful strategies in engineering capstone design education including perspectives and feedback from hundreds of engineering capstone design faculty regarding their personal experience with the course. | Provide recommendations based on the authors' vast experience teaching and managing engineering capstone design courses and engaging with the engineering capstone design community. This including multiple strategies for supporting capstone design courses. |
| 6. | (Kamaruzaman et al., 2018) | Malaysia | Issues discussed based of four main pillars: project information, faculty involvement, industrial involvement and assessment. | To accurately determine ways to incorporate complex engineering problems in capstone design project, more studies can be implemented, which are carried out to address the areas on the following:<br>To find out to what extent solving |

| No | Author/year | Country | Issues | Solution |
|---|---|---|---|---|
| | | | | complex engineering problems in capstone design projects can create better understanding for the engineering students. What are the characteristics of an ideal capstone design project that integrate complex engineering problems. |
| 7. | (Qattawi et al., 2021) | USA | A need to identify and understand the STEM educational challenges, and to assess the usefulness of existing methodologies using case-based analyses. | To develop a participatory pedagogy for manufacturing courses through the use of computer numerical control the use of manufacturing operations, and real-time monitoring, visualization and data analysis of machine energy use. |
| 8. | (Mahmood et al., 2014) | Malaysia | Current assessment methods | The paper put forward several recommendations to improve assessment methods for evaluating skills involving ethics, and project implications to environmental issues. Self-assessment surveys to evaluate the experience of the students are to be implemented and analysed in future works. |
| 9. | (Jin et al., 2015) | South Korea | Engineering educators have difficulty assessing students' design skills, and students struggle with engineering design projects because of a lack of clear guidelines. | This study develops a performance-based evaluation rubric that can assess and enhance students' engineering design skills in introductory engineering design courses. |
| 10. | (Sahni, 2023) | Australia | Issues on how project-based learning can be implemented to become an effective approach to developing graduate attribute. | Result shows development of understanding of sustainability was attributed to undertaking multiple projects and use of spread-sheeting tools. |
| 11. | (Alsalhi et al., 2021) | Qatar | Effective management and assessment of capstone design projects are often challenging and resource-intensive tasks. | This research resulted in better ways to teach, manage and assess the technical and nontechnical course outcomes. This paper presents some of the lessons learnt and reports the experience of designing and developing easyCapstone framework. |

**Table 2.** Literature Review on Capstone Design Project: Educational Frameworks or Learning Theories

| No | Author/year | Country | Framework | Learning Theory |
|---|---|---|---|---|
| 1. | (Qattawi et al., 2021) | California, USA |  PBL model | Constructivism<br>Cognitivism |
| 2. | (Sawang et al., 2013) | Canada |  Experiential learning environment for capstone design supporting design, innovation and leadership development in a community of practice.<br>  Innovation Policy Map-OSLO (left) and Mapping of the factors and conditions to the capstone design community of practice structure (right). | Constructivism<br>Cognitivism |

| No | Author/year | Country | Framework | Learning Theory |
|---|---|---|---|---|
| 3. | (Ballesteros et al., 2021) | Colombia |  <br>A. Techno-pedagogical framework<br>B. Redesigned UnOps course | Connectivism<br>Constructivism |
| 4. | (Alsalhi et al., 2021) | Qatar |  <br>Capstone design project activities and deliverables for the first semester. | Constructivism<br>Cognitivism<br>Connectivism |

| No | Author/year | Country | Framework | Learning Theory |
|---|---|---|---|---|
| 5. | (Wolf & McCoy, 2019) | USA |  Learning module development framework | Constructivism Cognitivism |

**Discussion**

A number of studies have been conducted by previous researchers on the capstone project that discusses numerous issues and suggested solutions as tabulated in Table 1. An excellent example, a previous study found that the design process starts with the problem phase, where students are expected to recognize and define the problem and the researcher suggested the solution that capstone design projects must begin with recognizing and defining their complex engineering problem. This is also supported by study who discovered that there is a skill gap among engineering graduates or skill requirements in the industry, so he proposed that a design-based learning (DBL) model be implemented as an educational approach for capstone design courses to meet the multidisciplinary design needs and skills' requirement as a solution (Qattawi et al., 2021). On the other hand, a study in Columbia by study discovered that it is required to increase students' perceptions of the development of teamwork and people skills (Ballesteros et al., 2021). At the conclusion of the investigation, he offered a model for redesigning the course to increase the technical skills and technology competence.

While other study having engaging in a discourse on the present state of engineering capstone design education and effective approaches, hundreds of engineering capstone design faculty members contributed their insights and feedback concerning their individual experiences with the course (Alexa Ray Fernando, 2022; Howe & Goldberg, 2019). Consequently, he offers suggestions derived from the authors' extensive expertise in instructing and overseeing engineering capstone design courses, as well as interacting with the engineering capstone design community. This encompasses several approaches to assist capstone design classes. In addition, other study finding in Malaysia that there are four pillars: project information, faculty involvement, industrial involvement and assessment being discussed (Kamaruzaman et al., 2018). In order to effectively integrate difficult engineering challenges into capstone design projects, more research can be conducted to specifically target the following areas: To find out to what extent the solving complex engineering problems in capstone design projects can create better understanding for the engineering students and what are the characteristics of an ideal capstone design project that effectively includes the complex engineering problems.

Several theories and models associated to the capstone projects have been detailed in Table 2. The aim is non other than to enhance the educational process of the engineering design course through collaborative project-based learning. From this review, it was determined that it is critical to focus on students' understanding of this capstone design course, particularly in chemical engineering. From a pedagogical standpoint, all of the listed models and frameworks have its own pros and cons, depending on context. The models and frameworks suggest appropriate approach for use as a learning and teaching strategy with senior project students. The models are expected to enhance the performance of final year students in this design course and effectively fulfil the programme objectives. In conclusion, the capstone design course is widely considered as a crucial educational exercise that offers engineering students the chance to tackle practical engineering problems. Furthermore, engineering schools are aware of this requirement and are currently revising their curricula to better prepare their graduates for the problems of the future. This capstone course gives instructors a means of assessing their

undergraduate students' overall education as well as identifying areas in which their students struggle. This can point to a place where a certain capstone design course needs work.

## 4. CONCLUSION

In conclusion, this paper has reviewed the important points to improve the students' understanding when doing capstone course in the final years of their engineering degree journey. Nevertheless, project-based learning with design component is very challenging and can provide students with timely feedback for their continued improvement. Engineers are expected to solve complex engineering problems as demanded by the industry and required by professional organizations and accreditation bodies. Therefore, it is important that higher education institutions participate in this effort to produce engineers who solve complex problem. Since complex problem are likely to be solved through design process, design education should be given adequate attention in the engineering curriculum. Thus, students should improve on their capstone design project, as the major culminating design experience requires knowledge and experience to become better engineers for future challenges. This will make them more employable and flexible in their working environment. To ensure the driver of change in the context of Industry 4.0, it is proposed to redesign the core concepts of engineering education by using a more holistic approach especially in the capstone design course.

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