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Contextual Knowledge Framework in CAD Education from the Perspectives of Practicing Engineers

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ABSTRACT

The contemporary industry landscape requires engineering graduates to have expertise in utilizing advanced Computer-Aided Design (CAD) tools. However, prevailing practices reveal a lack of contextual knowledge among Mechanical Engineering undergraduates and fresh graduate engineers in effectively employing 3D CAD modelling software for optimal product design development. Consequently, this study was undertaken to address this issue, with a specific focus on the integration of contextual knowledge into 3D CAD modelling. The study aims to elucidate the fundamental elements of contextual knowledge regularly employed by practicing engineers in their daily design endeavours, specifically in 3D CAD modelling. A transcendental phenomenology approach was used, and four engineers from the engineering department of a shipbuilding company in Peninsular Malaysia were purposefully selected as respondents. The analysis yielded three recurring themes central to the application of contextual knowledge in visualizing and presenting models through 3D CAD modelling: Realization, Design Intention, and Normalization. These elements are pivotal in assisting engineers in contextualizing their design work during the modelling and presentation stages of the new product development process.

1. Introduction

Over the past few years, a growing body of research has focused on enhancing the contextual competencies of engineering undergraduates [1,2]. A strong foundation in contextual competence not only enhances their comprehension but also makes them more competitive within the engineering profession, particularly in the field of engineering design [3,4]. The importance of developing contextualization skills among engineering undergraduates in engineering practice has also been emphasized within the ABET program accreditation criteria, specifically under Criterion 3 student outcomes 3(1) and 3(2) [3]. In the realm of 3D CAD modelling, the importance of contextual

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knowledge is of utmost importance, as emphasized by Grasso and Burkins, in enhancing engineers' ability to craft imaginative and innovative product designs [5].

Findings from structured interviews conducted in a preliminary study have revealed a deficiency in contextual knowledge utilization within the domain of 3D CAD modelling among both Mechanical Engineering undergraduates and fresh graduate engineers. This knowledge gap has resulted in challenges for product designers, hindering their ability to effectively contextualize their models to meet user and manufacturing needs, ultimately impeding optimal design outcomes. Čok *et al.,* [6] have highlighted common errors made by product designers, often prioritizing product functionality over manufacturability during the design phase. This oversight has led to instances where certain parts could not be feasibly machined during manufacturing. Consequently, this study was undertaken to enhance the contextual knowledge of engineering undergraduates in utilizing 3D CAD modelling software for engineering design tasks, thereby contributing to the broader initiative of reforming and shaping the future of engineering education. This study's primary objective is to establish a contextual knowledge framework that can effectively augment the foundational understanding of Mechanical Engineering undergraduates in applying 3D CAD modelling software. This research addresses two key questions: firstly, it identifies the essential elements of contextual knowledge pertinent to creating product designs, based on insights gleaned from the experiences of practicing engineers. Secondly, it examines how these essential elements are employed by practicing engineers across four critical contexts of digital product modelling: Model Creation, Model Manipulation, Model Visualization, and Model Transfer. This article presents the crucial findings pertaining to the essential elements of contextual knowledge employed in the four digital product modelling processes by practicing engineers in their routine design tasks. Its conceptual structure underscores the importance of contextual knowledge in acquiring 3D CAD modelling skills, thereby contributing to broader awareness within the engineering education community regarding the integral role of contextual knowledge in the 3D CAD modelling process.

2. Theoretical Framework

Embedded in the framework of cognitive constructivism, this study draws inspiration from Piaget's research on individual knowledge construction. This theory posits that individual knowledge is actively constructed through cognitive processes involving the analysis and interpretation of experiences [7]. As Al Mulhem [8] points out, this theory underscores the significance of learners' active engagement in discovering and exploring their surroundings to construct meaning and understanding [8].

In employing 3D CAD modelling for product design development, practicing engineers actively construct design knowledge by drawing upon their prior experiences gleaned from past design projects. These experiences prompt them to reorganize their cognitive structures to align with the requirements of a new 3D CAD model development. Within the framework of cognitive constructivism theory, Piaget characterizes this process as involving assimilation and accommodation [9,10]. Assimilation occurs when individuals encounter a novel experience and seamlessly integrate it into their existing mental framework [11]. Conversely, accommodation is the process by which existing knowledge is adjusted or modified in response to new experiences, necessitating revisions to better align with new situations [10,12].

Within the context of this study, the assimilation and accommodation process play a pivotal role among practicing engineers, serving as a guiding mechanism for enriching their contextual knowledge throughout the 3D CAD model development process. Typically, practicing engineers leverage 3D CAD modelling software to streamline the product design development process. However, each project they undertake presents its own unique set of criteria, specifications, standards, and requirements, all of which must be meticulously adhered to. In fulfilling their job responsibilities effectively, engineers must adeptly assimilate and accommodate their existing design knowledge.

During the construction process of 3D CAD models, practicing engineers frequently encounter novel ways to represent model features or alternative procedures for creating an object. Consequently, they must construct and reconstruct their own mental models by incorporating new information [11]. This iterative process of model construction and reconstruction activities fosters the generation of contextual knowledge pertaining to modelling techniques. This underscores the inherently constructivist nature of developing contextual knowledge in 3D CAD modelling. As new knowledge is incrementally acquired, engineers gain the ability to create more complex models. In this context, how practicing engineers represent their contextual knowledge in 3D CAD modelling depends on their deep understanding of modelling techniques and their contextualization of the model development process. A schematic representation of this theoretical framework is illustrated in Figure 1.

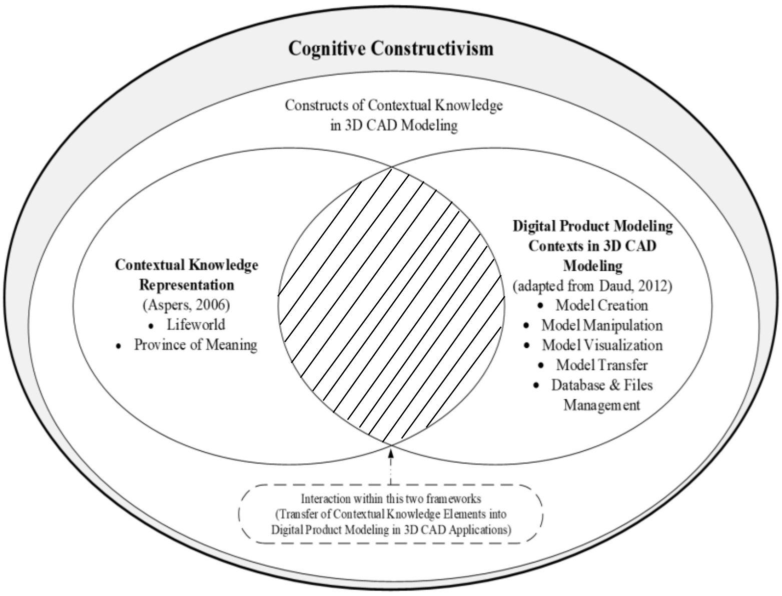


Fig. 1. Theoretical Framework of Research

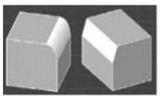
3. Contextual Knowledge in 3D CAD Modelling

Engineers' success in accomplishing design tasks relies heavily on the knowledge embedded within their cognitive minds [13]. Tennyson and Breuer [14] have categorized knowledge in the educational domain into three distinct types: declarative knowledge, procedural knowledge, and contextual knowledge. In light of the issue highlighted in the previous section, this study specifically focuses on exploring contextual knowledge. According to Tennyson and Breuer [14], contextual knowledge can be defined as an individual's understanding of how to apply specific concepts, rules, and principles, with a keen awareness of when, why, and where this knowledge should be applied to successfully execute a given task. Aspers [15] introduces two key elements to delineate contextual knowledge: the "lifeworld" and the "province of meaning". The "lifeworld" refers to the lived and experienced world, extending beyond mere physical existence to encompass the subjective experience itself [16]. The "province of meaning" denotes the ability to grasp the significance of an image or perceive it in a manner consistent with others, arising from shared experiences, educational backgrounds, and other commonalities [17]. These two fundamental elements, the "lifeworld" and the "province of meaning", play a pivotal role in addressing real-world challenges, with contextual knowledge serving as the catalyst for individuals to help an agent behave quickly, automatically, and appropriately for its current problem-solving situation [18].

In 3D CAD Modelling, contextual knowledge is defined as an individual's understanding of the rationale behind, the appropriate timing for, and the suitable contexts for utilizing specific concepts, rules, and principles when engaging in modelling tasks across the four digital product modelling contexts: model creation, model manipulation, model visualization, and model transfer. As previously discussed, contextual knowledge is comprised of two core elements: the "lifeworld" and the "province of meaning". For the purposes of this study, these two elements have been adopted as the framework for investigating contextual knowledge among practicing engineers. Hence, these elements have been contextualized within the context of this study. In this study context, the "lifeworld" element pertains to the practicing engineer's comprehension of the tangible real-world problems, situations, and practical applications they encounter while utilizing 3D CAD modelling techniques within the four digital product modelling contexts during product design [13]. As for the "province of meaning", it has been redefined as the practicing engineer's knowledge of having a shared understanding of 3D CAD modelling applications within the digital product modelling context with other engineers within the same manufacturing firm, as well as a clear understanding of customer requirements [13].

Table 1 illustrates the significance of contextual knowledge elements in the 3D CAD modelling process. In the real-world design environment of manufacturing, these two elements play a crucial role during product design using 3D CAD modelling software. For instance, when considering safety aspects, engineers must exercise foresight before designing the product using 3D CAD modelling software to ensure the final product is functional and safe for users. In the practice of 3D CAD modelling, filleting or chamfering of sharp edges is primarily done to enhance safety. Therefore, this study explores these essential elements of “lifeworld” and “province of meaning” in the context of 3D CAD modelling.

Table 1
Contextual Knowledge in 3D CAD Modelling Process

Modelling within the Contexts	Modelling Activities	Lifeworld	Province of meaning
Safety	Fillet Chamfer 	?	?

4. Digital Product Modelling in Product Design

Digital product modelling involves creating digital representations of physical products or systems using CAD software, 3D modelling tools, and other digital technologies. This technique is applicable across various sectors, including manufacturing, product design, architecture, and entertainment. The digital product modelling framework employed in this study has been derived and modified from Daud's [19] proposed framework of conceptual knowledge in 3D CAD modelling. This study has explored the four key constructs: Model Creation, Model Manipulation, Model Visualization, and Model Transfer. These constructs essentially encapsulate the standard procedures within the realm of 3D CAD modelling software applications. Figure 2 illustrates the process involved in product design development using 3D CAD modelling. As McEwan and Butterfield [20] noted, amalgamating these design facets establishes a comprehensive digital product modelling platform. This integration facilitates subsequent phases in the product life cycle, such as testing and certification, maintenance and operation, and the conceptual design process's required disposal integration aspect.

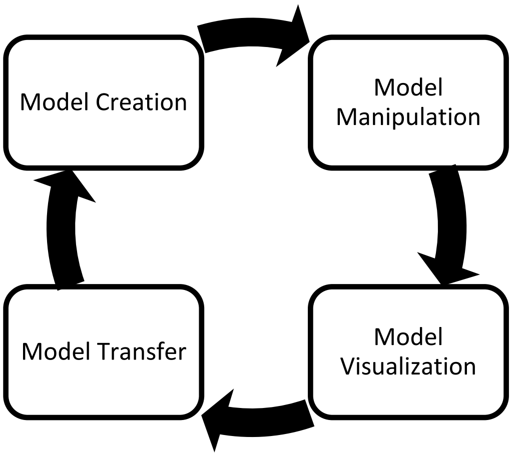


Fig. 2. Process Involve in Product Design Development in CAD Modelling

i. *Model Creation* – The process of generating a CAD model aligns with the part or product design's intended purpose and its subsequent utilization in downstream applications [21]. The establishment of this model creation context in this study encompasses the essential concepts of modelling techniques and their associated contextual knowledge elements, empowering engineers to create a functional virtual product design.
ii. *Model Manipulation* – The modelling process involves the reuse and modification of an existing CAD model to meet new design criteria and practical requirements [22]. Within the context of model manipulation, this study focuses on understanding and effectively utilizing the system to perform manipulation tasks, generating alternative solutions, and identifying the preferred one.
iii. *Model Visualization* – The process of employing visualization tools within a 3D CAD modelling system to present, distribute, and convey non-contextual information through engineering drawings and product designs [23]. Within this model visualization context, the primary focus is on exploring the essential components that engineers in practice utilize to visualize the model creation process throughout the model development process.
iv. *Model Transfer* – The process of transferring 3D CAD model data within the product development workflow to support downstream applications [24]. In this study, model transfer is examined to elucidate the contextual understanding of sharing and exchanging model data across different platforms, enabling progressive product model development and encompassing data transfer for downstream users.

5. Research Methodology

A qualitative research design employing a transcendental phenomenology approach was used to explore the experiences of practicing engineers as they applied the elements of contextual knowledge in their daily design tasks using 3D CAD modelling. This transcendental phenomenology approach enables the researcher to prioritize an objective description of the experiences of practicing engineers, minimizing the influence of researcher interpretations. To conduct this study, a homogeneous sampling method was utilized, resulting in the selection of four practicing engineers from a Shipbuilding Company in Peninsular Malaysia [25]. This sampling approach facilitated a comprehensive and representative exploration of practicing engineers' contextual knowledge in the development of 3D CAD models. The selection criteria for respondents in this study were restricted to individuals with practical experience using various types of 3D CAD modelling software for a minimum of three years as part of their daily job responsibilities. This aligns with the recommendations of engineering professional bodies by Engineering Accreditation Commission (EAC), which consider three years of practical experience as a milestone marking professional competence in their respective fields [26]. The demographic information of the four practicing engineers is detailed in Table 2.

Table 2
Practicing Engineers Background

No. of Practicing Engineers	**Gender**	**Position in the company (Technical Executive = Engineer)**	**Years of experience in using CAD software (years)**	**Types of CAD software has been used**	*** Personal skill level or working knowledge in using CAD software (Novice 1 → 5 Expert)**	**Educational Background**
1	Female	Senior Technical Executive	9	AutoCAD, PDMS	4	Mechanical Engineering
2	Male	Senior Technical Executive	6	AutoCAD, SolidWorks, CATIA, AVEVA	4	Mechanical Engineering
3	Male	Technical Executive	11	AutoCAD, RDM6, MAXSURF, HYDROMAX	5	Naval Architecture and Shipbuilding
4	Male	Technical Executive	5	AutoCAD, AVEVA, Maxsurf	4	Mechanical Engineering

* *As rated by the department superior*

To gain a comprehensive understanding of the experiences of practicing engineers, Husserl's concept of "epoche" (or bracketing) was employed, prompting the researcher to suspend their own judgments and adopt a fresh perspective on the phenomenon under investigation [27]. Data collection involved a combination of phenomenological interviews and document analysis methods. Each phenomenological interview lasted approximately one and a half hours and was conducted during the participants' free time. Four series of interviews were conducted, starting in March 2014 and ending in March 2015. Throughout the interviews, Moustakas' [28] phenomenological interview guidelines were followed, adhering to Kennedy's [29] recommendation to employ open-ended questions free of preconceived notions and leading terms. This approach facilitated a more interviewee-guided and narrative-rich exploration of the phenomenon under investigation.

The interview data was then analysed using Moustakas' Stevick-Colaizzi-Keen modification phenomenological analysis method [28]. This particular approach was chosen because of its alignment with the fundamental processes that helped the researcher address the research questions of this study and capture rich descriptions of the participants' experiences. The analysis phase began after all interview data had been transcribed. These transcriptions were then subjected to the horizontalization analysis process, which aimed to identify significant statements from each practicing engineer [28]. These identified significant statements were then used to construct the textural descriptions, providing insights into the essential elements of contextual knowledge as articulated by each practicing engineer in the four contexts of 3D CAD modelling. Subsequently, structural descriptions were formed to summarize details on how practicing engineers employed the essential contextual knowledge elements in the application of 3D CAD within four digital product modelling contexts. To shape the central theme of this study, textural and structural descriptions were integrated to create a synthesis that encapsulates the significance and core aspects of the experiences of practicing engineers. Additionally, supporting documents, including printed engineering drawings, drawing standards, and guidelines, were gathered from the engineers to enhance the reliability of the interview findings. A comprehensive visual representation of this operational research framework is presented in Figure 3.

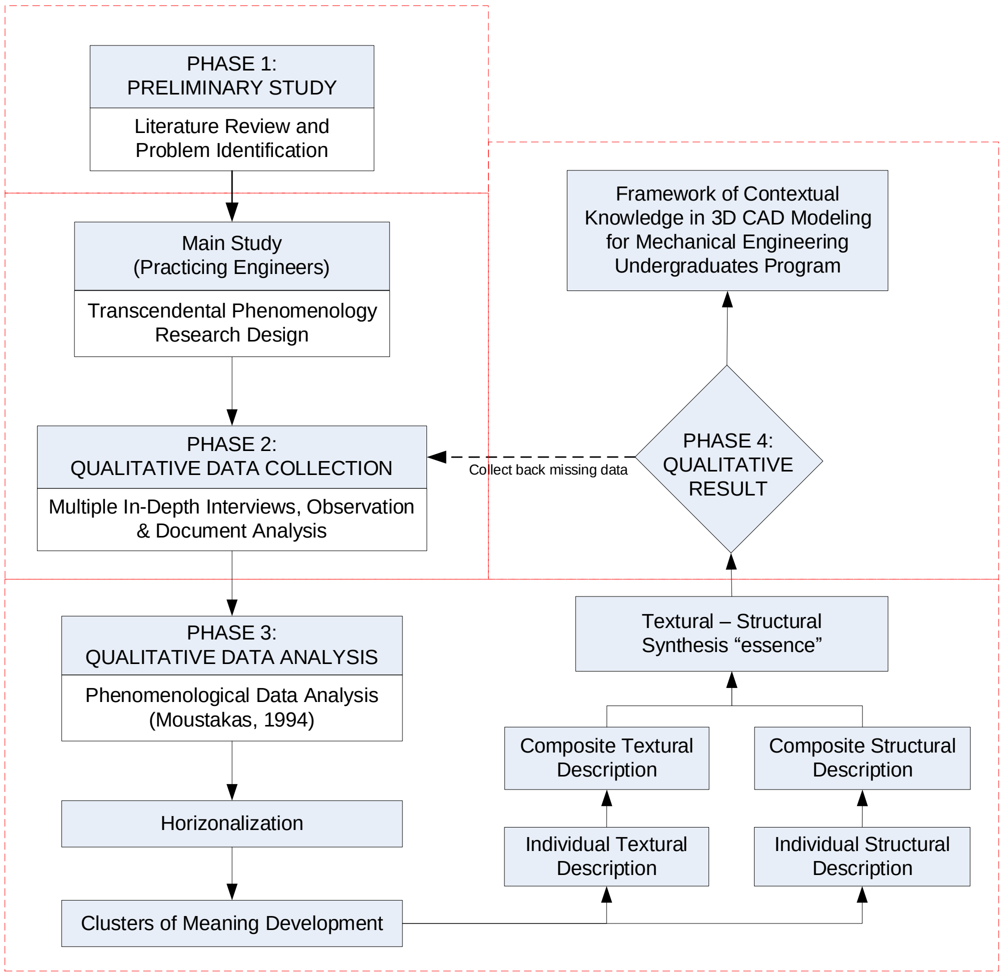


Fig. 3. Visual Representation of Operational Research Framework

6. Research Findings and Discussions

This article presents the findings of an investigation into how practicing engineers apply contextual knowledge when utilizing 3D CAD modelling software for product design. This section focuses on questions regarding the essential elements of contextual knowledge utilized by practicing engineers in 3D CAD modelling and how these engineers effectively employ these key elements. The study identifies three predominant themes in the application of contextual knowledge during the process of product design using 3D CAD modelling: Realization, Design Intention, and Normalization. These three themes emerged naturally based on the elements identified during data analysis within the four contexts of this study. As illustrated in Figure 4, four contexts are positioned centrally in the framework to represent the continuous process of CAD modelling, beginning with Model Creation, Model Manipulation, Model Visualization, and Model Transfer. These four contexts have been identified as the main modelling processes involved in CAD applications. Each context encompasses three main elements of contextual knowledge (Realization, Design Intention, and Normalization), placed in each quadrant. These three elements have been classified as the main contextual knowledge elements that should be integrated into CAD instruction during the creation, manipulation, visualization, and transfer of 3D CAD models. This research introduces the sub-elements of contextual knowledge according to their modelling contexts to facilitate the development of workable and effective product designs during the CAD modelling process. By incorporating these sub-elements into 3D CAD modelling teaching and learning, students can be expected to develop creative and innovative product designs and enhance their proficiency in using 3D CAD software for product modelling.

6.1 Contextual Knowledge Utilization in Model Creation

When it comes to the contextual knowledge elements of practicing engineers in the Model Creation context, all the practicing engineers have thoroughly integrated contextualization into their model creation processes. They have leveraged the element of realization to facilitate the use of their imaginative abilities in shaping designs that vividly contribute to the human environment. Additionally, the design intention element assists engineers in planning how the creation part should be achieved in the design development, while the normalization element ensures the created model aligns with standards and requirements.

The findings emphasize the importance of developing functional, production-friendly, and user-friendly product designs. During the CAD model creation process, engineers contextualize these three fundamental aspects. Overlooking contextualization during model creation can directly impact the product development timeline. As illustrated in Figure 4, the representation of contextual knowledge elements in 3D CAD Modelling reveals that during the part model creation process, practicing engineers must fully comprehend their created model, understand the intention behind the design model, and adhere to the normalization of modelling activities. These three main themes hold equal importance, implying that, during the model creation stage, practicing engineers must fully immerse themselves in contextualizing their created 3D CAD model.

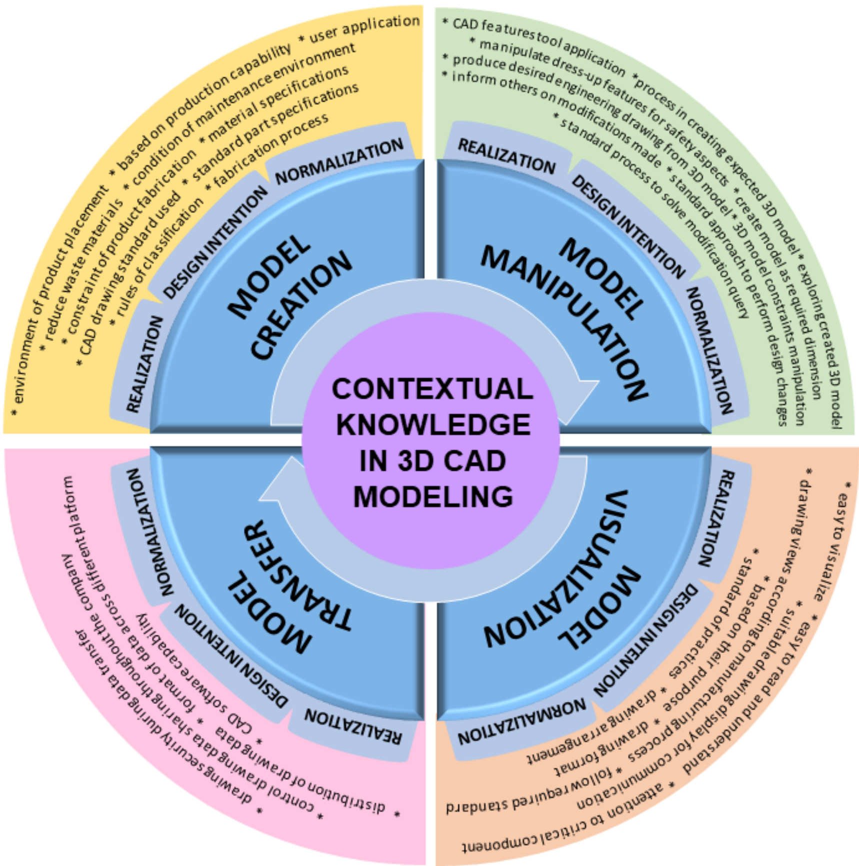


Fig. 4. Representation of Contextual Knowledge Elements in 3D CAD Modelling

6.2 Contextual Knowledge Utilization in Model Manipulation

In the context of Model Manipulation, practicing engineers have employed the element of realization to assist them in modifying designs that bring a tangible impact to the human environment. Concerning the design intention elements, practicing engineers have utilized them to plan how the creation part should be modified during the design development. As for the normalization elements, practicing engineers have applied all these elements to ensure the manipulated model adheres to standards and requirements.

Upon exploring the contextual knowledge of practicing engineers in the Model Manipulation context, the findings underscore the importance of enhanced proficiency in utilizing CAD modelling systems to effectively manipulate CAD applications for creating desired product designs. The specific elements that emerged in this model manipulation context are depicted in Figure 4. Based on the findings, it is implicitly demonstrated that a higher level of contextual knowledge among practicing engineers enables the full utilization of CAD modelling systems during the product design development process. By manipulating CAD models, practicing engineers have gained a deeper understanding of their ability to use and apply all the provided CAD modelling features.

6.3 Contextual Knowledge Utilization in Model Visualization

In the Model Visualization context, practicing engineers should emphasize realization elements. These elements empower them to help their imagination and create effective engineering drawings that clearly convey information for production or end-user applications. The design intention element aids in planning how to visualize and present the designed parts effectively in engineering drawings for comprehensive use during the product development process. Practicing engineers implement normalization elements to visualize the created model in adherence to commonly practiced engineering drawing standards and requirements.

Based on the findings of this study, it is evident that there is a strong connection between the produced engineering drawings and the engineers' knowledge and abilities. As depicted in Figure 4, practicing engineers stress the importance of engineers taking responsibility for producing engineering drawings that can effectively communicate and provide sufficient information to third parties during the product development process. Therefore, as engineers, they are required to produce functional engineering drawings to expedite the product development process.

6.4 Contextual Knowledge Utilization in Model Transfer

In the context of Model Transfer, practicing engineers have employed the realization elements, utilizing their imaginative abilities to transfer the created designs for the product development process. By understanding the manufacturer's requirements, this ensures that all drawing and data transfer processes are securely executed for the product development stage. Regarding the design intention element, practicing engineers have used it to plan how the creation part should be executed, based on the transferred data in the manufacturing process. The normalization element has ensured that the transferred model complies with standards and requirements.

In the Model Transfer stage, engineers share all created product designs in the form of CAD drawings or CAD data for product development. Based on the elements listed in Figure 4, most of the practicing engineers in this study consistently applied contextual knowledge elements when transferring the created CAD model for downstream applications. They acknowledged the importance of engineers maintaining product design confidentiality and safeguarding all company intellectual properties. Additionally, they emphasized the significance of engineers producing CAD data that can be seamlessly integrated across various CAD platforms. This need arises due to the diverse use of CAD modelling software among different companies and aligns with the various CAD modelling applications within their company's downstream user applications.

7. Conclusions

This article discusses the findings of a study that explored the elements of contextual knowledge among practicing engineers through four digital product modelling contexts. The aim was to construct a contextual knowledge framework for Mechanical Engineering undergraduate programs, focusing on 3D CAD modelling. The exploration in this study focused on understanding which contextual knowledge elements were utilized among practicing engineers during the application of CAD modelling systems in developing product designs, followed by an understanding of how they employed each contextual knowledge element in their daily design work. Based on the present findings, three main elements of contextual knowledge emerged in this study: Realization, Design Intention, and Normalization. The findings of this study can be significantly useful for instructors and academicians in higher institutions to incorporate and enhance the level of contextual knowledge among mechanical engineering students while using CAD modelling for their design work.

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