Pedagogical Framework to Fulfill and Improve the Understanding in Capstone Design Engineering Among STEM Graduates – a Mini Review

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May 13, 2023

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Abstract

Keywords

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 for modern technological advancements. In addition, engineering education in the 21st century requires students that are prepared to face the demands of dynamic and complex and work environment. Therefore, they need to engage experiences that comprise the complexity, innovation, and the application of knowledge in the chemical engineering curriculum. Sahudin et al. (2022) had reviewed that studies need to be conducted in order to determine the specific factors of graduate employability. Graduates need to understand the skills and characteristic employers are looking for to meet job requirements. Employers have highlighted the issue of graduates which is the lack of generic skills such as problem-solving skills. This has led to developments in student-centered learning such as project-based learning that have so far shown little impact on mainstream engineering education. With this learning technique, problem solving skills will be able to be applied especially in engineering design subjects. This paper discusses critical issues in engineering education, solutions and also their impact on accreditation requirements. It then looks at the nature of project-based learning, discussing and reviewing examples of its application among capstone design students. World Economic Forum reports that 74% of employers need a problem solver. Employers show distress due to the lack of graduates' key skills of which problem-solving is the highest (World Economic Forum, 2016). 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.

As a result, Washington Accord's (WA) Graduate Attributes (GA) have been refined over more than a decade and in 2013 were adopted by the signatories as the example. A defining feature of engineering professional is the ability to work with complexity and uncertainty focused on complex engineering problems 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 problem through design education. Engineering students should be able to produce design solutions to complex engineering problems that meet specific requirements with appropriate consideration for constraints. Refer to Figure 1, WA GA number 3 (WA3) requires engineering students to be able to produce design solutions for complex engineering problems that meet specified needs with appropriate consideration for constraints (Alexa Ray Fernando, 2022).

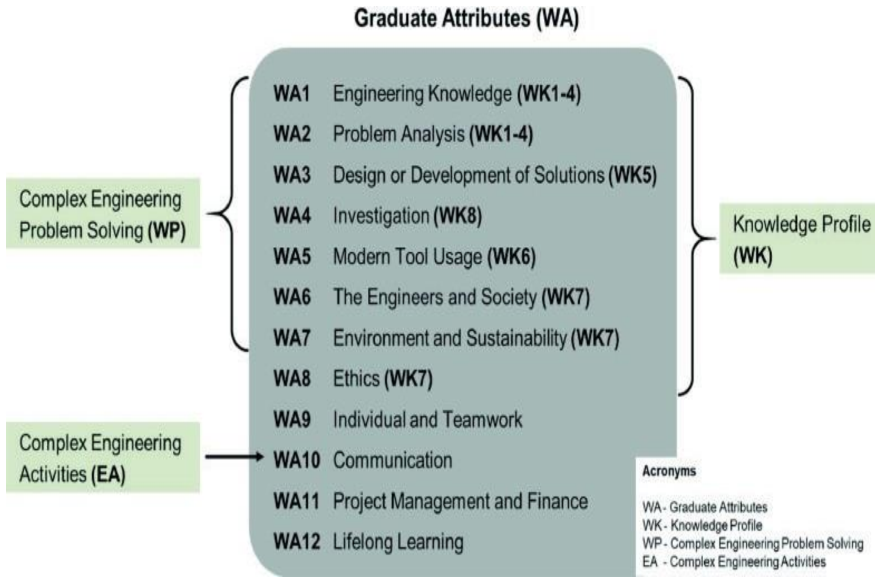


Figure 1: Complex Engineering Solving in WA's 12 Graduate Attributes

These attributes is widely implemented in culminating the design experience of engineering students through capstone design projects. Each higher education institution has its own way of designing and delivering capstone design projects, stating that one critical phase of the design process that students must be properly educated and guided on is problem definition and this depends on their understanding. That is why this research is important to carry out and need to be emphasized among engineering educators.

The development of capstone design courses is an effort to bring the practical side of engineering back to the engineering curriculum (Dutson et al., 1997). Additionally, it has been influenced by many sources including the ABET, engineering educators and numerous industrial companies. 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. The main objective of this design project is to provide a multidisciplinary experience and students will be able to integrate their knowledge from the core, intermediate and advanced course in the chemical engineering. For example, all seniors in third or fourth year program will use the skills and knowledge they have acquired through the major culminating design experience to provide evidence that they are prepared to work in engineering practice. According to Ocampo-López et al.,(2022), various authors discuss the development of capstone project with applications to a laboratories or process control courses which involves design, instrumentation, simulation, and control. However, the capstone project carried out in the most Chemical Engineering faculties in Malaysia include 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, real life practice as engineers for graduates to be able to work after graduation.

The Malaysian Ministry of Higher Education (MOHE), 2006 report on the future of engineering education, states employers think that the 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 project. Furthermore, different interpretations or expectations from universities and industries make it more difficult to include complex engineering problems in capstone design project. However, there are ways to reconcile this situation to both industry and universities. The first is to ensure that industry understands the expectations and learning outcomes from the faculty. For example, it can be achieved by sharing important information regarding the learning outcomes set by faculty. Industry trainers should allow enough time for students to develop alternative solutions for the projects to challenge students' thinking skills in capstone design. Another solution that needs be improved is may be that stakeholders (students, faculty, all academic administrators and industry) must first understand and identify the attributes and characteristic of complex engineering problem to incorporate them through capstone design project in the engineering curriculum. In addition, the faculty should also aim to prepare and train engineering graduates to be ready for capstone design project with consideration of other aspects of life. 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 problem they face require complex problems. Regarding this global issue, a study was conducted among final year students at the Faculty of Chemical Engineering Technology in University of Malaysia Perlis, Arau, Malaysia to improve the quality of their result. One of the objectives of the research is to identify their understanding in the capstone design course. Three consecutive years are required to study the appropriate learning approach for student design projects. 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. Goodyear (1999) 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. Although there is some research that 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 involving design (Alexa Ray Fernando, 2022).

A successful teaching process depends on the development of appropriate and effective teaching methods, techniques and strategies. McHenry et al., (2005) introduced constructivism as a learning theory that supports the development of engineers' competencies for engineering practice and through graduate education. As far as concerned, the teaching and learning approach of engineering education at the undergraduate level is focused on the development of the 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. Engineering education based on cognitive processes is adequate as 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 own understanding of the world. This means, they will generate their rules and mental models to understand their own experiences. Figure 2 is the example of an illustration of such a process model through constructivism.

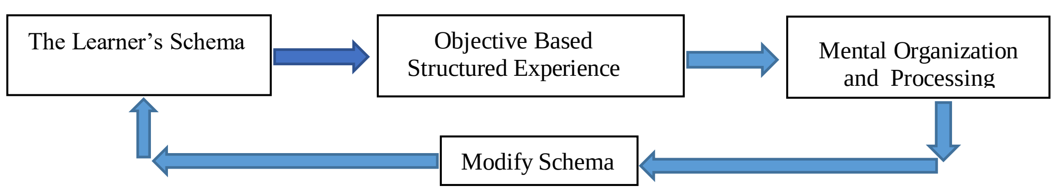


Figure 2: Process model of constructivism

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 in relation to 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 project according to the course content. The assessment centered is the design project implementation while the community in this framework is refer to the faculty involvement, educators, industry involvement and the tools. Figure 3 show an example of learning framework for capstone design project.

Figure 3: How People Learn (HPL) framework

Program objectives (POs), course learning outcomes (COs) and standard teaching plan can be used as context in this learning framework while the pedagogical approach used include constructivism, active learning and blended learning.

2. Literature Review

2.1 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 M. Krsmanovic (2019), UNESCO's concern is to educate engineers to meet the demands of modern labor in the labor market. This shows that STEM jobs have grown significantly over the past few years. With reference to the current situation and future trends, this study is conducted to develop engineers who can solve the big problems of the time need 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, due to the fact that 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.

2.2 Learning Theory and Methods Recommend for working 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. Campbell et al., (2015) have defined a generation as a group of individuals born in the same period of time who experience the same cultural context and in turn, create that culture. 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 (Case & Light, 2011) and collaborative learning (Mills J.E., and Treagust, 2003). Constructivism is the most efficient learning theory and process in the development of professional competence (McHenry et al., 2005b). 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 (Taajamaa et al, 2018). On the other hand, Freeman et al., (2014) stated that active learning and problem-based learning have been shown to improve performance in STEM classes and develop skills in solving complex problems. 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 in a group when doing capstone design. According to Gomez-del Rio & Rodriguez (2022), 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. 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 students and reinforced throughout the curriculum. Students need to understand the entire content related to the design in engineering. In the other hand, design-based learning has been discussed as an educational approach to support students in gathering and applying knowledge in open-ended assignment. According to Puente & Jansen (2017), this approach has become a practice among electrical engineering students. 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 show 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 methods will encourage students solve problems interacting each other, practice 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 project are incorporated into the curriculum to support students in achieving academic outcomes and industry expectations.

2.3 Capstone design project and students' understanding in chemical engineering design

Capstone design project 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 course work culminates in combing appropriate engineering standards and a variety of realistic constraints. Alexa Ray Fernando (2022) states that capstone design projects provide a rich learning experience for engineering students to solve complex engineering problems. However, the current situation shows that in most cases, capstone design students immediately jump to solutions idea without going through the proper design process. In the instrument created by Jin et al., (2015) to assess and improve design skills, he emphasized that the basic skill in design are the identification and definition of problems that comprise the phases of design problems. It is in this phase that knowledge and skills in complex engineering problems are required from students. Therefore, students undertaking capstone design project 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. Accordingly, the study conducted on final year students who attended the ERT 428 Plant Design II course at the Faculty of Chemical Engineering Technology of UniMAP, Malaysia is expected to produce findings about their level of understanding, especially the results in the capstone design course.

2.4 Student-centered pedagogical framework

Educational innovators have attempted to address this challenge by developing disruptive pedagogical framework learning technique such as inquiry learning, collaborative learning, flipped classroom, project-oriented problem-based learning, team-teaching and digital environments for education (Hutchings & Quinney, 2015). Most of these approaches are student-centered, while lecturers play a facilitative role to encourage 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). It is found that, the traditional engineering education approaches 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 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 show the summary of literature review on capstone design course and learning framework that been used in the research.

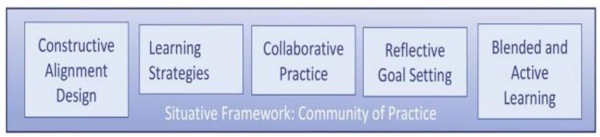
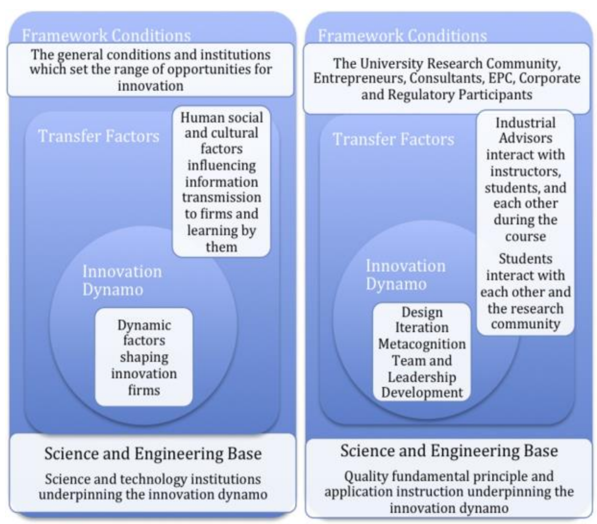
Table 1: Literature Review on capstone design project : Issues and solutions

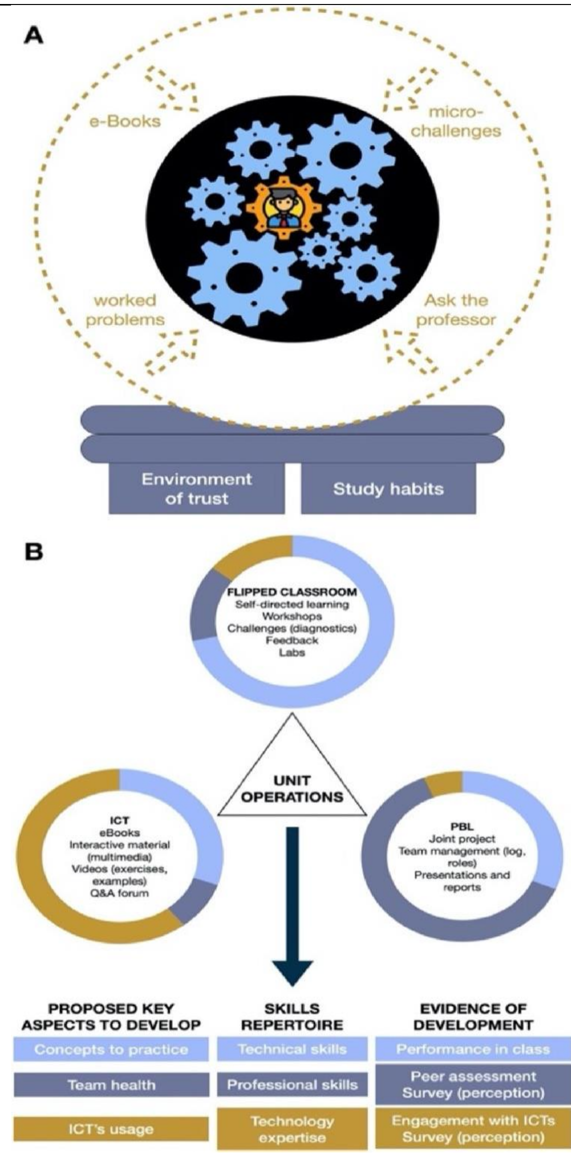
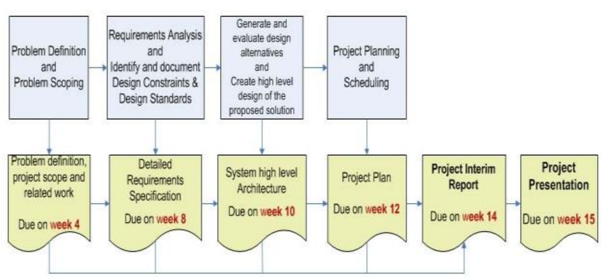
No.	Author / year	Country	Issues	Solution
1.	J. Alexa Ray Fernando et al. (2022)	Philippines	Design process starts with the problem phase where students are expected to recognize and define the problem.	Students doing capstone design projects must begin with recognizing and defining their own complex engineering problem.
2.	Ala 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.	M. Ballesteros, J. Sanchez, N. Ratkovich et al. (2020)	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.	M. Jamieson, J. Shaw (2020)	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.	S. Howe, J. 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.	F. 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: • To find out to what extent solving complex engineering problems in capstone design projects can create better understanding for the engineering students.

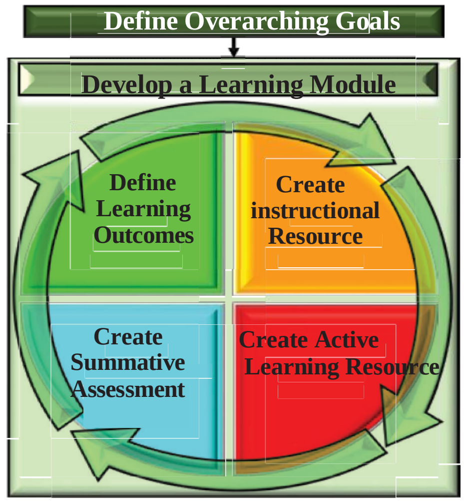
				• What are the characteristics of an ideal capstone design project that integrate complex engineering problems.
7.	A. Mirkouei, R. Binghe, C. McCoy et al. (2016)	USA	A need to identify and understand the STEM educational challenges, and to assess the usefulness of existing methodologies using case-based 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.	I. Pasya, S. Al-Junid, N. Buniyamin (2016)	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 analyzed in future works.
9.	S. 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.	M. Jollands, R. Parthasarathy (2013)	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.	Erradi, Abdelkarim (2012)	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.	Ala Qattawi et al. (2021)	California, USA		Constructivism cognitivism

			 PrBL model	
2.	M. Jamieson, J. Shaw (2020)	Canada	 Experiential learning environment for capstone design supporting design, innovation and leadership development in a community of practice.  Innovation Policy Map-OSLO (left) and Mapping of the factors and conditions to the capstone design community of practice structure (right).	Constructivism Cognitivism
3.	M. Ballesteros, J. Sanchez, N. Ratkovich et al. (2020)	Colombia		Connectivism Constructivism

			 A. Techno-pedagogical framework B. Redesigned UnOps course	
4.	Erradi, Abdelkarim (2012)	Qatar	 Capstone design project activities and deliverables for the first semester	Constructivism Cognitivism Connectivism

5.	A. Mirkouei, R. Binghe, C. McCoy et al. (2016)	USA	 Learning module development framework	Constructivism Cognitivism

3. Discussion

Many engineering programs throughout the world are using capstone design to help prepare students to engineering practice. While completing this literature review, it was found very important to focus on students' understanding toward this capstone design course especially in chemical engineering. From a pedagogical point of view, it is interesting to propose a suitable framework to be used as a learning and teaching technique among senior project students. This approach hopefully can improve the achievement of final year students on this design course. Although there is still a gap between the skills of engineering graduates and the qualifications or skills required in the industry, it is hoped that the development of design-based courses in engineering curriculum can meet the areas listed to improve the engineering skills. Capstone design course will provide student engineers with opportunities to solve real-world engineering projects and have been highly regarded as an important learning activity. Moreover, engineering programs recognize this need and are in the process of changing their curricula to better prepare their graduates for future challenges. This capstone course helps educators evaluate the students' overall undergraduate education and it also provides educators with a way to detect areas where students have difficulties. This may indicate an opportunity for improvement in a particular capstone design course.

4. Summary, Limitation and Future Work

In conclusion, this paper has reviewed the important points to improve the students' understanding when doing capstone course in the last years of their engineering degree. 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 in Malaysia. 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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Biographies

Farizul Hafiz Kasim is currently an Associate Professor at the Faculty of Chemical Engineering Technology, Universiti Malaysia Perlis (UniMAP) in Chemical Engineering programme. He has been in UniMAP since 2003. His bachelor and master's degree in chemical engineering were acquired from University Teknologi Malaysia in 1999 and 2001 respectively. He won a scholarship to continue his education in United Kingdom and subsequently acquired his PhD in chemical engineering from Newcastle University, UK in 2012. His research interests are in renewable energy, especially renewable energy from bioresources materials. He is a research fellow in Centre of Excellence for Biomass Utilization and had involved in numerous workshops and conferences on this area. He also has developed a strong interest in engineering education after 19 years teaching various chemical engineering courses in the university level. Prior joining UniMAP, Dr. Farizul was a consultant engineer in oil and gas industry. He was also the former Dean at Faculty of Bioprocess Engineering at UniMAP

Aziah Pauzi is a senior lecturer for Chemistry subject in the Department of Science at the Penang Matriculation College (2014-2021) and currently, she is a PhD student at Faculty of Chemical Engineering Technology, University Malaysia Perlis (UniMAP), Arau, Malaysia (2021-2025). She earned her Bachelor in Chemical Engineering from University Science Malaysia, USM, Penang, Malaysia, (1999) and her Masters in Science Education from University Science Malaysia, USM, Penang, Malaysia (2012). She worked for 3 years as Quality Assurance Engineer at Smart Glove Corporation Sdn. Bhd. (1999-2001) before joining the education as a teacher. After about 11 years teaching in schools, she later became a lecturer in Penang Matriculation College for 7 years. She was an active member in innovation group. She won gold medal award from five innovation competition since 2018. Currently, she was active in doing research in engineering education field.

Zaki Yamani Zakaria is the Director of Centre for Engineering Education (CEE), Universiti Teknologi Malaysia. He has been with the School of Chemical & Energy Engineering, Universiti Teknologi Malaysia (UTM) since 2008. He acquired his first degree in Chemical Engineering from University of Bradford, UK in 1999; Chemical Engineering Master Degree & PhD from Universiti Teknologi Malaysia (UTM) in 2004 and 2013, respectively. His main research interests are in engineering education, catalytic reaction engineering, and safety, health & environment (SHE). Before joining the faculty, he was a practicing engineer (2003-2008). Dr. Zaki became a Professional Engineer (BEM) and Chartered Engineer (IChemE) in 2010. He was appointed as a Professional Technologist in 2018 by Malaysia Board of Technologist (MBOT). He was appointed as Research Fellow under Centre for Engineering Education (CEE) in 2019 and two years after that appointed as the Director of UTM CEE. He has actively been involved in engineering education since 2014 in the area of Active Learning (AL), Cooperative Learning (CL) and Problem-Based Learning (PBL). Dr. Zaki has been involved in numerous AL, CL, PBL courses and workshops as co-trainer and facilitator since 2017. He is also an Editor for ASEAN Journal for Engineering Education (AJEE) and a member of Society of Engineering Education Malaysia (SEEM) since 2020, besides once in a while delivering talks related to Engineering Education Experiential sharing. In 2021 he participated in the Safety Champion in Engineering Education (SCEE) Fellowship program, which was organized under Royal Academy of Engineering (RAE), UK.