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A New Design Framework for Comprehensible Graphical User Interfaces for Parametric Computer-Aided Design Tools

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Abstract. Previous research in human-computer interaction (HCI) has focused relatively little attention on making parametric Computer-Aided Design (CAD) tools user-friendly. This study aims to address key research questions about the difficulties beginners encounter when using parametric CAD tools, the reasons behind these challenges, and the principles of interface design that can improve their understanding. To answer these questions, a comprehensive three-stage design framework for CAD Graphical User Interfaces (GUIs) is proposed. The first stage involves analyzing user experience (UX) within the context of the CAD interface, followed by developing customized solutions to meet specific requirements in the second stage. Finally, the framework includes rigorous testing and evaluation of the CAD GUI solutions against the identified requirements. Statistical analysis was used to validate the improved usability perception of the new interfaces. This framework leads to the creation of rules supporting the design of understandable GUIs for parametric CAD tools. Ultimately, this research contributes to advancing comprehensible GUIs by shedding light on the challenges beginners face, offering practical recommendations to enhance their experience, and facilitating a better understanding of tools to increase their efficiency.

Keywords: Graphical user interface, Computer-Aided Design, Usability, User experience, Eye-tracking
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1 INTRODUCTION

The majority of design and engineering work has been digitized over the past 30 years. Today, CAD (Computer-Aided Design) software has largely been used to assist engineering design processes by facilitating the visualization and tests through 3D prototype designs. The market is dominated by 3D CAD, a segment that was worth 5.5 billion U.S. dollars in 2018 (statista.com). The global CAD market is forecast to reach 13.83 billion U.S. dollars in size by 2028. CAD tools transform the nature of how things are designed; the development of and changes to these digital tools impact not only output and process efficiency but also innovation processes [44]. In light of the significant digitization of design and engineering work through CAD tools, there has been a rising awareness of the crucial role played by the user experience (UX). UX refers to a holistic view [4] of the overall experience that a user has before, during, and after using or interacting with a product or service, including their emotions, attitudes, and behaviors [23], and the impact of these on their actual usage [23,75]. UX is an important aspect to consider because it can significantly impact users' comprehension, especially beginners, since the use of an interface differs based on the user's comprehension level [36]. The experience of using the interface can impact users' satisfaction, reduce errors and frustration, and ultimately increase productivity and performance. However, the CAD tool interface's UX is frequently its weakest and most underdeveloped feature; its use is often neither an easy nor natural way for a user to express themself in approaching a particular task [61]. From year to year, CAD tools' interfaces have integrated a host of new features and functionalities. However, the functionalities offered by CAD tools have come at a cost because the tools themselves have become highly complex [34]. "Parametric" CAD tools in particular, which enable the modification of geometry without the need to recreate the entire model, are typically goal-oriented and focused on efficiency [50]. This makes existing interfaces tedious, complex, non-intuitive, and difficult to learn. Consequently, users without in-depth knowledge of the domain are not able to use the tools effectively [48] [39] [2]. Visual representations of interfaces can affect users' abilities to comprehend their tools' potential and can be a barrier in CAD education and engineering practices [26,67]. UX best practices contribute to enhancing the quality of user interactions and perceptions concerning goods and services [64]. Some research studies highlight the presence of "usability" issues in CAD software as challenges related to UX; however, there are relatively few suggestions available on how to effectively address these concerns. As such, challenges emerge when considering how to propose a comprehensible user interface (UI) for beginners using CAD tools. It is worth noting that the field of "usability" and UX research in CAD remains very limited [34]. Therefore, this research aims to investigate how to propose a comprehensible UI for beginners using parametric CAD tools. This aim is addressed by two research questions:

RQ1: What kinds of difficulties do beginners most commonly encounter when they use parametric CAD tools and why?

RQ2: Which interface design rules can help beginners improve their comprehension of the parametric CAD tool interface?

These questions are addressed by the following research objectives:

- To enhance and update the current body of knowledge by investigating UX challenges in the comprehension of parametric CAD tool interfaces.
- To determine at which point beginners experience misunderstandings and difficulties when using a parametric CAD tool, such as SolidWorks, in this study.
- To investigate how we can solve these misunderstandings and difficulties using graphical user interface (GUI) rules to have a better understanding of parametric CAD tools.

This study proposes a three-stage design framework, which employs UX methods, including eye-tracking experiments, questionnaires, and card sorting, to assess the UX of beginners utilizing the SolidWorks CAD tool. To the best of our knowledge, no previous work has investigated the design of a comprehensible graphical user interface (GUI) for a parametric computer-aided design (CAD) tool using a combination of user experience (UX) methods and eye-tracking to enhance the understanding of beginners. From an applied perspective, the results of the present study reveal how beginners perceive a parametric CAD tool interface and allow the identification of where misunderstandings arise. Moreover, it permits the classification of the causes of these misunderstandings and difficulties; it highlights improvement points in the UI. This study also allows us to propose CAD interface design rules to facilitate the comprehension of CAD tools. The results contribute to the future development of comprehensible GUIs for parametric CAD tools, offering insights into the challenges faced by beginners while providing practical recommendations for improving their experience and better comprehension of the tools' potential to enable more efficient use.

This paper is structured as follows: Section 2 presents a literature review focused on the limitations of CAD tool interfaces and explores the potential solutions offered by UX methods. Section 3 explains the methodology and the design of the research framework. Section 4 details the application of the framework. Lastly, the discussion and conclusion are presented, and the findings are analyzed.

2 STATE OF THE ART

2.1 Parametric Versus Direct Modeling CAD Tools

Since the development of parametric CAD tools in the mid-1960s, new functionalities have been added to allow users to carry out multiple tasks while improving interactivity and shortening the time-to-market [17]. Henceforth, CAD tools have been fully integrated into the multifunctional engineering environment, incorporating analytical and computer-aided manufacturing capabilities. [34]. Currently, CAD tools integrate 3D CAD modeling, parametric modeling, feature technology, and knowledge technology. It is parametric modeling that led to the development of a model that is not a single object but has the potential for a family of objects called instances. Parametric CAD models permit the modification of geometry without the need to recreate the model. Parametric modeling facilitates the intelligent refinement of design attributes through the utilization of feature-based, solid, and surface modeling design tools. By employing parametric commands and establishing associations between features, solids, and surface elements, parametric modeling ensures accuracy in the design process. [3,78]. It follows a structured engineering process; its design intent is visible as long as the user knows the construction of the model and its parameters. However, parametric modeling is complex and can be difficult and time-consuming if its principles are misunderstood. [12,79]. Direct modeling was developed in the 1980s to create a form and provide a straightforward history-free process rapidly [77,79]. With easy manipulation such as push and pull, engineers can directly work with multimodal interfaces, including haptic or VR/VA devices, allow new interaction with CAD tools, and increase team engagement while also providing more intuitive interactions for non-CAD specialists. However, as illustrated in Table 1, this type of direct modeling lacks design automation and has weaker dimension-oriented editing [78].

	Parametric modeling	*Direct modeling*
Pros	Accuracy Features-based modeling Structured engineering process A systemic, mathematical approach for CAD Feature Design Tree (historical visualization) Visible design intent Automated changes / Adjustment Pattern available (constraints & relationship between elements)	Geometrical creation (Modeling clay) History-free process Straightforward Flexible Quick manipulation Easy to learn Versatile
Cons	Not very intuitive Complex Hard to handle Rigid / Linear construction Time-consuming	Underdeveloped automation Hard to understand the design intent (no parameters specify intent) Impossible for automatic adjustment No pattern features, weaker dimension-oriented editing, no history of dimension measurements

Table 1: Comparison of Parametric modeling vs. Direct modeling (adapted from Hoffman & Kim (2001) [24], Bodein, Rose & Caillaud (2014) [8], Zou & Feng (2019) [77], and Ault & Phillips (2016) [3]).

2.2 Declarative vs. Strategic Knowledge

Conventional pedagogical methods still dominate the teaching of CAD. This approach, rooted in behaviorism, tends to compartmentalize the modeling process into discrete steps, emphasizing algorithmic procedures necessary for constructing the topology and geometry of the model within the confines of the CAD software. The domain concerns declarative knowledge and adaptive expertise [42]. While this method adequately addresses the technical aspects of geometric modeling, it neglects to bridge the gap between the created CAD model and the underlying design intent. Despite its abstract nature, design intent plays a crucial role in guiding the modeling process toward achieving its rationale [54]. Notably, there has been a growing recognition of the need to shift the educational focus from mere declarative knowledge—pertaining to the operation of specific CAD systems—to a more holistic understanding of design principles that transcend software boundaries [53]. This shift is underscored by the concept of strategic knowledge, which encompasses an understanding of various methods for achieving design goals and the ability to select the most appropriate approach [55–57]. The importance of incorporating strategic knowledge into CAD education has been underscored by various scholarly works [6,13,69,73,74]. Central to this paradigm shift is the recognition of design intent as a fundamental aspect of strategic knowledge.

2.3 Limitations of Parametric CAD Tool Interfaces

CAD developers have focused mostly on adding functionality to their CAD toolsets rather than making those tools fundamentally more usable [61]. Parametric CAD tools have become highly complex, making them difficult to work with; their interfaces tend to limit satisfaction, efficiency, and reliability for users [29]. Hence, the interaction between the engineer and the current CAD tool is not without problems. CAD tools include several hundred operations, many of which have sub-menus and detailed options. If options for each menu item are considered, the number of possible operations grows exponentially. Since this number exceeds the cognitive load that an average user can handle, an efficient and user-friendly UI is critical to the users of these systems [39]. Moreover, poor user performance during use can have a severe impact on the quality of the design and productivity of the user since engineering design using CAD often entails delicate choices between ideal designs, practicality, functionality, and market constraints [34].

2.3.1 CAD tool interfaces

The use of CAD tools requires an adapted learning process [16,21,74]. Indeed, the user interaction in a CAD tool is non-intuitive, as the 3D modeling subspace has to be mapped to the *x*- and *y*-axes of input devices such as a mouse. This interaction is inherently complex and cognitively demanding due to the necessity of switching between three-dimensional and two-dimensional subspaces and the separation of the input space from the modeling space. Consequently, this increases the difficulties and the learning time, particularly for beginners [2,48]. The complexity involved in the comprehension of “spatial cognition” makes tangible interaction important for 3D software [65]. Beginners do not have a complete understanding of CAD tools; thus, problems concerning functionality and confusion are frequent [67]. Moreover, user interface (UI) complexity in CAD tools, which involve a multitude of commands and an extensive range of sub-commands or options, can overwhelm beginners and potentially hinder their comprehension of CAD. Effectively, the challenge of visualizing 3D objects on a 2D screen is related to the development of spatial visualization skills. It is evident that spatial visualization is crucial in the context of CAD. The significance of spatial ability, particularly when users are engaged in virtual media, is well documented in several studies [41,68,72]. As such, simple and cognitive GUIs may help users perceive the interface with easier perception, which may lighten the mental load. The "over-loaded with commands problem" and "under-use" of the interface, along with the issue of consistency of interface with the use of relevant metaphors corresponding with mental mapping, create problems related to the interface design [67]. Indeed, the use of an interface differs based on the users’ experience level. The interactive interface should, therefore, present different manipulation options for experts and beginners. Adapting interface design to the knowledge level of users will decrease the mental barrier, and the ease of recognition will lead to ease of use [39]. Allowing users to customize various settings to their needs and preferences is helpful, particularly in complex applications like most 3D parametric engineering tools [39]. The overloaded interface of CAD can cause panic even before use begins, leading to feelings of frustration [27]. This justifies the need for a Human-Computer Interaction (HCI) study of CAD GUI.

2.4 HCI for the Design of Comprehensible CAD GUI

2.4.1 HCI theories and approaches

In terms of computer interfaces, Human-Computer Interaction (HCI) has long studied how better interactive systems can be designed by evaluating their usefulness through user trials [14,51]. HCI seeks to bring the power of computers and communication systems to people in ways and forms that are both accessible and useful in our working, learning, and communication environments [19].
According to Nielsen [49], a usable system is not a one-dimensional property of a UI. In fact, a system is usable when it is: easy to learn, easy to remember, relatively error-free or error-forgiving, and pleasant to use. The Nielsen Norman Group (Interaction design) also proposed a set of 10 "heuristics" [50] (broad rules of thumb and not specific usability guidelines) for HCI, especially for "web usability." The general principles for interaction design state that a system should, for example, appropriately and promptly keep users informed about its status, show information in ways users understand from how the real world operates, and, in the users' language, be consistent so users are not confused over what different words, icons, etc. mean. Norman's (2010) contends that devices, computers, and interfaces should *function correctly* and *be intuitive and easy to use*. He highlights six design principles: *visibility, feedback, affordance, mental mapping, constraints, and consistency*. Similarly, Stone [66] cites visibility, affordance, feedback, simplicity, structure, consistency, tolerance, and accessibility. Meanwhile, Shneiderman [62] proposes eight golden rules of interface design: strive for consistency, enable frequent users to use shortcuts, offer informative feedback, design dialogue to yield closure, offer simple error handling, permit easy reversal of actions, support internal locus of control, and reduce short-term memory load. The UI must support these principles as it is an intermediate support between the user and system; the user communicates with the computer system via the UI. Typical CAD UI usually follows a certain standard. The GUI is configured with icons and menus. The GUI allows for more effective communication between the user and the system [19]. The 'user'-computer interaction is a problem-solving process that prioritizes the user experience [20,58]. The perception lived by the user is called UX. UX gives to the user the feeling that the product/system is "useful." This occurs via the UI as shown at Figure 1. As such, UX is a key success factor of software systems [30]; it leads to pleasant use and better engagement for users. The fact that the intent of the designer is not always linked to the perception of users [22] raises the need to study UX for interface design. Unfortunately, user involvement is less widely performed in design processes than ergonomic principles [32].

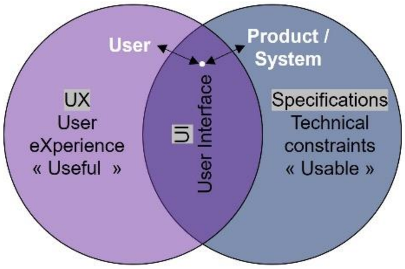

Figure 1: UI as an intermediate between the User & Product/System, UX as the user's perception.

This research seeks to understand the user's perception of using the complex interface, combining UX methods in a holistic manner [38].

2.5 Related Works on the Design of CAD Tool Interfaces

Several authors have studied the design of adapted CAD tool interfaces in order to improve the user's comprehension and interaction. Table 2 reflects related works for comparing the key contributions and limitations of each study, which serves as a basis for this work. These related works offer interesting contributions to the design of CAD tool interfaces by studying the icon's perception [67], the usability principles identification [39], the completion time, error rates, and satisfaction [33], the use of serious game elements to provide more engaging and intuitive environments [34], the use of Nielsen's heuristics to evaluate the usability, and the creation of multimodal interfaces to improve interactivity with the CAD tool [19,48]. Beyond the fact that these studies are somewhat dated or only focused on direct modeling CAD tools, they also include significant limitations that require addressing. These limitations should be overcome by considering the entirety of the layout (holistic approach), and not only the icons or menus, and by addressing the UX and not only 3D models, including by staying focused on the design of a CAD tool GUI to avoid the use of additional devices that can be expensive and complicated to use, especially for beginners.

Related Works	*Topic*	*Contribution / Key Findings*	*Limitations*
Szewczyk et al., (2003) [67]	Students' expectations and predictions about CAD tool usage.	Distinguish the "interface background" and the "working commands." Group editing tools together. Beginners need to understand all of what they see. Advanced users do not expect the software to be fully comprehensible.	Does not address the layout, only the icons. Dated.
Song & Guimbretiere (2009) [63]	Interaction between CAD and printed paper model via digital pen.	New input system. Temptation of tangible interaction with CAD modeling.	Instead of simplifying, it complicates by adding mediums.
Lee et al., (2010) [39]	Usability principles identification for the design of CAD tools UI.	The proposed UI principles are Consistency, Visibility, Feedback, Recoverability, Maximization of Workspace, Graphical Richness, Direct Manipulation, Familiarity, Customizability, Assistance, Minimalist Design, and Context Recognition. In total, 10 CAD tools such as SolidWorks are studied.	Does not address beginners, only advanced users. Parametric and direct CAD tools are mixed. Some UI principles seem contradictory to each other. Does not address UX.
Kolarić et al., (2010) [33]	Evaluation of two GUI prototypes for parametric CAD modeling.	Measure of task completion time, error rates, and satisfaction. User satisfaction was significantly higher for the "split" interface. Task completion times are significantly shorter when the "split" interface is being used. No significant difference in error rates between the two interfaces.	Does not address holistic aspect (only 3D models and not all CAD interfaces).

Kosmadoudi et al., (2013) [34]	CAD GUIs enhancement using serious games elements to provide more engaging and intuitive environments.	Focused on CAD GUIs. Review of CAD GUIs problems. Integration of game GUIs in the design environment of CAD.	Mainly focused on solutions from serious games.
Haapasalo et al., (2003) [19]	Applicability and usability in CAD UIs by evaluating empirical results through Nielsen's usability heuristics.	Use of Nielsen's heuristics as frame. From simple proposition of UI to usability. Focus on user context.	Dated. The evolution of novel CAD interface should be considered. Total knowledge of design process is not considered.
Nanjundaswamy et al., (2013) [48]	Multimodal interface to improve interactivity with CAD tool.	Focus on user interactivity. Three different modalities (gestures, brain-computer interface, and speech) used for creating an interactive and intuitive 3D CAD modeling interface.	Does not address parametric CAD tools. Difficult to implement all devices in comparison to a GUI.
Sequin (2005) [61]	CAD tool creating for geometrical shapes in association with aesthetics.	Consideration of "beauty functionals." Rapid prototyping tools to visualize.	Focus on aesthetic visualization. Physical interfaces like haptic technology rather than cognitive UI.
Madrigal & Jeong (2022) [43]	Personalization process of 3D printed products using parametric design.	Personalization as a competitive tool with parametric design. User involvement to process 3D modeling.	A single product is studied. Focus on personalization but little attention to the user's understanding.

Table 2: Related works on the design of CAD tools.

Despite the advantages of UX research for improving UX, parametric CAD tools are typically goal-oriented and focused on efficiency, which can be seen in the limitations of these tools [60]. Approaches to UX in CAD tools lack theoretical and empirical investigation [23]. With this lack of consideration of users' perceptions of 3D CAD tool interfaces, this research aims to integrate UX design methods like ethnography, questionnaires, card sorting, and eye-tracking to propose applicable rules in order to design a comprehensible interface for parametric CAD tools. Applying these methods to CAD systems empowers us to achieve a holistic comprehension of users' needs, behaviors, and experiences. By combining qualitative and quantitative insights from ethnography, questionnaires, card sorting, and eye-tracking, we can inform evidence-based design decisions that prioritize ease of use, leading users to understand CAD tools comfortably. The aim is to identify difficulties and challenges faced by beginners, enhance the overall UX, and develop better user-centric CAD tools. Thus, our paper endeavors to bridge the gap between UX research and CAD systems, underscoring the potential of user-centric design approaches in shaping the future of CAD tools. The complexity of CAD tools is relative to the need for additional functionalities in designing products with complex functions, but this complexity should be controlled and not be at the expense of users. While most commercial CAD systems offer users the ability to make GUI customizations based on user preference, future products should go further by considering the user, especially beginners, from the first launch of the software. All CAD experts start as beginners, and the first contact with software should not affect the designer's mental image of the CAD interface irremediably. Finally, the rise of parametric modeling requires the adoption of a new vision for understandable use in the CAD industry's needs [67]. The purpose of this study is to design a framework to identify users' perception of the CAD interface, propose a comprehensible GUI, and finally test the GUI in order to establish user-friendly interface proposals.

3 METHODOLOGY

Despite the need of UI evaluation for beginners, there is no universal or standard method [1], and none specific to the field of CAD interface. Encouraged by user-centered design [15,52], this research aims to investigate how beginners perceive and use the CAD tool to propose a comprehensible UI. This paper presents a research framework divided into three stages:

First stage: Analysis of the user in the context of use of a CAD Interface.
Second stage: Development of solutions to meet requirements.
Third stage: Testing and evaluation of CAD GUI solutions based on requirements.

The first stage answers the first research question: "RQ1 - What kinds of difficulties do beginners most commonly encounter when they use parametric CAD tools and why?". UX methods like ethnography, eye-tracking, card sorting, and questionnaires are employed to identify interface problems and to detect their causes. Then, these problems are transformed into requirements. The second stage addresses the second research question: "RQ2 - Which interface design rules can help beginners improve their comprehension of the parametric CAD tool interface?". This stage consists of developing solutions to meet the requirements from the previous stage by defining the principles of a CAD GUI, mapping the requirements to the principles, mapping principles to the solutions, configuring GUI solutions, and finally, ranking the solutions. The third stage validates the ease of understanding UI solutions by using eye-tracking tests. Eye-tracking serves as a validation method, allowing measurement not just of task completion times and error rates but also of user satisfaction and overall experience. Tests and evaluations of a CAD GUI based on requirements are completed, and the best competitive solutions are selected from the second stage. These three stages are part of an iterative process that enables the convergence toward a new CAD GUI, as illustrated in Figure 2.

After the iteration of these three stages, the results of the framework generate a proposed new CAD Graphical Interface. Each stage is detailed as follows.

3.1 First Stage: Analysis of the User in the Context of Use of a CAD Interface

The first stage aims to discover the users' difficulties with 3D CAD interfaces. The expected output of this stage is a list of misunderstandings and difficulties that arise when using the system. The "Ethnography" method is used to assess the problems. This UX method apprehends what people do within real-world contexts rather than what they say they do; it provides a richer, more realistic overview of how people apply the tool [47], permitting researchers to shed interpretations and access non-verbal behaviors [7]. The CAD users were invited to respond to a questionnaire (Appendix A). This exploratory questionnaire [59] was used to gather data on opinions, uses, and needs, plus to identify the causes of the difficulties. This questionnaire is divided into four sections: 1. The user's profile and experience level; 2. Difficulties in using the interface and expectations; 3. Detecting elements that help the understanding of the 3D construction during the adapted courses; and 4. Expression of the user's process to describe their construction logic.

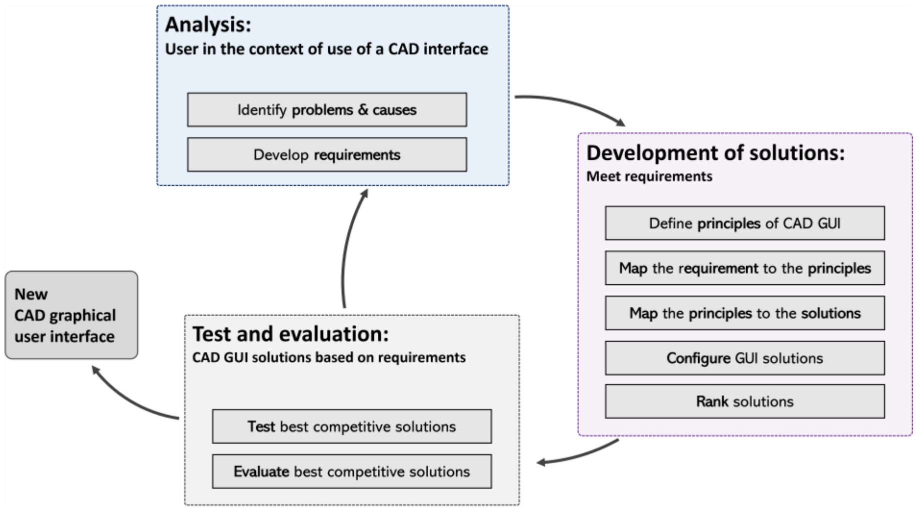

Figure 2: Global view of three-stage design framework with iteration to achieve a user-friendly CAD interface.

This questionnaire provides a list of the difficulties and repetitive errors related to the interface design of this CAD tool. According to relevant research findings [37], it is crucial to combine questionnaires with other quality assessment methods in order to achieve interpretable results. To better understand the complex relationship between the interface and user's understanding and their behavior, the card sorting method was also applied at the same time as the questionnaire. The card sorting method is useful for demonstrating the mind mapping of users. This method [35] is generative and is relevant to understanding how users think about the interface structure when a design proposal is not yet determined. It helps to detect the variability in different people's mental models and the vocabulary that they use to describe the same concepts. In this paper, the printed card sorting method was adopted to add a more participatory and collaborative approach [70]. Card sorting can be done in a focus group, which is a collective discussion activity to explore a set of specific issues [31]. The advantage of a focus group is that participants stimulate and encourage each other [11]. Focus groups were invited to sort cards comprising various CAD interface commands (icons and texts) printed on cardboard (Appendix B). Users were asked to create clusters and to name them. This method uncovers the users' perceived interface. At the end of this stage, the comparison of categorizations within the groups and the difficulties expressed by the questionnaire were listed. These problems were then transformed into requirements to develop interface solutions.

3.2 Second Stage: Development of Solutions to Meet the Requirements

This stage consists of designing an improved GUI for 3D CAD. The elements were collected from questionnaires, card sorting, and focus groups conducted in the previous stage and then categorized according to their respective requirements. The result is an aesthetic and appealing interface that offers better usability perception [9] and more effective usability of the system [25]. Visual aesthetics and the UI are related [71]; visual perception directly influences the users [28] with easiness. Norman's design principles and Nielsen's interface heuristics were listed to map the requirements to the rules, and then GUI applicable rules were ideated. For example, "Consistency" should be given by a pattern (repetition) with a color code. To solve the complexity of the interface, the principles of aesthetic and minimalist design can be applied to simplify and spacing. Effectively, simple and clear elements are better than too many scattered elements. These rules, adapted for a CAD interface, were applied to configure different interface solutions. The ranking of interface solutions was achieved through the utilization of the Analytic Hierarchy Process (AHP) [69], one of the most extensively employed and powerful multiple criteria decision-making (MCDM) methods for resolving complex decision problems [76]. The exploration begins with a clear articulation of the problem at hand: evaluating interface solutions based on a set of criteria. Stakeholders engage in pairwise comparisons to ascertain the relative importance of criteria and the performance of each alternative against those criteria. Synthesizing the preferences of criteria involves analyzing the pairwise comparison data to establish the relative weights of each criterion. Once the relative weights of criteria are obtained, normalization and averaging ensure coherence and consistency. Similarly, the normalization and averaging of scores assigned to each alternative for every criterion result in relative scores reflecting the performance of alternatives concerning individual criteria. By comparing the overall scores of alternatives, weighted by the results of each criterion, the ranking of interface solutions was achieved. Through the systematic application of the AHP, ensuring a rigorous and comprehensive decision-making process, the interface solution that best meets the set of criteria was selected.

3.3 Third stage: Testing and Evaluation of CAD GUI Solutions Based on Requirements

This stage aims to validate the developed solutions of the second stage. After ranking solutions from the previous stage, an eye-tracking test with the best competitive solutions comparing current interfaces was completed. These interface solutions were evaluated using a "heat map" that allowed the gathering and visualization of data about the most and least attention-capturing sections, gaze flow (the eye direction of what users are looking at), and a questionnaire used to understand users' perceptions. Eye-tracking can be used to measure task completion times, error rates, user satisfaction, and experience [5]. It permits researchers to track the user's eye paths to identify the elements that are perceived first and which interface elements are seen the most, allowing evaluation of the quality of information organization on the screen [35]. As illustrated in Figure 3, an eye-tracking sensor was settled at the bottom of the computer screen, giving 60-90 cm distance between the tester and the desktop screen. After the calibration, the testers were allowed to respond only with their voices, preventing disruption of the eye-tracker sensor. To note all reactions simultaneously, a camera recorded the whole screen scene as well as the conversations.

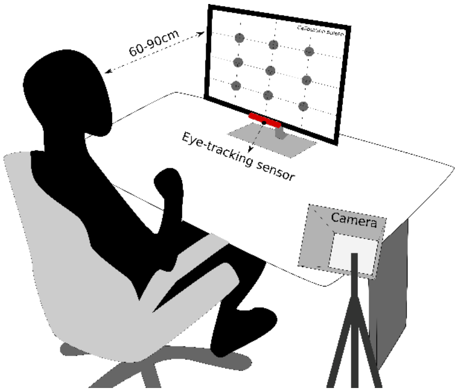

Figure 3: Eye-tacking test protocol (illustration).

The eye-tracking protocol timeline is presented in Figure 4. It commenced with an introduction to the protocol and calibration. Once the protocol was explained (Appendix C) and the ethical form approved, testers were instructed to speak aloud rather than indicate with their fingers or shake their heads to avoid measurement errors. The "think-aloud" method is largely employed during eye-tracking [40] and, in this case, was helpful in understanding the perception of the interface. The testers were asked to examine several series of interfaces designed from the second stage. The testers were asked to verbalize their perceptions of the interface during the initial five-second projection. To prevent the think-aloud method from disrupting the task at hand [18], the same interface was presented in separate sections, each with a question designed to ascertain the user's status or specific function.

Each series included three requests:

- First, five seconds of "think-aloud" was required. "Think-aloud" is a simple usability test that users use to think out loud. The aim is to obtain their general perception of the interface.
- After the general perception, users were requested to specify their current location within the system.
- Finally, users were asked to find a specific icon. The completion time for the whole process was measured.

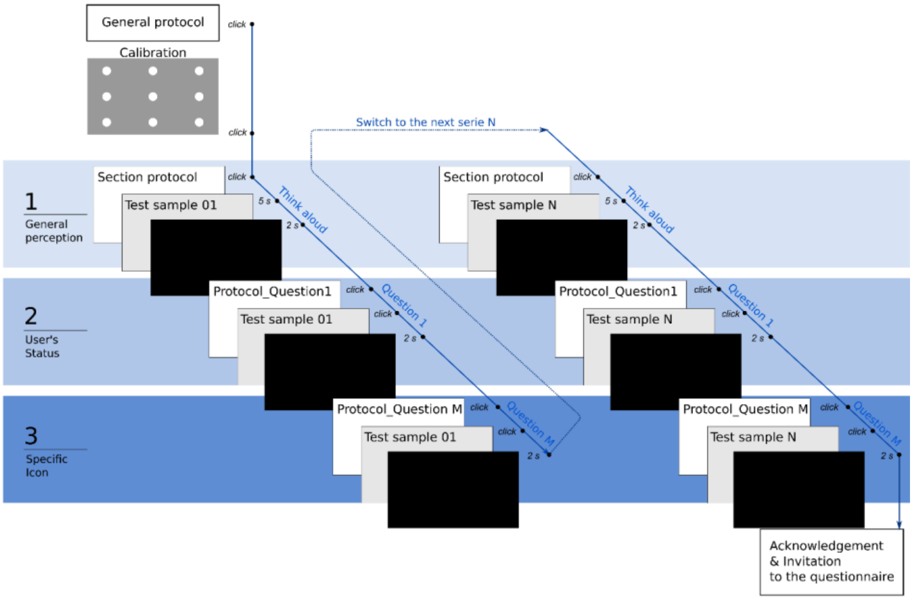

Figure 4: Protocol timeline for the eye-tracking test.

To prevent the difficulty of measuring exact timing with gaze-based interaction tasks [41], each task question should be separated with an intermediate break-out screen, even if the questions are on the same image. As such, a black screen was inserted for two seconds between each image and question to release the tester's gaze. Each transition was initiated by the interviewer clicking on the tester's voice request. The advantage of five-second perception is particularly suited to the early stages of the design process, even on the non-operational graphical model [32]. Eye-flow and heat map measurements were used on the interface solutions to assess whether the enhanced interface elements draw greater attention to the critical areas of the interface and whether they effectively guide users toward the necessary zone. After the eye-tracking experiment, the users were invited to answer a questionnaire (Appendix D) on usability perceptions (with the solutions). The questionnaire structure was inspired by SUS (System Usability Scale) [10] and CUSQ (Computer Usability Satisfaction Questionnaires) [37]. It is structured with usability scales measuring agreeability, understanding, consistency, visibility, distinction between elements, finding demanded function, layout, icon signification, and text comprehension. All the conversations that occurred during the questionnaire completion were noted down. The detailed framework, encompassing the developments and processes of the three phases, is depicted in Figure 5. This comprehensive framework provides a structured approach and serves as a roadmap for the application. Figure 5 offers a clear representation of the interconnections and progression within the framework, fostering a more seamless exploration of the application's intricacies.

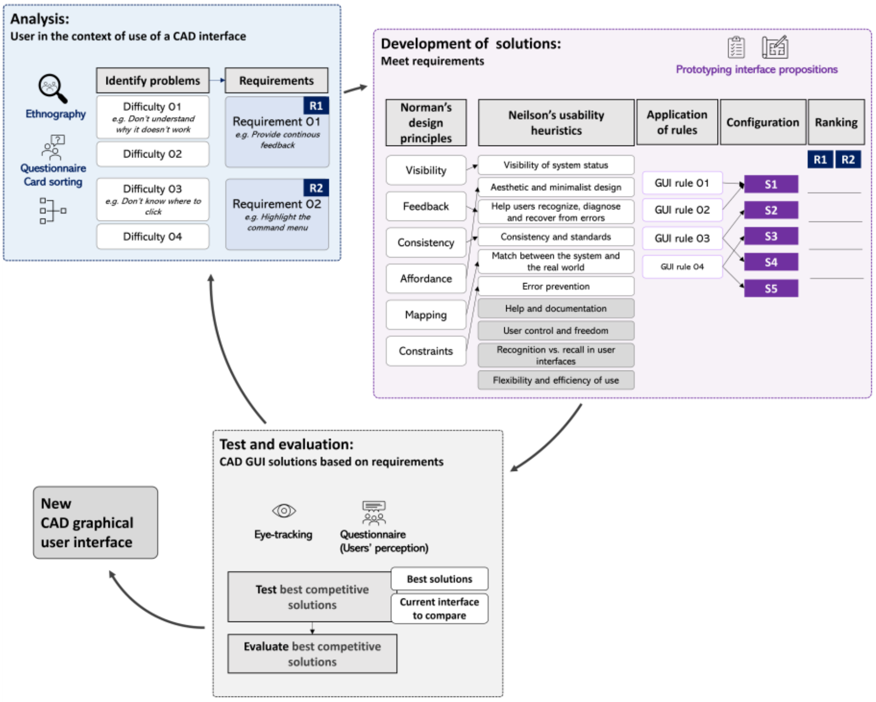

Figure 5: Detailed view of design framework (Rn=Requirement n, Sn=Solution n).

4 APPLICATION

This section focuses on the application of the detailed framework to develop a new CAD interface that caters specifically to the needs of beginners in the field. The primary objective is to design an intuitive and user-friendly CAD interface that supports beginners' learning process. By applying the research findings, the envisioned CAD interface aims to simplify design tasks, streamline the workflow, and enhance overall usability for beginners. This work is dedicated to addressing the distinctive challenges faced by CAD beginners, ultimately empowering individuals entering the field with a robust and user-centric tool that fosters enhanced usability in CAD systems.

4.1 First Stage: Analysis of the User in the Context of CAD Interface Use

This stage presents the results of UX methods, including ethnography, questionnaire, and card sorting, in order to identify beginners' difficulties in using the CAD interface and their causes. Detailed demographic data is provided in Appendix E. One of the primary difficulties faced by beginners was the process of projecting a 3D object onto a 2D screen. Moreover, the interface has a lot of windows and icons in a patchwork relative to parameter 3D functions. The large number of icons and small screen sizes can make the interface overwhelming for beginners. Users may not even be aware of their location within the system, resulting in a lack of understanding regarding their current status. The main difficulties originate from confusion between various elements (e.g., construction line vs. centerline, dimension vs. measure) and various status tabs (e.g., in or out of sketch). Lack of feedback about users' conditions (e.g., keyboard shortcuts) leads to mistakes and user confusion.

The particularity of the French version of SolidWorks should be emphasized. Most of the text on the buttons in the "Solid" tab, called the "Features" tab in SolidWorks, starts with "Bossage/Base," while the next word of the functional description is more important. Often, users do not even distinguish the differences between the various functional buttons, and consequently, they do not understand when to use them and for what. Overall, the ethnography study reveals several areas of opportunity for improvement. Participants experienced difficulty in visualizing 3D volumes projected onto a 2D screen and confusion among different interface elements. Additionally, they faced challenges in identifying various status tabs and did not receive feedback regarding their status. The interface was cluttered with numerous windows and icons, and French users faced cultural challenges. Lastly, participants had difficulties distinguishing between different functions. After completing a 15-hour practical CAD lesson on SolidWorks, which involved tasks such as 2D sketching, adding and cutting volumes, and applying patterns, participants were questioned (as detailed in Appendix A). The questionnaire asked users to share their impressions of the CAD interface and to identify any difficulties they encountered while using it. Table 3 presents the list of primary difficulties identified, organized by frequency of occurrence.

Difficulties	*Frequency*	*Details*
Comprehension	16	Comprehension of how the system works. Misunderstanding of text and icons.
Visibility	12	Knowing where the user is in the software, in which status, and at which stage. Conceptual distinguishment between the "Sketch" tab and the "Solid" tab.
Projection 3D	11	Understanding of construction in 3D.
Global vision	5	Master vision of a set of structure of interface. Vision of hierarchical structure.
Unfamiliar function	4	Construction of Bezier curves (vector curves).
Forgivability	2	Ability of the user to recover from the case of error action.
Dimension	2	Order a dimension.

Table 3: Results of the questionnaire about difficulties (n=46).

There are two recurring difficulties with regard to the system status' visibility and the comprehension of construction logic. Beginners were focused on the final 3D appearance, providing very limited information about the steps and processes involved in building. This confirms the difficulty of 3D volume projection detected using ethnography. Lack of global vision and confusion among the various available actions were frequent issues. Simultaneously, card sorting with four focus groups was conducted to gather qualitative insights. Participants in the focus groups sorted 40 printed cards (each with an icon and text; for further details, see Appendix B) into categories based on their understanding of them and perceived functionalities. The results of this stage formed the perceived categories of the interface, as shown in Figure 6. Pivot table analysis was conducted to identify patterns and areas of potential misinterpretation. The items were placed on the x-axis, while named and clustered groups were placed on the y-axis. The card sorting was conducted with four focus groups, resulting in four totals for each item.

Users made a clear distinction between sketch items and functions to make a solid volume; nevertheless, it was interesting to notice that the "Functions" group was formed before the "Sketch" group in each card sorting. Beginners were strongly oriented by the form of icons, and they read the text of icons to estimate their consequences. Because of this icon-oriented understanding, there was confusion about the icons that included those of "Sketch" and those of "Functions." Evidently, the appearance of icons orients the perception. The functions for adding and cutting a volume follow the same logic but have different results in 3D. As previously noted, users can experience confusion when presented with various forms of icons due to a lack of a general view of the 3D projection.

	Instant 2D	Instant 3D	Convert Entities	Additional functions	Extruded Boss/Base	Revolved Boss/Base	Display Style	Revolved cut	Fillet/Chamfer	Hole Wizard	Offset on Surface	Additional functions Boss/Base	Pattern	Additional functions Cut	Shaded Sketch Contours	Rapid Sketch	Offset Entities	Repair Sketch	Sketch Icons
Functions			2	4	4	4	2	4	4	4	4	4	1	4	1		1		
Sketch	1	1													2	4	1	4	4
Visual	3	3					1								1				
Commands																			
Entities			2														2		
Pattern													3						
Historic																			
Support																			
Question Mark							1												
Grand Total	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

	Curves	Smart Dimension	Exit Sketch	Quick Snaps	Mirror Entities / Sketch Pattern	Sketch	View Orientation Icons	Apply Scene	Dsiplay Style Sub-Menu	Visualization Icons	Hide/Show	Feature Manager Design Tree	Search Commands	Hide/Show Sub-Menu	Trim Entities	Options & Rebuild (Tricolor)	Apply Scene Sub-Menu	Reference Geometry	Display/Delete Relations	Grand Total
Functions				1																44
Sketch	4	4	4	2	1	4									1				2	39
Visual							4	4	4	4	4			2		1	2	2	1	36
Commands												2	2	1	1	2				8
Entities															2					6
Pattern					3															6
Historic												1	1			1		1		4
Support												1	1							2
Question Mark				1										1			2	1	1	7
Grand Total	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	152

Figure 6: Card Sorting Results (Pivot Table Analyze: x-axis= items of cards, y-axis=named groups).

The representation of 2D icon images impacts 3D comprehension. This assessment leads to the notion that improved GUI can counter the difficulty of 3D visualization. As a side note, half of the sessions classified the icons for applying patterns in a separate category, while SolidWorks classifies these icons as native to the "Solid" tab with functions. Ambiguous jargon and difficulty in visibility, like the distinguishment of different levels of the system, are recurrent and repetitive problems. At the end of the first stage, identified problems were transformed into requirements to design a comprehensible and cohesive CAD interface (Figure 7).

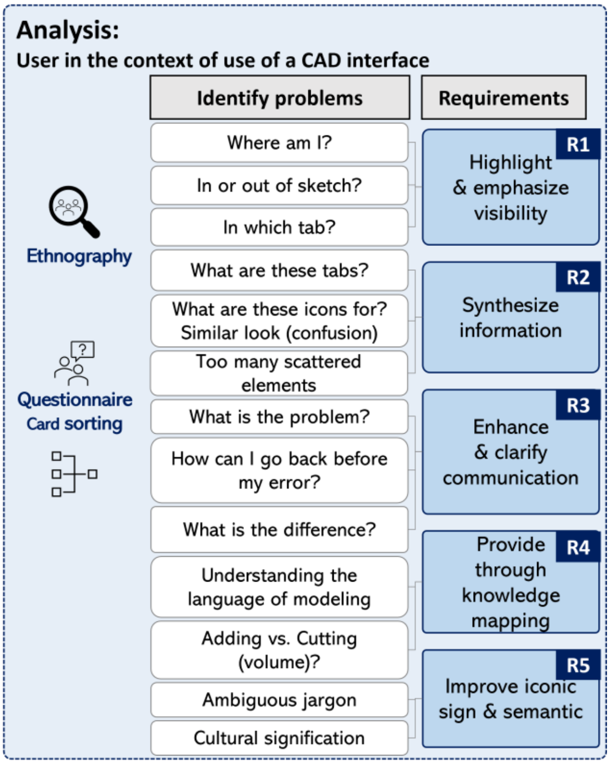

Figure 7: First stage: Analysis of the user in the context of use of a CAD interface (R1=Requirement 1, R2=Requirement 2, R3=Requirement 3, R4=Requirement 4, R5=Requirement 5).

The challenge of determining the user's current tab and editing status led to the establishment of Requirement 1 (R1), emphasizing the need to enhance visibility. Requirement 2 (R2) was crafted to aid in understanding icons and tabs by synthesizing information. To address issues such as lack of feedback, difficulty in notifying recoverability, and unclear distinctions, Requirement 3 (R3) was introduced. Requirement 4 (R4) focuses on knowledge mapping; mental mapping refers to mental models that users construct to understand and navigate through a designed system or interface. Requirement 5 (R5) is dedicated to improving icons and semantics, respectively. The next section describes the development of solutions to meet these requirements using GUI principles.

4.2 Second Stage: Development of Solutions to Meet the Requirements

This second stage included the creation of GUI solutions to test the improvement of CAD understanding. The solutions were created by applying graphical rules such as the following.

Solutions to meet R1: *Highlight and emphasize visibility* – Due to lack of visibility, users have difficulty knowing their status within the system, i.e., in the "Sketch" tab or in the "Solid" tab; in or out of "Sketch editing." In fact, the iconographies (V/X buttons) for "Exit Sketch" are hardly visible because they are blurred, making it hard for a beginner to notice. In fact, they do not know why they should leave "Sketch editing." To address this problem, the icons were sharpened and contrasted in saturation. Moreover, the consideration of "eye-flow" becomes an important aspect to guide users. The V/X buttons (to exit "Sketch editing") were relocated on the pathway between the command manager and the central piece.

Solutions to meet R2: *Synthesize information* - Too much information leads to confusion. Adhering to the minimalist design, there should be a few essential tabs at the beginning—users can always add more tabs as they gain experience. In this case, only two tabs, the "Sketch" tab and then The "Solid" tab should be visible in chronological order.

Solutions to meet R3: *Enhance and clarify communications* - The current tab in use is outlined and colored with the command manager. Both applying a highlight color for the command manager and dressing the background with the same hue clearly indicates the user's status by color code. In this case, coloring the "Sketch" tab in green and the "Solid" tab in orange is proposed.

Solutions to meet R4: *Provide thorough knowledge mapping –* Users face difficulty distinguishing between different icons in the current "Solid" tab. To solve this ambiguity, considering how users perceive and conceptualize the icons within the tab, the "grouping" principle is applied. The icons are grouped by their nature of functions into four groups (adding volume, cutting volume, pattern, and advanced functions). The grouping enhances the visibility and hierarchy of the system. Applying "Pattern" is separated into another group; some advanced functions are removed, permitting more spacing between the icons (i.e., between groups).

Solutions to meet R5: *Improve icons and semantics* – Currently the icons and signs are confusing and difficult to distinguish. To solve this, the texts were re-adopted, e.g., from "Bossage/Base" to "Volume." Additionally, these texts were differentiated using size and contrast, depending on their content levels. By mapping these five requirements to Norman's design principles and Neilson's usability heuristics, it is possible to create applicable graphical rules and potential alternative solutions (Figure 8). The second stage of the process entails the detailed development of solutions. This stage entails the transformation of graphical user interface designs (GUIDs) into configurations of solutions. To propose a set of GUID rules that can be applied, Norman's design principles were aligned with Neilson's UI heuristics. Subsequently, the solutions for each "Sketch" and "Solid" tab were ranked according to the AHP method. The requirement for emphasized visibility is foremost among design principles while applying the affordance principle is required for synthesized information and improvement of signs.

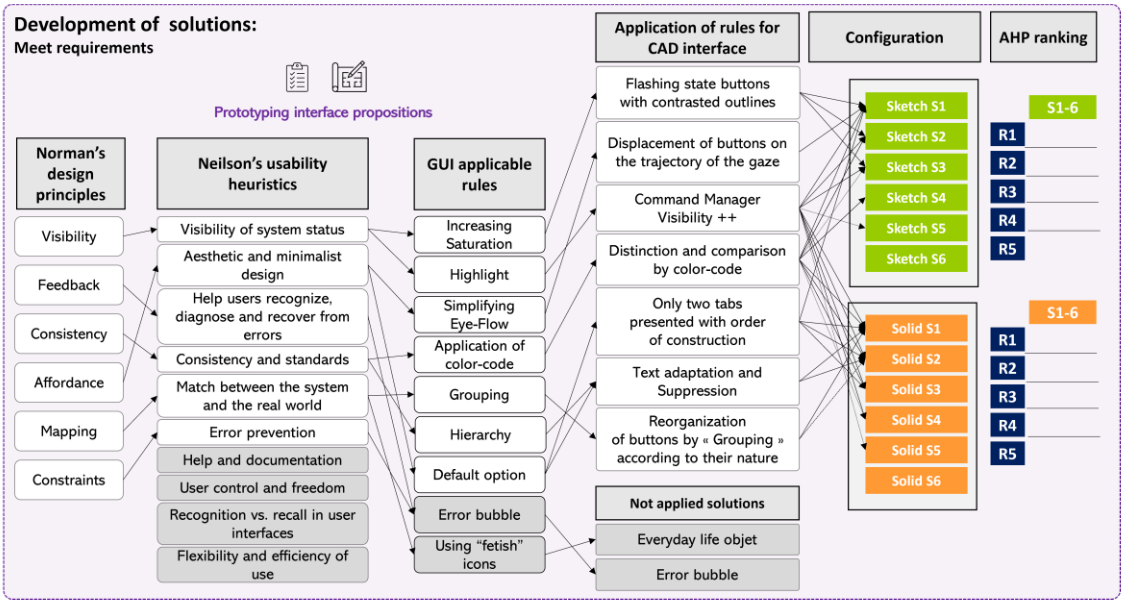

Figure 8: Second stage: Detailed development of solutions (Development of solutions from Graphical User Interface Design (GUID) to configuration of solutions). (Sketch Sn=Solution n for "Sketch" tab, Solid Sn=Solution n for "Solid" tab).

To enhance communication comprehension, it is recommended to put constraints in place to prevent errors and ensure graphical consistency. The configuration of graphical rules was updated to enhance UX. A color code was applied to distinguish between the "Sketch" tab solutions in green (Figure 9) and the "Solid" tab solutions in orange (Figure 10). Additionally, it is suggested that the "Command Manager" area be highlighted to enhance visibility as a general solution, except for the "Sketch" solution 6 and "Solid" solution 6 as neutral and non-modified solutions. The default option should be applied, especially for those who are new to the software interface, with only two tabs in the order of construction presented, the "Sketch" tab followed by the "Solid" tab.

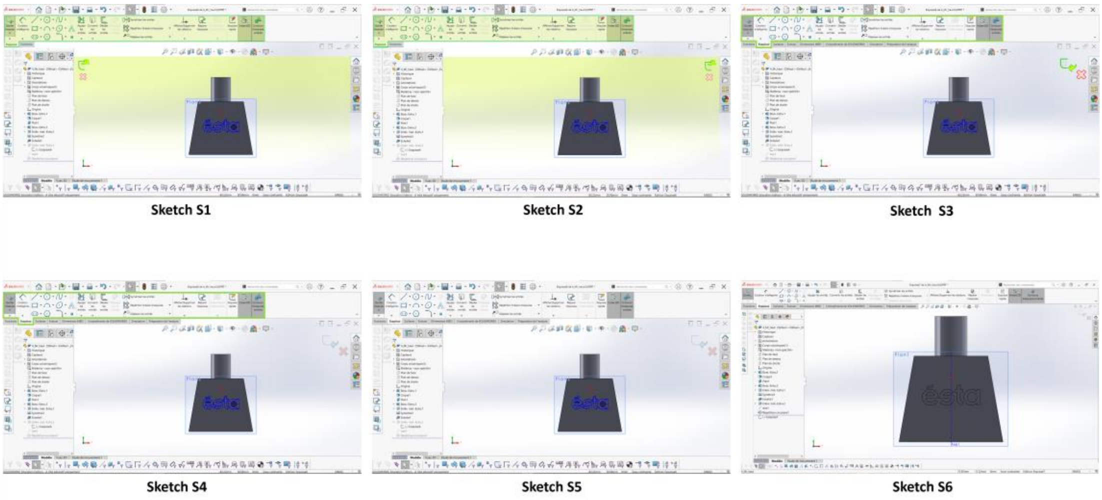

Figure 9: Sketch tab solutions.

For the "Sketch" tab solutions, flashing state buttons with contrasted outlines have been added to solutions 1, 2, and 3 for optimal UX. The status icons have also been relocated to improve the eye flow in solution 1. For the "Solid" tab solutions, the descriptive texts have been adapted and suppressed for solutions 1 and 2. Additionally, the interface proposal provides for the reorganization of buttons by grouping them according to their type.

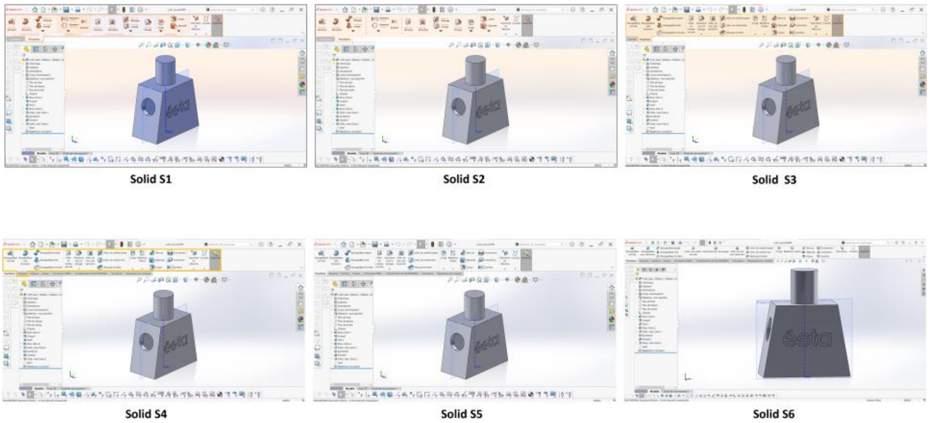

Figure 10: Solid tab solutions.

The process of ranking configurations using the AHP, as outlined in Section 3.2, involves a systematic approach to evaluating and prioritizing various configurations based on multiple criteria or factors. In this context, configurations are varied by different setups of arrangements within the GUI of SolidWorks including aspects such as layout, menu organization, and button placement. The AHP method provides a structured framework for decision-making by breaking down complex decisions into smaller, more manageable components. It involves establishing a hierarchy of criteria and alternatives, then comparing the alternatives pairwise against each criterion to determine their relative importance. Through this process, numerical weights are assigned to each alternative, reflecting their overall suitability or desirability. Once the configurations had been evaluated and ranked using the AHP method, the aim was to identify the most competitive solutions—that is, the configurations that best meet the predefined criteria and objectives of the study. These top-ranked configurations were then selected for further consideration or implementation in improving the GUI of SolidWorks. In this application, the *goal* is to find the best competitive solutions to design a comprehensible GUI for a CAD tool; *criteria* are the five requirements (R1 to R5), with *evaluated alternatives* as the solutions (S1 to S6) for the "Sketch" tab and "Solid" tab configurations. Firstly, a peer comparison is made, based on expert opinions (the authors'), that determines the importance of requirements with respect to the *goal*. Secondly, the normalized weight of each requirement is calculated, with the help of a judgment matrix A_c, where the expert opinions are synthesized (see Table 4). Each requirement's importance is obtained from the eigenvector of the double-entry matrices normalized to 1. Requirement 1 as a visibility issue was estimated as the most important, followed by requirements 2 and 3 for information and communication. Ranked least important were requirements 4 and 5, considering the knowledge mapping, and improving icons and semantics, respectively.

A_c	*R1*	*R2*	*R3*	*R4*	*R5*	*Weighted sum value*	*Weights*	*W sum / C W*	λ_{max}	*CI*	*CR*

R1	1.00	2.00	3.00	5.00	7.00	2.31	0.46	5.03			
R2	0.50	1.00	1.50	2.50	3.50	1.16	0.23	5.03			
R3	0.33	0.67	1.00	2.00	2.00	0.78	0.15	5.07	5.04	0.009	0.008
R4	0.20	0.40	0.50	1.00	1.50	0.45	0.09	4.94			
R5	0.14	0.29	0.50	0.67	1.00	0.34	0.07	5.13			

Table 4: AHP ranking with weight for "Sketch" tab and "Solid" tab, Ac (Criteria), R1, R2, R3, R4, R5 (Alternatives), λ max (Maximum Eigenvalue), CI (Consistency Index), and CR (Consistency Ratio).

The criteria, denoted as Ac, serve as the evaluative dimensions for assessing the alternatives. Each row corresponds to a distinct criterion, while requirements 1 to 5 stand as the alternative options under consideration for each criterion. The numerical values within the table signify the outcomes of pairwise comparisons between these alternatives with regard to each criterion. For instance, a value of 2.00 in the cell representing R1 and R2 under criterion R1 implies that R1 is perceived to hold twice the importance of R2 concerning criterion R1. The weighted sum value is the cumulative total of the weighted values for each alternative across all criteria. These values are derived from the pairwise comparisons and encapsulate the overall significance of each alternative. Weights represent the relative significance of each criterion, calculated from the weighted sum values, thereby elucidating the contribution of each criterion to the decision-making process. The calculation of the ratio between the weighted sum value and the sum of weights for each alternative, depicted in column 9, aids in evaluating the consistency of judgments made during the pairwise comparisons. The calculated λ max, standing at 5.04, is utilized in determining the Consistency Index (CI) and Consistency Ratio (CR). CI is computed as (λ max - n) / (n - 1), where n denotes the number of alternatives. In this study, the resulting value of 0.009 signifies the degree of inconsistency in the judgments made during the pairwise comparisons, indicating a consistent assessment. CR, serving as the ratio of CI to a predetermined random index, provides an assessment of the consistency of judgments. With a calculated value of 0.008 in this study, lower values denote better consistency in judgments. After applying the calculated requirements weights, the alternative solutions are compared as presented in Table 5 for the "Sketch" tab and "Solid" tab configurations.

Sketch tab	*S.1*	*S.2*	*S.3*	*S.4*	*S.5*	*S.6*	*CI*	*CR*
R1	19.81	12.37	6.38	3.73	2.21	1.39	0.04	0.03
R2	6.99	6.99	3.67	3.67	0.98	0.65	0.00	0.00
R3	5.68	5.68	1.48	1.48	0.67	0.46	0.03	0.03
R4	3.90	1.91	1.32	1.14	0.42	0.32	0.10	0.08
R5	2.39	2.39	0.48	0.48	0.48	0.48	0.01	0.01
Solid tab								
R1	19.81	12.37	6.38	3.73	2.21	1.39	0.04	0.03
R2	6.86	6.86	6.42	1.28	0.86	0.68	0.05	0.04
R3	4.42	4.42	4.08	1.51	0.60	0.43	0.06	0.05
R4	3.84	2.85	0.76	0.90	0.37	0.28	0.04	0.03
R5	2.86	2.12	0.57	0.67	0.27	0.21	0.04	0.03

Table 5: Judgment matrix for determination of the importance of requirements (Solutions as alternatives of AHP ranking).

Table 5 presents the results for two sets of tabs, the "Sketch" tab and the "Solid" tab, with the criteria weights that were assigned in Table 4 to each requirement (R1, R2, R3, R4, R5) in each solution (S.1, S.2, S.3, S.4, S.5, S.6) throughout the AHP process. Metrics for assessing the consistency of judgments, such as CI and CR, are provided. These metrics aid in evaluating reliability and consistency. The values of CI and CR in Table 5 suggest a high level of consistency in the prioritization of requirements. The CI and CR are calculated as $0 < 0.10$, thus the weights are consistent. As expected, the configuration with more applications of graphical rules receives a better ranking. Solution 1 in the "Sketch" tab that underwent the most configuration changes—including increased saturation and a new placement on the trajectory of state buttons, as well as the application of a color code with simplified tabs—is considered the most suitable for meeting all requirements. Regarding the "Solid" tab solutions, it is noteworthy that solution 1—with configuration changes such as increased visibility through contrast and color code, and further through text customization and application of grouping according to construction logic—is classified as the best for all requirements. Finally, the selected best competitive solutions are tested with eye-tracking in the following section.

4.3 Third Stage: Testing and Evaluation of CAD GUI Solutions Based on the Requirements

This third stage allows us to test and evaluate the best competitive solutions. To improve UX, high-contrast icons have been implemented to aid in exciting "Sketch editing." This change was applied to solve the visibility of status, responding to requirement 1. The interface has been streamlined by placing the "Sketch" tab before the "Solid" tab, resulting in only two tabs: "Sketch" and "Solid." The application of a default option and new order address requirement 2. To fulfill requirement 3, to differentiate between the tabs, the color code is applied to the background area of the command manager: green for the "Sketch" tab and orange for the "Solid" tab. To respond to requirement 4, hierarchical mapping by grouping ensures efficient organization of functions within the command manager, enhancing user workflow. When adapting the text for French, the "Solid" tab texts are adjusted to accommodate French language preferences and conventions, to facilitate ease of understanding and usability for French-speaking users. The best competitive solutions are tested with the current interfaces as presented in Figure 11.

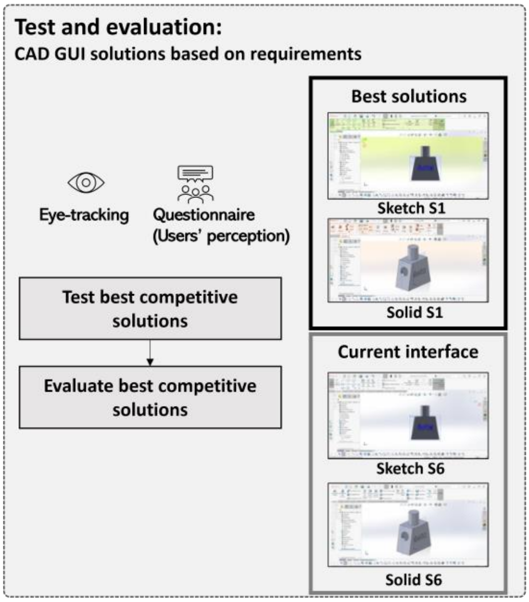

Figure 11: Third stage: Testing and evaluation by comparing the best competitive solutions and current interfaces.

A total of 19 participants were recruited and categorized according to their level of expertise. Four individuals were designated as having no prior knowledge (referred to as "zero-knowledge"), 10 were classified as "beginners," and five were labeled as "advanced beginners." The primary objective of the eye-tracking test was to determine which interface, among the existing interfaces and leading competitive solutions, facilitated optimal user comprehension. As illustrated in Figure 12, the eye-tracking test timeline commenced with the introduction of the general protocol and calibration phase, after which participants evaluated four series of interfaces.

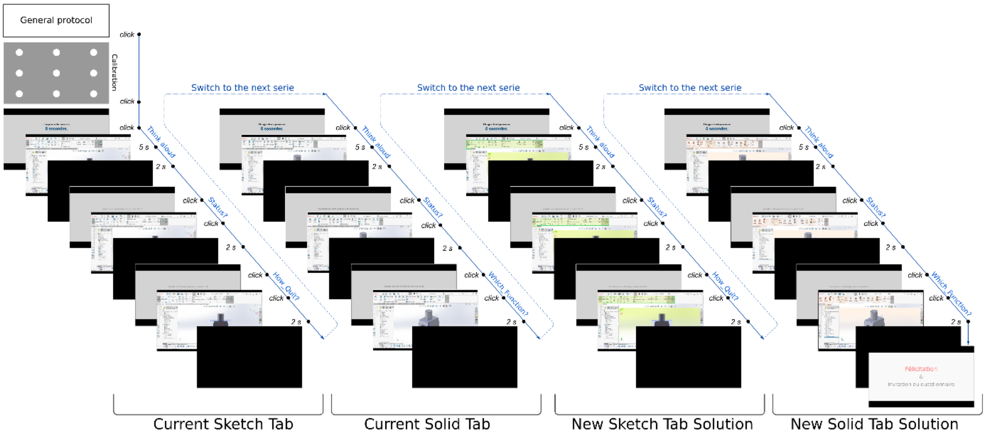

Figure 12: Eye-tracking test timeline.

Each interface includes three tasks: first, five seconds of perception with thinking aloud; second, a question about the user's status; and third, to find the demanded function on the interface. To avoid bias arising from users becoming adapted to the same interface category, the timeline is designed with alternative "Sketch" and "Solid" tabs of the current interfaces and the best competitive solutions. The most noteworthy are characterized by having visibility augmented by grouping and contrast, enhanced comprehension due to minimalist design and color code, and cohesion understanding enhanced via mapping and graphical hierarchy. Grouping the functions in separate tabs helps significantly with distinguishing visibility. Every new interface solution received better perception in all domains including layout design and adjusted text. Additionally, a comparison of the time taken to find the demanded function (Table 6) demonstrates ease in the users' understanding of a new interface, as it is expressed by users and affirmed by time spent.

	Zero-experience users	*Beginners*	*Users at ease*
Current interface	3164.5	3072	2234.4
New Interface	562.25	795	591.6

Table 6: Comparison of time to the whole fixation on the area of interest (ms).

The appearance variation must be applied with caution. The shaded buttons draw attention like the colored zone. The findings are not only about the color or contrast but also the importance of the location. The complexity of trajectory in the current interface (Figure 13) was evident, presenting a stark comparison to the lighter and relieved trajectory observed with the proposed solution (Figure 14).

The swift change of gaze flow elucidates a notable improvement with the proposed new interface solution. Participants exhibited a more simplified and appeased gaze flow when navigating the new interface, contrasting sharply with the overloaded gaze flow observed with the current interface. The current interface presents too many elements that are nonessential for beginners. In the new interface proposition with just two essential tabs presented, the users are appeased; they state that they see their status more clearly. The analysis of the heat map in the current interface within the "Sketch" tab shows a dispersed navigation pattern that spans the entire screen, as shown in Figure 15.

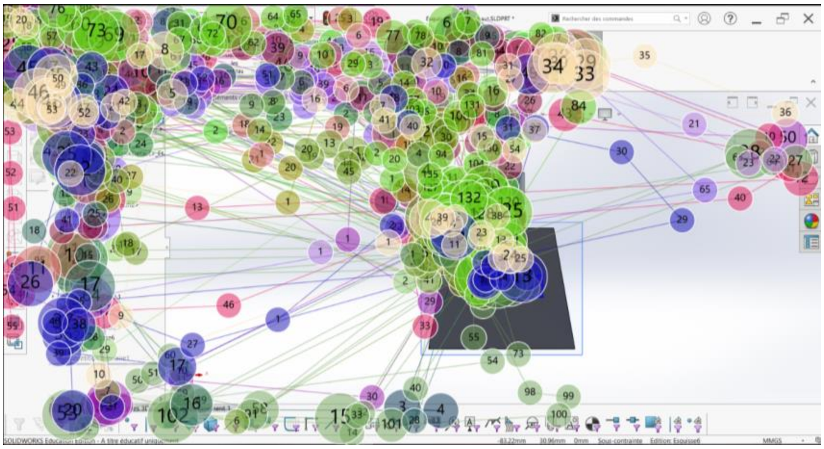

Figure 13**:** Gaze flow of the current interface.

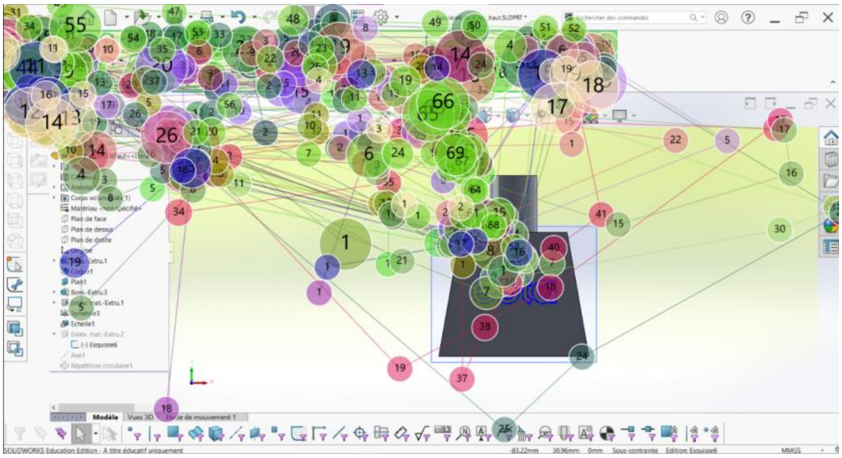

Figure 14: Gaze flow of the new interface solution.

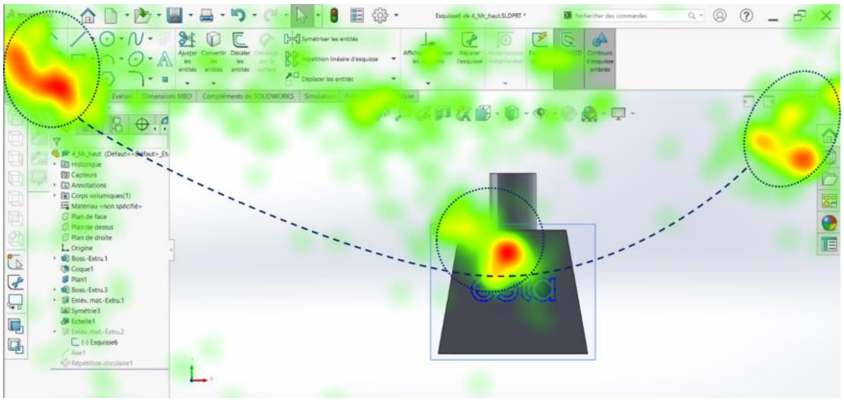

Figure 15: Heatmap of current “Sketch” tab (to quit).

It is worth noting that the new interface design, as shown in Figure 16, introduces replaced and contrasted icons that facilitate quick and easy identification. This results in a more concise and simplified eye-flow trajectory. The traced location of the heat maps of the new proposition interface (solution 1) compared to the current interface (solution 6) demonstrates a straightforward and user-friendly enhancement.

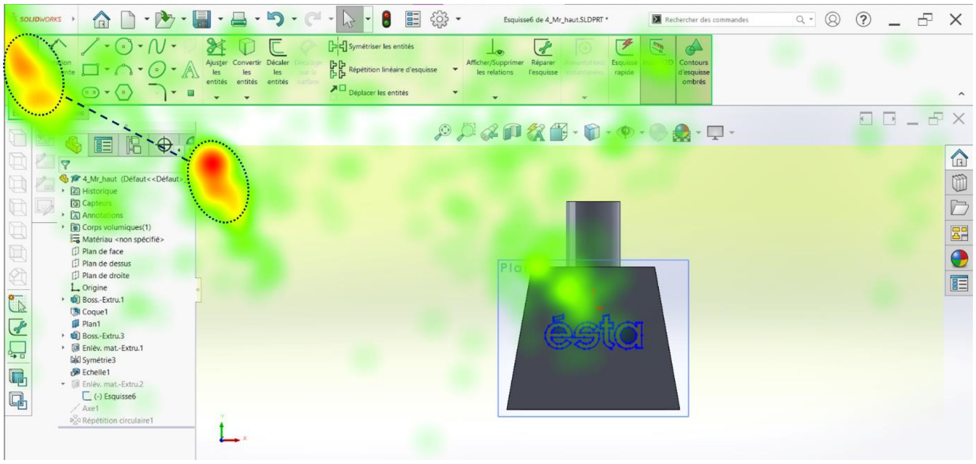

Figure 16: Heatmap of new "Sketch" tab solution (to quit).

A consistent interface applying a color code and adequate contrast is mandatory. The new interface has corrected some errors produced in the current interface. These findings underscore the importance of interface design in facilitating smoother and more efficient visual navigation experiences. The new interface solution demonstrates promising potential in enhancing user interaction and reducing cognitive load compared to the current interface. By prioritizing simplicity and ease of navigation, interface designers can create more user-friendly and visually appealing interfaces, ultimately enhancing UX and satisfaction. In order to confirm the improvement of usability perception of the new interfaces, a statistical analysis first checked if the data were normally distributed by applying a Shapiro-Wilk test. As the test results showed that all the data significantly deviated from a normal distribution, we used the Wilcoxon Signed-Rank Test. All tests were conducted in 95% confidence intervals. The results are presented in Table 7 and Table 8.

Score (Current – new)	*Question 1 (Agreeable)*	*Question 2 (Understandable)*	*Question 3 (Consistent)*	*Question 4 (Status Visibility)*	*Question 5 (In/Out Sketch)*	*Question 6 (Icon location)*
Mean	2.368 – 3.000	2.158 – 3.158	2.895 – 3.158	2.895 – 3.684	2.789 – 3.684	3.105 – 3.684
Median	2.000 – 3.000	2.000 – 3.000	3.000 – 3.000	3.000 – 4.000	3.000 – 4.000	3.000 – 4.000
Std. dev	0.684 – 0.816	0.765 – 0.602	0.567 – 0.765	0.994 – 0.582	0.749 – 0.582	0.737 – 0.582
Results	Z = -2.389, p = 0.017	Z = -3.272, p ≤ 0.001	Z = -1.667, p = 0.096	Z = -2.539, p = 0.011	Z = -2.877, p = 0.004	Z = -2.495, p = 0.013

N=19, p < 0.05

Table 7: Average score of users' perception of current interfaces vs. new interfaces ("Sketch" tab).

Score (current – new)	*Question 1 (Agreeable)*	*Question 2 (Understandable)*	*Question 3 (Consistent)*	*Question 4 (Status Visibility)*	*Question 5 (Distinction)*	*Question 6 (Finding Functions)*	*Question 7 (Layout)*	*Question 8 (Icon Signification)*	*Question 9 (Text comprehension)*
Mean	2.474 – 3.737	2.263 – 3.474	2.684 – 3.579	2.842 – 3.737	2.211 – 3.684	2.316 – 3.474	2.211 – 3.579	2.737 – 3.368	2.895 – 3.421
Median	3.000 – 4.000	2.000 – 4.000	3.000 – 4.000	3.000 – 4.000	2.000 – 4.000	2.000 – 4.000	2.000 – 4.000	3.000 – 4.000	3.000 – 4.000
Std. dev.	0.612 – 0.452	0.562 – 0.612	0.820 – 0.607	1.015 – 0.562	0.631 – 0.478	0.671 – 0.612	0.713 – 0.692	0.806 – 0.831	0.567 – 0.692
Results	Z = -3.739, p < 0.001	Z = -3.624, p < 0.001	Z = -3.314, p < 0.001	Z = -2.812, p < 0.005	Z = -3.816, p < 0.001	Z = -3.508, p < 0.001	Z = -3.589, p < 0.001	Z = -2.762, p = 0.006	Z = -2.887, p = 0.004

N=19, p < 0.05

Table 8: Average score of users' perception on current interfaces vs. new interfaces ("Solid" tab).

The newly designed "Sketch" tab interface received better scores in all the elements—Agreeable (Z = -2.389, p = 0.017), Understandable (Z = -3.272, p ≤ 0.001), Status Visibility (Z = -2.539, p = 0.011), In/Out sketch (Z = -2.877, p = 0.004), and Icon location (Z = -2.495, p = 0.013)—except one, Consistent (Z = -1.667, p = 0.096). In fact, the similarity of the perception about the consistency between icons is legitimate; for the "Sketch" tab, the icons were not changed; they were just highlighted together with their command manager toolbar. For the "Solid" tab interface, all the elements—Agreeable (Z = -3.739, p < 0.001), Understandable (Z = -3.624, p = < 0.001), Consistent (Z = -3.314, p < 0.001), Status Visibility (Z = -2.812, p ≤ 0.005), Distinction (Z = -3.816, p < 0.001), Finding functions (Z = -3.508, p < 0.001), Layout (Z = -3.589, p < 0.001), Icon signification (Z = -2.762, p = 0.006), and Text comprehension (Z = -2.887, p = 0.004)—are validated for improvement. The icon enhancement by grouping and recoloring brings out the best perception, even though the shapes themselves were not changed. Furthermore, the accompanying text is important for beginners who seek a command by reading the text. For even the more experienced users, adjusting and reordering the text in the "Solid" tab can prove advantageous. However, some semiotic problems remain, for example, the significance of "Révolution" for French and the "Revolved cut" icon appearing like "Camembert." In any case, the perceived "Solid" tab's text, size, and contrast understandability confirm the improvement. The overall improvement for new interfaces is supported by the usability perception questionnaire.

5 KEY FINDINGS AND DISCUSSIONS

Figure 17 presents an overall view of the framework and provides detailed insights into its contents. A detailed summary of the methods used can be found in Appendix E. The implementation of the framework began with Stage 1, which focused on analyzing users within the context of their CAD interface usage to identify specific requirements. Stage 2 involved developing solutions that incorporated GUI principles and configurations for ranking purposes. In the final stage, the solutions were tested and evaluated, leading to the proposal of a new CAD GUI.

These three stages are iterated until a suitable proposal is reached. This framework generated interface design rules for CAD (Table 9). The results answered the two research questions: "RQ1 - What kinds of difficulties do beginners most commonly encounter when they use parametric CAD tools and why?" and "RQ2 - Which interface design rules can help beginners improve their comprehension of the parametric CAD tool interface?".

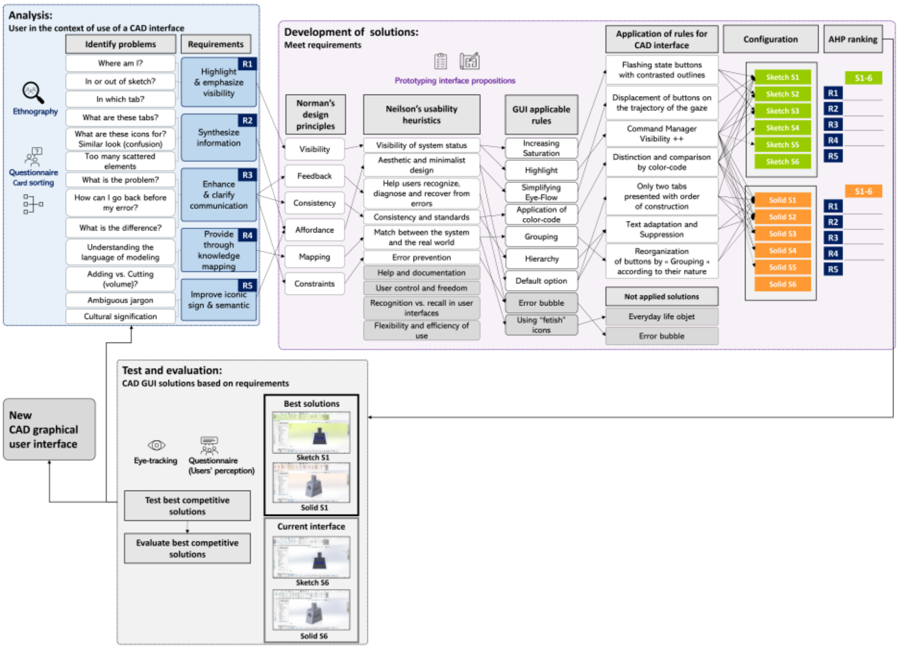

Figure 17: Detail contents of three-stage design framework: [Stage 1] Analysis resulting in requirements (R1=Requirement 1, R2=Requirement 2, R3=Requirement 3, R4=Requirement 4, R5=Requirement 5); [Stage 2] Development of solutions from Graphical User Interface Design (GUID) to configuration; [Stage 3] Testing and evaluation for the identification of the most competitive solutions.

CAD Interface key factor	*Graphical Interface Design rules*	*Applicable example*
Contrast & color code	To use a noticeable contrast	Improvement of visibility by contrast of "exit sketch icons"
	To enhance the "command manager" (main operation toolbar)	Highlight and outline the present tab with a color code
	To indicate clearly and permanently the user's location	Current item blinks when the user is inactive
		Background color indicator (Coherence with defined color code)
Default option (The simpler presetting the better)	To display minimum setting tabs	Only two tabs setting for beginners ("Sketch" tab & "Solid" tab)
	To cluster same nature functions	Grouping the same functions together
	To design for concise eye-flow	Replacement of "exit sketch icons" on the eye-flow curve
	To hide advanced buttons (basic setup for starting)	Hierarchy by frequency level of use
		The advanced functions do not need to be visible

	To distinguish clearly between icon texts	Shorten the icon texts Same beginnings in the icon texts are not repeated
Minimalism design & clear communication	To avoid unnecessary emphasis of buttons	Clear outlines of command area
	To provide continuous information & feedback	Spontaneous feedback bubbles when an error occurs
	To offer fail-safe design	Visual and/or sound warning
	To help and recall with a potential solution	Not only alert but also give a tip to solve the problem
	To enhance the possibility to recover the error	Easy and powerful ability to go back using “undo” button Rebuild button replacement
Semiological study (icons & texts)	To apply a distinctive style form	Distinguishing line styles & color applications
	To use distinguishing commands and texts	Dimension vs. measure
	To consider the cultural context To adapt cultural vocabulary and icons	Consider meaning of "révolution" in French
Consistency		Rethink some icons
	To enhance mental mapping	Present the tabs in order of chronological construction logic
Uncertainty avoidance	To have consistency in visual representation	To watch out for using the grey shaded button
	To preview the effect	Animated preview

Table 9: CAD interface design rules.

Firstly, the results suggest that the visibility of the user's status is not obvious. Indeed, users were generally unaware of their location within the system, resulting in diminished awareness of their current status. According to Lee et al. [36], the user’s status should be clearly visible and not hidden under several layers of hierarchy. This issue was addressed by applying Nielsen’s first heuristic, called "Visibility of system status." This heuristic suggests that a system should always keep users informed about what is occurring through appropriate feedback within a reasonable amount of time. In other words, the system should clearly communicate to users its current status and progress, providing feedback on user actions and system responses in a timely manner. Applying a highlighted color to the command manager and using the same hue for the background allows for a clear indication of the user's status through color coding. This interface improvement seemed to suit beginners. Secondly, the results showed that too much information leads to confusion. Indeed, users were perturbed by the complexity of the CAD UI, with its hundreds of commands and thousands of sub-commands or options. Some users even used the word "panic" to express their perception of the CAD UI. According to Lee et al. [36], the design of CAD tools has become overly complex, resulting in a cognitive load on users that is beyond their capacity to handle. This issue was addressed by applying Nielsen’s eighth heuristic, called “Minimalism design.” This heuristic proposes to keep the design simple and minimalist, which enables users to focus on essential elements and tasks, making the interface more usable and effective. By reducing the number of tabs to two and removing some icons, the layout becomes clean and uncluttered with clear and concise visual elements. The results indicate that the confusion between different elements of the UI, such as icons, menus, cursor, and lines, can be a significant problem for beginners. Indeed, beginners often lack a global vision of the CAD interface, making it difficult for them to understand the various actions available. This confusion often arises due to the lack of clear cues in the CAD UI. Consequently, users are forced to spend more time and effort searching for the right action, leading to frustration and poor UX. Moreover, the results also indicate that beginners are strongly oriented toward icon forms and tend to rely heavily on them to estimate the consequences of an action. As a result, icon appearance plays a critical role in orienting users' perceptions; any confusion or misinterpretation of the icons can lead to significant usability issues. Therefore, this issue was addressed by applying Nielsen's fourth heuristic, called "Consistency and standards." This heuristic proposes that the UI should follow consistent standards and conventions, that is, internally within the application and externally with other similar applications. This means that the UI should behave in a predictable and familiar way, based on established standards and practices. Users should be able to use their prior knowledge and experience to navigate through the interface; they should not have to relearn how to perform basic tasks. Grouping icons and using a new hierarchical organization for them, provides clear cues and minimizes confusion. These results are in line with Szewczyk [57], who states that beginners would like to have all tools arranged in one managing tool with all editing tools grouped. Such a consistent order would prevent users from making many mistakes caused by confusion of icons.

6 CONCLUSIONS

In this research, we have presented a comprehensive framework for developing a new CAD interface specifically tailored for beginners' needs in the field. By integrating insights from UX research and applying user-centric design principles, we aimed to create an intuitive and user-friendly CAD interface that simplifies design tasks and enhances the learning experience for beginners. This framework holds great potential in empowering individuals entering the field with a powerful tool that promotes usability and proficiency in CAD systems. Our proposed design framework has proven to be effective in assessing beginners' UX and identifying areas for improvement in the interface design of the SolidWorks CAD tool. Through the use of questionnaires, card-sorting techniques, and eye-tracking experiments, we gained valuable insights into users' perceptions, preferences for design elements, and interaction patterns. By following our design framework, CAD tool designers can obtain data-driven insights to enhance the interface design and overall UX of their CAD tools. Furthermore, this study has implications for CAD trainers, enabling them to identify and anticipate challenges faced by beginners and improve CAD education accordingly. It is worth noting that if CAD tool designers intend to target a wider audience, they must consider simplifying their interfaces. However, it is important to acknowledge the limitations of our research. We tested only two interfaces; future investigations could explore additional interface combinations. Future research endeavors could also focus on developing a pre-set plug-in that allows users to switch between different interfaces, thereby enhancing their tool understanding and overall performance. Overall, this research contributes to the field by offering a comprehensive framework, insights from UX research, and practical implications for designing CAD interfaces that cater to beginners' needs.

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