Comparison of fresh and graduate engineering students' design conceptualisation process.

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Abstract:

21st century engineering graduates should be proficient in engaging their conceptual thinking and analytical capabilities to proffer solutions to societal problems. Various literatures dwelling on problem-solving skills indicate that fresh engineering undergraduates are not adept at conceptualising solutions to design problems. However, the process of conceptualising solutions to design problems has not been well developed, understood and managed in many engineering curricula. In order to illuminate our understanding in regards to how engineering students conceptualise solutions to design problems at various stages of their educational programme, ten fresh engineering undergraduate and ten engineering postgraduate students were interviewed with a view to exploring: (i) what approaches they employ in identifying design problems? (ii) how they determine the relevance of the identified design problems to the needs of their community? (iii) how they conceptualise design solutions to the identified problems? and (iv) how they organise information when conceptualising solutions to design problems? Subsequent analysis of the responses reveals the existence of variation in the design conceptualisation process of fresh undergraduates and postgraduates. It was established that postgraduate students tend to use broader and more complex strategies in conceptualising solutions to design problems as compared to fresh undergraduates. Furthermore, postgraduate students employed experience, information sources, and prior knowledge acquired from various subject domains to conceptualise solutions to design problems whereas fresh engineering students could only employ previous experience and information sources to identify design problems relevant to their community needs but lack the capability to engage their prior knowledge to conceptualise solutions to design problems. Finally, these findings are expected to assist engineering educators to further understand how to develop an introduction to engineering curriculum to equip students with relevant and core engineering analytical skills for conceptualising solutions to design problems.

Keywords— conceptual thinking, engineering design, engineering students, engineering curriculum, problem solving.

1 INTRODUCTION

It is important for engineering educators to understand the pedagogy of equipping students with relevant and core analytical skills for conceptualising solutions to design problems if universities and colleges are to produce graduates with 21st century employment competencies. According to Kolb [1], the promotion of knowledge and skills to conceptualise solutions to a design problem enables engineering learners to transform abstract understanding into a reflective one based on an active involvement in the learning activities. The process of conceptualising solutions to design problems entails iterating back and forth between multiple sources of prior knowledge and practical experience as well as generative and evaluative design stages through which learners decide on the most appropriate solution to the problem among alternative solutions [2]. Hence, the process of conceptualising a solution to the design problem involves the engagement of a mental framework to construct meanings of one's surroundings and activities.

Available literature on engineering design education have indicated that fresh engineering undergraduates lack the ability to conceptualise solutions to design problems, hence, this results in sub-optimally designed products and artefacts [3]. In addition, it had been reported that engineering students at junior levels of undergraduate studies have high levels of information literacy skills (an important aspect of conceptualising solutions to design problems), even though they sometimes seem over-confident [4-7].

Analysis of these findings suggests that engineering students may not be aware of their deficiencies; they may not recognise the need to change their learning styles to improve their skill of conceptualising solutions to design problems. In an attempt to both understand how engineering students conceptualise solutions to design problems and also sensitise engineering educators to students' deficiencies, it is pertinent to assess the variation in the conceptualisation process of engineering students when solving design problems. Therefore, the purpose of this study is to answer the following research questions in order to establish how engineering students conceptualise solutions to design problems at various stages of their educational career:

- What approaches do fresh and postgraduate engineering students employ in identifying design problems?
- How do fresh and postgraduate engineering students determine the relevance of the identified design problems to the needs of their community?
- How do fresh and postgraduate engineering students conceptualise design solutions to identified problems?
- How do fresh and postgraduate engineering students organise information when conceptualising design solutions?

2 LITERATURE REVIEW

Accrediting bodies such as Accreditation Board for Engineering and Technology (ABET) and Engineering Council of South Africa (ECSA) require that Engineering Design be a principal exit level outcome for all accredited engineering programmes. Therefore, the current trend in engineering design education is to incorporate the aspect of conceptualisation into solving the design problem. This pedagogical approach is premised on the fact that there exists a considerable overlap between the process of conceptualising solutions to design problems and the engineering design process. Hence, this study is important because it has potential to not only reveal the approach adopted by engineering students in developing solutions to design problems but also to enhance the final products being designed. Therefore, findings from this study will illuminate the understanding of engineering educators who teach introductory engineering design to fresh engineering undergraduates in tailoring the instructional delivery to address deficiencies in how they conceptualise solutions to design problems.

Meanwhile, the conceptualisation stage in design entails the process of planning the design solution by applying logical or critical thinking and reasoning which culminates in making a rational choice among a range of alternatives. This is achieved by recalling and recognising prior learnt engineering theoretical concepts and design problem solving experiences to construct schematic images for the current design problems. In agreement with Lawson [8], we posit that previously learnt engineering theoretical concepts and design problem solving experiences are stored in the learners' mind and organised in schematic form of diagrams, mathematical concepts and symbols, and representations which are employed as reflective knowledge to solve design problems deriving from the precedents and schemata as gambits.

Schon [9] opined that engineering students employ drawings, graphical construction and sketches as medium of communication for explicating the implicit knowledge through conscious construction and exploration into an explicit one. Furthermore, Oxman [10] also affirmed that students conceptualise solutions to design problem by combining previously taught theoretical concepts, case studies, photographs and information from their site inventory session and transforming these ideas at first into rough sketches and then into a scaled layout drawing and a mock-up model. Hence; drawings, graphical construction and sketches provide explicit linkages between the design problem and conceptual solution. In summary, conceptualisation transforms the abstract knowledge into a concrete end with design solutions in the form of graphical depictions which are related to design concepts.

According to Lawson [8, 11] as well as Menezes & Lawson [12], prior knowledge, episodic memory that aids the recall of images previously perceived, case study precedence and recursive approaches, and strategies employed throughout the process constitute the elements of the conceptualisation process. Meanwhile, engineering undergraduate designers are unable to recognise from the schemata unlike the experts. This is because fresh undergraduates have difficulties in linking previously taught engineering theoretical concepts and design problem solving experiences to proffer solutions to design problems, hence, the inability to engage in reflective thinking necessary for generating new ideas [13, 14]. For instance, in comparing the process and outcomes for senior and fresh engineering students in an engineering design problem, Atman *et al.,* [15] established that senior engineering students gathered more information and considered more alternative solutions as they transitioned between the design steps more often and moved into the final steps further than fresh students. Atman and co-investigators also corroborated in a follow-up study that first year engineering students do not dedicate much time to problem scoping and develop alternative solutions [16]. Conceptualisation of solution to design problems and information gathering were identified by Atman and colleagues [3] as needed areas for instructional attention since major differences between expert engineers and novices were found in this area. Finally, it was reported that fresh engineering students have difficulties in employing information to conceptualise solutions to an engineering design project as they either misrepresented or exaggerated or used the information source inappropriately or superficially [17].

3 METHODS

This study employs a qualitative research approach dwelling on ethnographic methodology to achieve the research objectives. This research design is adopted because it is able to gather rich observational data as engineering students at various stages of their educational career conceptualise the design process and support the observational evidence with work artefacts and interview data. Hence, a thick description of the approaches adopted by the participants when conceptualising solutions to engineering design problems is generated. Meanwhile, this study portrays a range of responses while highlighting the similarities and differences among the participants in addition to identifying the relevant competencies that are needed to conceptualise solution to design problems.

3.1 Task

Fresh undergraduate engineering students were instructed to find a relevant problem confronting their community and think about how they would conceptualise design solutions to solve the problem. They were given a period of twelve weeks to complete the task. Prior to engaging in the tasks, they were also given an introductory presentation highlighting background information on how to conceptualise solution to design problems by the second author. During the project, they were instructed to brief the first author as well as the second author (who served as project supervisor) fortnightly. During the briefings, fresh undergraduates were asked to present their strategies for implementing design solutions for the problem, including how they identified the problem and its relevance during the first meeting. Fresh undergraduates also provided information about their progress and outlined the strategies to complete the given task. During the briefings, a situated environment was maintained by allowing the participants to be actively immersed in the task while using problem-solving (critical thinking) skills. The observations made by the first and second authors during the briefings as the fresh undergraduates were conceptualising solutions to design problems were recorded in a notebook. Fresh undergraduates were commended when significant progress was made while suggestions were offered to them in overcoming their challenges. After they had completed the task, they were required to deliver final oral presentation and written reports. The engagement of the undergraduates in these activities was expected to promote their communication skills, reflection and metacognition.

In order to allow for comparison of the design conceptualisation skills at various stages of engineering education career, postgraduate students studying for masters and doctoral degrees were asked to look at their research projects as an exercise requiring design conceptualisation. This study only engaged postgraduate students who provided evidence of journaling their research experience and agreed to continue with the process of conceptualising solutions to their research problem over time as the fresh undergraduates were working on their design task.

3.2 Data Sources

In an attempt to engender trustworthiness in regards to findings from this study, we employed triangulation which allows for investigation of alternate explanations for our findings as follows: (i) Both groups of participants documented their activities in writing and sketches in a notebook. Sketches consisted of drawings of product/process being designed, concept maps of how they developed their ideas in designing solution to the problem. Hence, they kept track of how they were conceptualising solutions to design problems, data analysis and conclusions from analysis as well as their next line of action. After the project, the notebook was collected for analysis. (ii) Notebook recorded observations by first and second authors during briefings and final presentations which detailed how fresh undergraduate engineering students conceptualised solutions to design problems. (iii) Work artefacts such as typed memoranda, presentation slides and written reports were collected from both groups of participants. (iv) The first and second authors interviewed all the participants by employing a semi-structured format with open ended and directed questions. The interview which lasted about fifteen minutes for each participant was held in a meeting room located at the Engineering Workshops & Laboratories Building on the campus and was video recorded. It was transcribed by the first, third and fourth authors. The interview served as a check on the interpretation of data from other sources. Four main questions were developed to represent aspects of the design conceptualisation process, namely 1. How did you come about this project? 2. Why are you engaged in this project? 3. How did you design the project? 4. How did you organise information in designing your project? Deeper levels of conversation were elicited when interviewing the participants by using follow-up questions. Hence, the outcomes which address each of the research questions are reported.

3.3 Participants

Purposive sampling of engineering students was implemented in an attempt to understand the variation which exists in the design conceptualisation process of fresh and graduate engineering students The participants participated voluntarily in this study without being offered any form of compensation in cash or in kind. Two student teams comprising of ten students each (Table 1) were selected from the Departments of Mechanical, Energy, & Industrial Engineering; Civil & Environmental Engineering; Electrical, Computer & Telecommunications Engineering; Mining & Geological Engineering; and Chemical, Metallurgical & Materials Engineering at Botswana International University of Science & Technology, Palapye, Botswana. The premise for chosen the undergraduate team was founded on an independent, holistic assessment of 50 teams in which they were identified by the authors as representing a mix of academic orientation while the ten postgraduate students were chosen on the basis of their research projects being assessed to contain design elements in respect of products or process development. Similar to the approach adopted in studies dwelling on problem solving strategies as seen in Atman *et al.,* (1996), the selection and discussion of participants' solutions employed in this study is deemed to be representative of the general students' population at both undergraduate and postgraduate engineering education.

The undergraduate participants were assigned the design tasks as part of the Introduction to Engineering module in the first week of the 2014/2015 session second semester. Prior to this module, undergraduate participants had completed engineering design and graphic modules in high school while the postgraduates have an average of two years working experience in private or public engineering establishments before they proceeded on further study. The first and second authors interviewed the participants and analysed the progress towards conceptualising solutions to design problems and provided expertise in research methodology. The fifth and sixth authors directed the research programme to characterise the ways students conceptualise solution to design problems.

Table 1. Student demographics

Gender	Fresh engineering students (n = 10)	Graduate engineering students (n = 10)
Male	8	10
Female	2	-

3.4 Data Analysis

Research data including notebooks, work artefacts, observation and interview transcripts obtained from this study were analysed with a view to developing and interpreting the conceptualisation process of the participants. For instance, the transcribed interview data were divided into two groups: fresh undergraduates and postgraduate students. The interviews were read with a view to carrying out open coding to allow for emergent themes. The researchers met as a team to discuss potential codes and then agreed on the coding schemes with a view to identifying the emerging categories. The categories were then discussed in an attempt to establish broader themes. Furthermore, content analysis was applied to the sketches made by the participants with a view to facilitating the categorisation of the sketches into specific types of activities, forms, and patterns. Hence analysis of the participants' design processes provided insights into the relationship between design activities, forms, and patterns. Overall, it establishes to a certain extent engineering students' abilities in conceptualising solutions to design problems. Therefore, by identifying and examining students' activities, forms, and patterns, this study has highlighted the relationship between conceptualisation and knowledge integration in an attempt to elucidate the process of conceptualising solutions to design problems.

4 RESULTS

4.1 What approaches do fresh undergraduates and postgraduates employ in identifying design problems?

Analysis of the observational data gathered during briefings as well as the interview transcript reveals that (i) observation of the operations of the existing equipment as well as (2) operational challenges encountered from past experiences constitute the main approaches adopted by fresh undergraduates in identifying design problems. For instance, the testimonial by a fresh undergraduate student confirms this assertion: "*I grew up rearing cattle in rural areas where our livestock used to get lost, therefore, that experience helped me in identifying the problem of cattle straying away from the owners with a view to designing a cattle tracking device.*" Meanwhile, there was consensus among engineering postgraduates who claimed that they identified design problems through prior work and research experience in mining and construction industries, previous knowledge gained from modules taught during undergraduate training, consultation of industrial experts in their knowledge area in addition to reading journal articles and listening to news and documentaries on television and radio. An assertion by one of the postgraduate students that "*several brainstorming sessions I had with the experts -------------- while working in an energy-related research institute helped me in identifying the design project on fuel cell I am currently working on*" validates the claim by the graduate engineering students. Moreover, analysis of the study journal of a postgraduate student working on natural fiber composites revealed that concepts on mechanical performance of composite materials learnt through undergraduate laboratory practicals in materials science module while studying in at undergraduate level in a British University motivated his interest in developing such technological material using locally available natural fibers so as to reduce importation of composite materials to Botswana.

4.2 How do fresh undergraduates and determine the relevance of the identified design problems to the needs of their community?

Both fresh undergraduates and postgraduates claimed that they determined the relevance of their design/project by evaluating the negative consequence of non-attendance to the design problem or the benefits of solving the design problem. A fresh engineering student working on the re-design of fire extinguisher corroborated this fact during final presentation and group report that "*the benefit of re-designing a lighter fire extinguisher which is easier to carry, easily available and for which the users need no training to use form the motivation for choosing their design project.*" In addition, a postgraduate student stated during interview that "*the problems associated with environmental pollution resulting from combustion processes in thermal plants determined the relevance of the design of fuel cells which aims to address the highlighted problem*".

4.3 How do fresh undergraduates and postgraduate students conceptualise design solutions to identified problems?

Analysis of data obtained from fresh engineering students' activities journals, observations during briefings/presentations and interview transcripts revealed that the strategies they adopted for conceptualising solutions to design problems included (i) generating ideas, (ii) evaluating the ideas relative to the requirements of the design problem and (iii) using the decision matrix to rate the value of idea in an attempt to make a choice among a range of alternatives to conceptualise solution to the design problem. In addition, it was discovered from the study journal that fresh engineering students employed sketches to conceptualise solution to the design problem. Figure 1 shows the sketch of how fresh engineering students conceptualise the re-design of existing fire extinguishers.

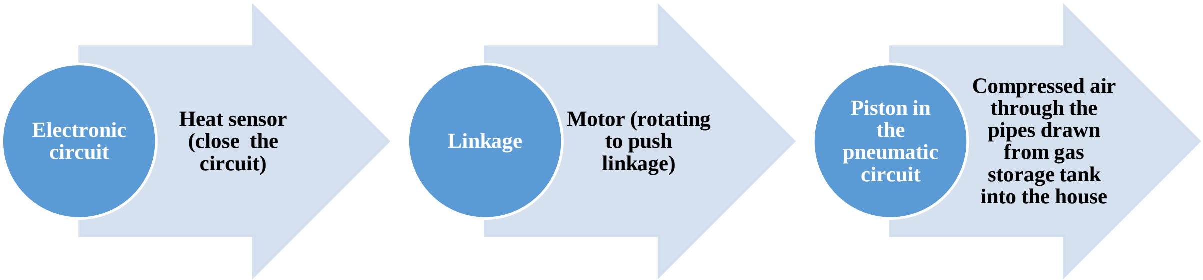

Figure 1. A sketch of the conceptualisation process on the re-design of fire extinguisher.

Analysis of the conceptualisation approach adopted by fresh undergraduates, as supported by the data gathered from interview and observation transcripts, indicates that they could not relate the design of the electronic circuit, pneumatics and diffusion of carbon dioxide to the relevant theoretical concepts/equations drawn from high school mathematics, physics and chemistry. For instance, it was confirmed during briefings and interviews that fresh undergraduates could not relate the process of transportation of the compressed air (carbon dioxide) to the fact that it diffuses when explaining why the rationale for choosing long pipe in preference to shorter one in transporting the compressed air. Contrary to the outcome on fresh undergraduates' conceptualisation approach, it was discovered that postgraduate students (i) considered the missing gap in current level of knowledge through literature review from journals and textbooks as well as consultation with peers, experts and supervisors; (ii) applied engineering principles gained from different courses they were taught during their undergraduate training; (iii) double checked their conceptualisation process in addition to (iv) developing different ideas, (v) evaluating the ideas relative to the requirements of the design problem and (vi) using the decision matrix to rate the value of idea in an attempt to make a choice among a range of alternatives while conceptualising solution to the design problem. Figure 2 shows the conceptualisation approach of a postgraduate student, obtained from his study journal, who designed a dye removing adsorbent material from a textile effluent. During interview, the postgraduate student reported that he conceptualised solution to his design problem by employing chemical concepts dwelling on water chemistry and environmental science modules as well as materials characterisation techniques. He also recognised the role of studying journals like *Journal of Environmental Management* and *Water Research* in conceptualising solution to the design of the dye removing adsorbent material.

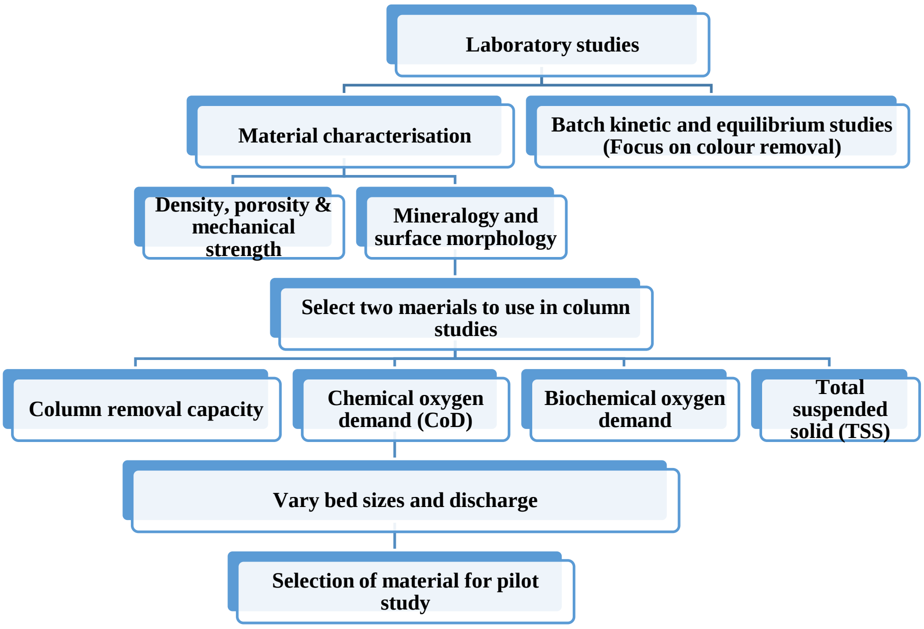

Figure 2. A sketch of the conceptualisation process on the design of a dye removal adsorbent material by a postgraduate student

4.4 How do fresh undergraduates and postgraduate students organise information when conceptualising design solutions?

It was discovered from study journals that fresh engineering students kept the reference sources of their work, documented their findings and kept notes on information together with reference. During interview, a fresh engineering student reported that "*I organised the information --------- by documenting my findings in my notebook which I then shared with my colleagues*" in response to the question "*show me how you did that* -----?" Meanwhile, postgraduate students reported via interview that they often saved copies of the information obtained from journal sources on folders in their computers which are then grouped according to subject in addition to using notes, notes with references, bibliography for organising information. This was corroborated by a postgraduate student who reported that "*I discuss my findings or information gathered from literature search with my peers and supervisor in order to identify relevant information, ---------------thereafter, I organise my information in folders in order to ensure they are properly classified according to topics------------------. For example, my design of composite materials from natural fibers demand that I classify information based on different natural fibers, treatment techniques of fibers and various properties of composite materials-------------.*"

5. DISCUSSION

The primary goal of this study is to illuminate our understanding in regards to how engineering students conceptualise solutions to design problems at various stages of their educational career. Similar to other studies such as Atman *et al.,* [15, 16] which compare both conceptualisation approaches of both fresh undergraduates and postgraduate students, findings from this study emphasise the existence of variations in the conceptualisation approach adopted by fresh undergraduates and postgraduate students. Although, both fresh undergraduates and postgraduate students adopted approaches entailing observation of the operations of the existing equipment as well as operational challenges encountered from past experiences in identifying design problems; however; postgraduate students made use of prior work and research experience in industries, previous undergraduate training, consultation of industrial experts, reading journal articles and listening to news and documentaries on television and radio.

As noted earlier on, both groups determined the relevance of their design/project by evaluating the negative consequence of non-attendance to the design problem or the benefits of solving the design problem. Therefore, it was observed that both groups always decide the relevance of carrying out a design project through personal judgement. Furthermore, postgraduate students employed previous experience, information sources and prior knowledge acquired from various subject domains to conceptualise solutions to design problems whereas fresh engineering students could only employ previous experience and information sources to identify design problems relevant to their community needs but lack the capability to engage their prior knowledge to conceptualise solutions to design problems. This finding could be attributed to the fact that the training scheme which the fresh engineering undergraduates were exposed to so far had not prepared them to recognise from the schemata unlike the postgraduate students. Therefore, the fresh undergraduates have difficulties in linking previously taught theoretical scientific concepts at high school as well as design problem solving experiences to proffer solutions to current design problems, hence, the inability of the fresh undergraduates to engage in reflective thinking necessary for generating new ideas [13, 14]. Finally, there are similarities in the approaches adopted by both fresh undergraduates and postgraduate students in organising information during conceptualisation of solution to design problem. For instance, the two groups kept reference sources of their work, documented their findings and kept notes on information together with references. Nevertheless, postgraduate students were able to classify their information according to subjects and could elucidate what they did with relevant information. This finding suggests that postgraduate students are capable of employing relevant information to inform their approach of design conceptualisation unlike fresh students who could not relate the information to their design [17]. Again, it is evident that further instructional delivery for fresh undergraduates in design courses should emphasise conceptualisation of solutions to design problems and information gathering as identified by Atman and colleagues [3].

6. IMPLICATIONS AND LIMITATIONS

One of the implications of this study is that design educators at tertiary levels should introduce fresh undergraduates to this module by emphasising that design problem identification is not only carried out via observation of current happenings around us as well as past experiences, but also through relevant work and research experience, knowledge of scientific principles gained from high school curriculum and consultation of experts. Moreover, educators should also highlight the role of reading journal articles as well as watching and listening scientific documentaries on television and radio respectively in order to have idea of how to identify design problems. Most importantly, new engineering concepts being taught in other modules at tertiary level should be related to the process of conceptualising solution to design problems when educators are delivering instructions to fresh undergraduates [18, 19]. It is also pertinent that learning interventions which reinforce the process of conceptualisation of solutions to design problems are developed so as to enhance the potentials of fresh undergraduates' life-long learning skills [18, 19]. Therefore, further studies should employ quantitative research approach to explore how the differences in the conceptualisation process of fresh engineering undergraduates and postgraduates generalise to the broader engineering student population. The limitation of this study is that it has not considered the use of frequency charts to explore the variation in conceptualisation of solution approaches to design problem within each of the groups. This perspective needs to be explored in future studies with a view to understanding the strength of each category while it is also extended to specific engineering disciplines.

7. CONCLUSIONS

This study sought to illuminate our understanding as regards to how engineering students conceptualise solutions to design problems at various stages of their educational career. Engineering postgraduate students used broader and more complex strategies in conceptualising solutions to design problems as compared to fresh undergraduate counterparts. In addition, postgraduate students employed previous experience, information sources and prior knowledge acquired from various subject domains to conceptualise solutions to design problems whereas fresh engineering students could only employ previous experience and information sources to identify design problems relevant to their community needs but lacked the capability to engage their prior knowledge to conceptualise solutions to design problems. Finally, instructional delivery for fresh undergraduates in design courses should emphasise conceptualisation of solutions to design problems and information gathering using relevant experience from previously attempted design problems as well as scientific principles from high school science curricula in order to equip students with relevant and core engineering analytical skills for conceptualising solutions to design problems.

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