DeReFrame: A design-research framework to study game mechanics and game aesthetics in an engineering design process

Zoe Kosmadoudi

Submitted for the degree of Doctor of Philosophy

Heriot-Watt University

Engineering & Physical Sciences/EPS

April 2019

ABSTRACT

The main aim of this research is to study gaming techniques and elements that may potentially be beneficial to the future development of CAD systems for engineering design, in particular to maintain cognitive engagement. A design-research framework, called DeReFrame, was employed to construct an experimental game-based CAD framework exploring this. This research is based on reviews from the literature and experimental studies and include quantitative and qualitative data analysis methods measuring engineers' performance and emotional responses.

The thesis presents the construction process of the framework (DeReframe) to study a set of game mechanics and game aesthetics in an engineering design process and compare this with the traditional CAD. The framework was used to design and implement a game-based CAD system, called ICAD which was embedded with the following game mechanics of Directional Goals, Progression, Performance-Feedback and Rewards-Achievement.

The DeReFrame and ICAD evolved through the experimental studies. In each case, selected game mechanics were at the core of each interaction and iteration which gave rise to feelings of progress, competence and mastery. The final results from the DeReFrame framework and ICAD indicated that gamified approaches should be included in engineering design with CAD: in particular the game mechanics of performance-feedback and rewards-achievements influence engineers' behaviour by supporting them within the problem-solving process creating an engaging-challenging interaction.

In conclusion, this research has shown that a framework, that includes both engineering requirements and gamified aspects into consideration, cam serve as a basis for implementing game-based CAD to facilitate performance by providing engaging experiences for engineers.

DEDICATION

To my partner for his encouragement and patience.

Research Thesis Submission

Name*:*	ZOE KOSMADOUDI		
School:	Engineering & Physical Sciences/EPS		
Version: *(i.e. First, Resubmission, Final)*	Resubmission	Degree Sought:	Doctor of Philosophy

Declaration

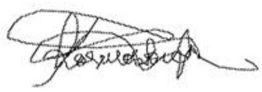
In accordance with the appropriate regulations I hereby submit my thesis and I declare that:

1. The thesis embodies the results of my own work and has been composed by myself
2. Where appropriate, I have made acknowledgement of the work of others
3. Where the thesis contains published outputs under Regulation 6 (9.1.2) these are accompanied by a critical review which accurately describes my contribution to the research and, for multi-author outputs, a signed declaration indicating the contribution of each author (complete Inclusion of Published Works Form – see below)
4. The thesis is the correct version for submission and is the same version as any electronic versions submitted*.
5. My thesis for the award referred to, deposited in the Heriot-Watt University Library, should be made available for loan or photocopying and be available via the Institutional Repository, subject to such conditions as the Librarian may require
6. I understand that as a student of the University I am required to abide by the Regulations of the University and to conform to its discipline.
7. Inclusion of published outputs under Regulation 6 (9.1.2) shall not constitute plagiarism.
8. I confirm that the thesis has been verified against plagiarism via an approved plagiarism detection application e.g. Turnitin.

* *Please note that it is the responsibility of the candidate to ensure that the correct version of the thesis is submitted.*

Signature of Candidate*:*		Date:	26/04/2019

Submission

Submitted By *(name in capitals):*	ZOE KOSMADOUDI
Signature of Individual Submitting:	
Date Submitted:	26/04/2019

For Completion in the Student Service Centre (SSC)

Received in the SSC by *(name in capitals):*	

1.1 Method of Submission *(Handed in to SSC; posted through internal/external mail):*			
1.2 E-thesis Submitted (**mandatory for final theses)**			
Signature:		Date:	

Inclusion of Published Works

Declaration

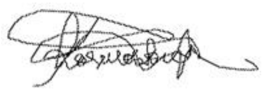
This thesis contains one or more multi-author published works. In accordance with Regulation 6 (9.1.2) I hereby declare that the contributions of each author to these publications is as follows:

Citation details	Z. Kosmadoudi, R. Pooley, T. Lim, J. Ritchie, R. Sung, 'Information System Methodologies in Game Industries', in International Simulation and Gaming Association, Singapore, 2008
Z. Kosmadoudi	Designed and directed the project.
R. Pooley	Supervised findings.
T. Lim, J. Ritchie, R. Sung	Provided feedback on manuscript.
Signature:	
Date:	26/04/2019

Citation details	Z. Kosmadoudi, T. Lim, J. Ritchie, Y. Liu, and R. Sung, 'Evaluating User Interfaces for Engineering Tasks with Biometric Logging', in TMCE, Ancona, Italy, 2010
Z. Kosmadoudi	Design and performed the experiments. Analysed and presented data. Wrote manuscript.
T. Lim, J. Ritchie	Encouraged to investigate BAMZOOKi and supervised findings
Y. Liu, and R.Sung	Provided feedback on manuscript.
Signature:	
Date:	26/04/2019

Citation details	Z. Kosmadoudi, T. Lim, J.M. Ritchie, R. Sung, Y. Liu, I.A. Stănescu, A. Ştefan, 'Game Interactivity in CAD as Productive Systems', in Computer Science, vol. 15, pp. 285-288, 2012
Z. Kosmadoudi	Developed and presented theory. Wrote manuscript.
T. Lim, J.M. Ritchie	Supervised findings.
I.A. Stănescu	Consulted and inputted on the Serious Games concept interwoven within game interactivity
R. Sung, Y. Liu, A. Ştefan	Provided feedback on manuscript.
Signature:	
Date:	26/04/2019

Citation details **(Computer-Aided Design Journal Top 5 Most Downloaded Articles in 2013)**	Z. Kosmadoudi, T.Lim, J. Ritchie, S. Louchart, Y. Liu, R. Sung, 'Engineering design using game-enhanced CAD: The potential to augment the user experience with game elements', *Computer-Aided Design*, vol. 45, no. 3, pp. 777-795 March 2013
Z. Kosmadoudi	Conceived and presented the idea. Wrote manuscript.
T. Lim, J.M. Ritchie	Supervised findings.
S. Louchart, Y. Liu, R. Sung	Provided feedback on manuscript.
Signature:	
Date:	26/04/2019

Citation details	Y. Liu, Z. Kosmadoudi, R. Sung , T. Lim, S. Louchart , J. Ritchie, 'Capture User Emotions during Computer- Aided Design' in *IDMME - Virtual Concept*, Bordeaux, France, 2010
Y. Liu	Developed the theoretical formalism, performed the analytic calculations and numerical simulations. Wrote manuscript.
Z. Kosmadoudi, Y. Liu	Design and carried out the experiments. Both authors discussed and results and commented on the manuscript.
R. Sung , T. Lim, S. Louchart , J. Ritchie	Supervised findings.
Signature:	
Date:	26/04/2019

Citation details	Z. Kosmadoudi, T. Lim, J. Ritchie, Y. Liu, and R. Sung, ‘Game AI architecture for teaching the engineering design process’, in eLearning and Software for Education, Bucharest, Romania, 2013, pp. 48–54
Z. Kosmadoudi	Designed the conceptual idea and wrote the manuscript.
T. Lim, J. Ritchie	Supervised and advised on structure and direction.
Y. Liu, and R. Sung	Provided feedback on manuscript.
Signature:	
Date:	26/04/2019

Citation details	Z. Kosmadoudi, T. Lim, J. Ritchie, Y. Liu, R. Sung, J. Baalsrud Hauge, S. Garbaya, Robert E. Wendrich, I.A. Stanescu, ‘Harmonizing interoperability - Emergent serious gaming in playful stochastic CAD environments’, in F*irst International Conference on Games and Learning Alliance (GALA 2013)*, Paris, France, 2013
Z. Kosmadoudi	Designed the conceptual idea and wrote the manuscript.
T. Lim, J. Ritchie	Supervised and advised on structure and direction.
Y. Liu, R. Sung, J. Baalsrud Hauge, S. Garbaya, Robert E. Wendrich, I.A. Stanescu	Provided feedback on manuscript.
Signature:	
Date:	26/04/2019

Citation details	A. Sivanathan, T. Lim, J. Ritchie, R. Sung, Z. Kosmadoudi, Y. Liu, ‘The application of ubiquitous multimodal synchronous data capture in CAD’, *Computer-Aided Design*, Available online 11 October 2013
A. Sivanathan	Designed the model and computational framework and analysed data.
T. Lim, J. Ritchie, R. Sung	Supervised findings.
Z. Kosmadoudi, Y. Liu	Helped on carried out experiments to gather data for the evaluation of the model.
Signature:	

Date:	26/04/2019

Citation details	Y. Liu, J. Ritchie, T. Lim, Z. Kosmadoudi, A. Sivanathan, R. Sung, ‘A fuzzy psycho-physiological approach to enable the understanding of an engineer’s affect status during CAD activities’, *Computer-Aided Design*, vol. 54, pp. 19-38, 2014
Y. Liu	Developed the theoretical formalism, performed the analytic calculations and numerical simulations. Wrote manuscript.
Z. Kosmadoudi, Y. Liu	Design and carried out the experiments. Both authors discussed and results and commented on the manuscript.
J. Ritchie, T. Lim, A. Sivanathan, R.Sung	Supervised findings.
Signature:	
Date:	26/04/2019

Citation details	Z. Kosmadoudi, T. Lim, J.M. Ritchie, R.Sung, Y. Liu, ‘Analytic models in game based productive systems’, in *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, New York, USA, 2014
Z. Kosmadoudi	Conceived and presented the idea. Wrote manuscript.
T. Lim, J.M. Ritchie, R. Sung, Y. Liu	Provided feedback on manuscript.
Signature:	
Date:	26/04/2019

Citation details	J. Ritchie, T. Lim, R. Sung, A. Sivanathan, C. Fletcher, Y. Liu, Z. Kosmadoudi, G. Gonzalez, H. Medellin, ‘Knowledge capture in virtual reality and beyond’ in ‘Advances in computers and information in engineering research - Volume 1’ ASME, New York, USA, v1, pp531-555. ISBN: 978-0-7918-6032-8, 2014
J. Ritchie, T. Lim, R. Sung	Designed and directed the project.
A. Sivanathan, C. Fletcher, Y. Liu, Z. Kosmadoudi, G. Gonzalez	Provided feedback on manuscript.
Signature:	
Date:	26/04/2019

TABLE OF CONTENTS

LISTS OF FIGURES

LISTS OF TABLES

LIST OF PUBLICATIONS

Z. Kosmadoudi, R. Pooley, T. Lim, J. Ritchie, R. Sung, 'Information System Methodologies in Game Industries', in International Simulation and Gaming Association, Singapore, 2008

Z. Kosmadoudi, T. Lim, J. Ritchie, Y. Liu, and R. C. W. Sung, 'Evaluating User Interfaces for Engineering Tasks with Biometric Logging', in TMCE, Ancona, Italy, 2010

Z. Kosmadoudi, T. Lim, J.M. Ritchie, R.C.W. Sung, Y. Liu, I.A. Stănescu, A. Ştefan, 'Game Interactivity in CAD as Productive Systems', in Computer Science, vol. 15, pp. 285-288, 2012

Z. Kosmadoudi, T.Lim, J. Ritchie, S. Louchart, Y. Liu, R. Sung, 'Engineering design using game-enhanced CAD: The potential to augment the user experience with game elements', *Computer-Aided Design*, vol. 45, no. 3, pp. 777-795 March 2013 (**Computer-Aided Design Journal Top 5 Most Downloaded Articles in 2013**)

Y. Liu, Z. Kosmadoudi, R. C. W. Sung , T. Lim, S. Louchart , J. Ritchie, 'Capture User Emotions during Computer- Aided Design' in *IDMME - Virtual Concept*, Bordeaux, France, 2010

Z. Kosmadoudi, T. Lim, J. Ritchie, Y. Liu, and R. C. W. Sung, 'Game AI architecture for teaching the engineering design process', in eLearning and Software for Education, Bucharest, Romania, 2013, pp. 48–54

Z. Kosmadoudi, T. Lim, J. Ritchie, Y. Liu, R. Sung, J. Baalsrud Hauge, S. Garbaya, Robert E. Wendrich, I.A. Stanescu, 'Harmonizing interoperability - Emergent serious gaming in playful stochastic CAD environments', in F*irst International Conference on Games and Learning Alliance (GALA 2013)*, Paris, France, 2013

A. Sivanathan, T. Lim, J. Ritchie, R. Sung, Z. Kosmadoudi, Y. Liu, 'The application of ubiquitous multimodal synchronous data capture in CAD', *Computer-Aided Design*, Available online 11 October 2013

Y. Liu, J.M. Ritchie, T. Lim, Z. Kosmadoudi, A. Sivanathan, R.C.W. Sung, 'A fuzzy psycho-physiological approach to enable the understanding of an engineer's affect status during CAD activities', *Computer-Aided Design*, vol. 54, pp. 19-38, 2014

Z. Kosmadoudi, T. Lim, J.M. Ritchie, R.C.W. Sung, Y. Liu, 'Analytic models in game based productive systems', in *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, New York, USA, 2014

JM. Ritchie, T. Lim, R. Sung, A. Sivanathan, C. Fletcher, Y. Liu, Z. Kosmadoudi, G. Gonzalez, H. Medellin, 'Knowledge capture in virtual reality and beyond' in 'Advances in computers and information in engineering research - Volume 1' (Eds: Michopoulos JG, Paredis CJJ, Rosen DW, Vance JM) ASME, New York, USA, v1, pp531-555. ISBN: 978-0-7918-6032-8, 2014.

NOMENCLATURE

AI	*Artificial Intelligence*
CAD	*Computer Aided Design*
CADG	*Game-based CAD*
CADGnoGOAP	*Game-based CAD no GOAP*
CADT	*Traditional CAD*
Calc	*Calculations*
EEG	Electroencephalogram
FLOs	*Function Levels Operators*
GOAP	*Goal Oriented Action Planning*
GOMS	*Goals, Operators, Methods, and Selection rules*
GSR	Galvanic Skin Response
HR	Heart Rate
ID	*Interaction Design*
L1	*Level 1*
L2	*Level 2*
RO	*Research Objectives*
RQ	*Research Questions*
SGs	*Serious Games*
UE	*User Engagement*
UX	*User Experience*

Chapter 1: Introduction

Today, gaming extends beyond its initial boundary of entertainment and is now associated with the process of problem solving while providing the analytical questioning of scientific viewpoints through active gameplay. Many studies have investigated games for their positive impact on domains other than entertainment: educators [1],[2], medical scientists [3], [4] and many others [5],[6],[7] have explored the potential of gaming methods and technologies within their disciplines for a more effective, immersive and engaging learning/training.

In fact, games have created a new domain in the context of learning: Serious Games (SG) have proven to help in the development of different skills ranging from analytical and spatial skills, to strategic skills and insight to visual selective attention [8] . Further potential benefits of games include, improved self-monitoring, problem recognition and problem solving and decision making [8], [9], [10]. More specific impacts have been reposted by [11] indicating increased student confidence and abilities in spatial modelling, design composition, and form creation while exposed to three-dimensional perception experience of computer's gaming.

As with Serious Games and digital gaming, advances in computer aided design (CAD) systems have seen the introduction of hardware devices, simulation and visualisation tools to improve interactivity and the understanding of the elements of the design [12], [13]. Nowadays CAD is no longer only about providing an environment for the designer to accurately construct geometry but one that has many added functionalities so that it can assume a multi-functional engineering environment incorporating analytical and computer aided manufacturing capabilities, allowing engineers to carry out multiple tasks. Unfortunately, the interaction between the engineer and current CAD systems is not without problems. The functionality offered by CAD systems in the engineering design process has come at a cost; the tools have become highly complex, requiring cyclical operations even for simple actions, making them cumbersome and difficult to work with and thus having a substantial negative impact on the design experience of the engineer.

The main aim of this thesis is to investigate the role of game-based approaches for engineering design process with CAD via a novel research framework. This endeavour is significant because engineering design research is shy of frameworks that successfully integrate gaming elements. In game-based systems, this is due to the fact that most engineering game-based solutions that provide guided instruction training typically do not support real engineering problem-solving activities. However, a major flaw in the research of game-based engineering is the lack of a design-research framework to support the evolution of design-based engineering activities. Thus, in this thesis, a design-research framework has been constructed that forms the theoretical basis for investigating game-based CAD and comparing it with other CAD approaches.

1.2 Motivation

Despite the benefits of the high-level functionality and specialization of CAD, engineers' interactions and the associated user experience (UX) seems to have been compromised (Chapter 2). This is one of the key motivations of this thesis: to understand why and to investigate an implementation of a new design-research framework to enrich the engineering design process in CAD to improve engineering interaction and the UX. The majority of current CAD systems focus on partial design automation through modules and functions, increasing the complexity of those systems. This results in poor usability, which further extends to poor user-system interaction. This is a key issue for modern CAD as the interaction of the engineers with these systems requires both motivation and effort to use.

Inspiration for this thesis was taken from the field of play, games and CAD. It is intended that game approaches can benefit the engineering design process by allowing engineers to experience a better interaction while reducing design lead times and promoting decision-making.

1.3 Research Aims, Questions and Objectives

1.3.1 Research Aim

The aim of this research is to determine if game mechanics embedded in CAD systems will improve an engineer's performance and emotional response during the design process. This work focuses on the parametric design of mechanical components using selected games mechanics. Engineering design goals are driven by the engineering design task supported by game mechanics integrated within the CAD.

1.3.2 Research Questions (RQ)

To address this, aim the following research questions were developed:

1. What are the key differences between CAD and game system interfaces and functionality?
2. Can an experimental framework be put in place to compare game and non-game-based CAD systems?
3. What are the key metrics, that can be used to measure an engineer's response to a game-based CAD interface?
4. Do game mechanics affect an engineer's CAD performance and design strategy?
5. Do game mechanics affect an engineer's emotional response?

1.3.3 Research Objectives (RO)

To answer the research questions (RQ) the following research objectives were set:

1. To investigate the CAD and gaming literature to compare key CAD and game systems design, interfaces, and operation.
2. To identify key metrics to measure a user's experience in operating, productive computer-based systems such as CAD systems and games.
3. To design and implement a framework for engineering design-based CAD trials, using a selection of game mechanics so that the latter's impact can be readily identified.
4. To identify and select key methods for the objective and subjective evaluation of an engineer's user experience in relation to identified performance and emotional metrics.

1.4 Overall Research Approach

To answer the research questions, the research process follows three main cycles (as seen also in Figure 1):

Literature review: Research current literature on engineering design with CAD to identify deficiencies, gaps and limitations and explore the opportunities of gaming approaches with which to address these.

Explorative study: Introduce a short experiment to compare conventional CAD system and a game-based CAD system embedded with game mechanics and review the experimental approach and psycho-physiological analysis methods as means of measuring the impact of game mechanics (if any) on an engineer's user experience while working on an engineering design task.

Experimental designs: Initiate the design circles of development, evaluation and iteration of game-based CAD based on the experimental findings (see Figure 1).

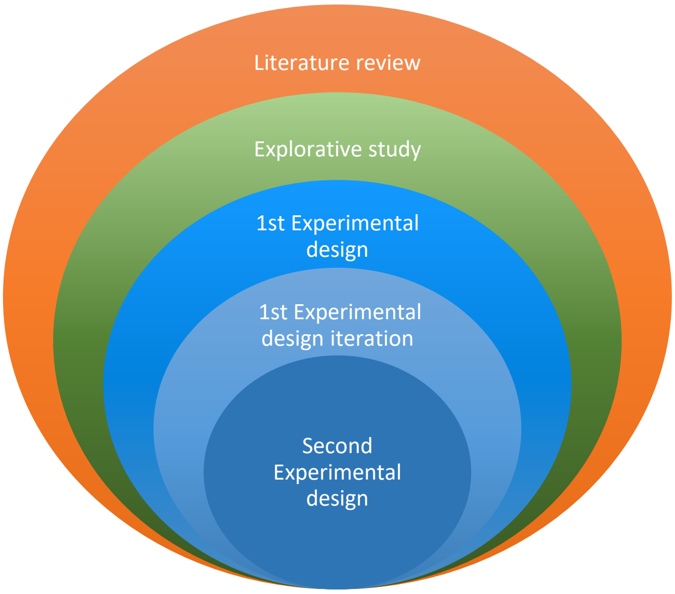


Figure 1 Research approach

1.5 Thesis Structure

CHAPTER 2 provides a review of the CAD functionality and usability problems, followed by an investigation of games and CAD as rule-based systems. The chapter concludes with identifying gaps in current CAD systems design that may be addressed using game-based approaches.

CHAPTER 3 presents the explorative case study on the game approaches for engineering design providing the basis for testing the experimental framework to drive the empirical experiments.

CHAPTER 4 undertakes a description a design-research framework. Interaction metrics are presented along with the design, implementation and analysis of game-based CAD for engineering design.

CHAPTER 5 presents the first experiment study comparing an engineering design task in a game-based CAD system against a traditional CAD system.

CHAPTER 6 presents the first design iteration of the experimental study with the addition of exploring engineers' brain activity within the two comparative systems.

CHAPTER 7 documents the second experimental study with the new improved framework and game-based CAD implementation as well as the study results.

CHAPTER 8 draws together the conclusions, highlights the contribution of the thesis and identifies important future work.

Chapter 2: Computer-Aided Design and Games for Engineering Design

Computer-Aided Design (CAD) spans all areas of product development and while such systems are highly functional they are more often than not very difficult to use [14]. Though CAD has enhanced design processes it has also created a barrier to ease of use due to increasingly complex functionality and the addition of more and more sophisticated features. Many engineers experience difficulty interacting with CAD due to it compromising their creativity and motivational capability [15].

This chapter investigates the opportunities of gaming within engineering design processes. It begins with a brief overview of CAD frameworks, its components, and CAD UX issues. Games are then introduced, and design and engagement mechanisms identified that could be transferred to other serious productive systems such as a CAD. The chapter concludes with gaps in CAD that need addressed, so to support the engineering design process and the opportunities that gaming presents to address these by proposing a game-based CAD. UX measures are also presented to evaluate the potential impact of game-based CAD in engineering design.

2.1 CAD frameworks, parametric design methods and the user experience (UX)

Modern CAD frameworks integrate a number of software components [16] along with a collection of mechanisms at many different levels of abstraction [17] from model definition through to user interaction and simulation. The CAD framework developed by Harrison [18] in the 90s and, later, the JESSI (Joint European Submicron Silicon Initiative) Common Framework [19] represent a collection of mechanisms or facilities (programming/extension languages, data management, user interface facilities, etc.) to assist hardware engineers in designing with CAD.

Modern CAD frameworks coordinate design automation through modules and functions that manage data by optimising different types of resources under a single software infrastructure [20]. A key module has been high-level programming languages and its fundamental constructs of data manipulation for parametric design methods. Knowledge-based (expert) parametric design systems such as Myung et al [21] allow configuring mechanical products and assemblies through APIs (application programming interfaces) and the use of intelligent rule elements (IRE) [20]. Other examples include [22],[23],[24].

A general CAD framework (Figure 2) consists of data handling, design management, user interface, tools, design data (access, storage, and configuration) and process management services (application dependencies) or modules [20].

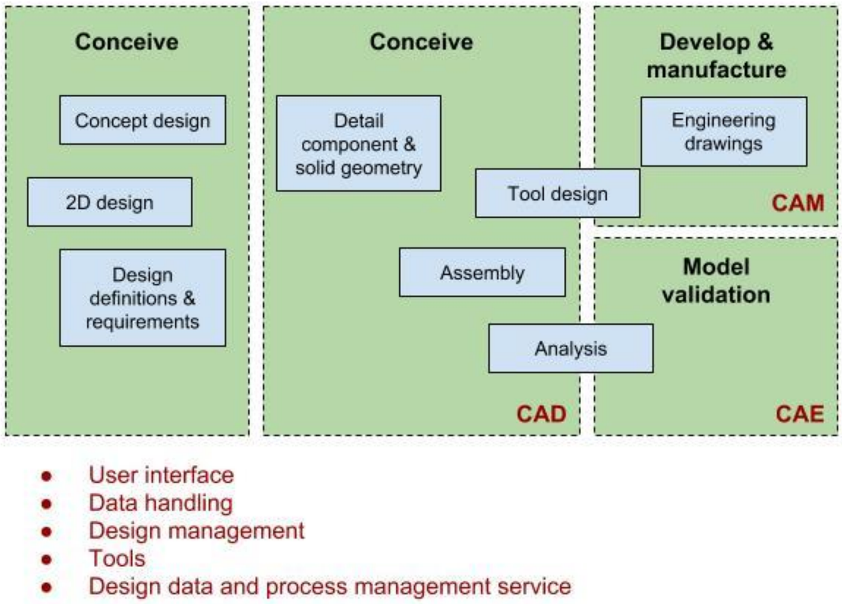


Figure 2 Design processes and CAD framework [20]

Table 1 lists a variety of CAD features used during an engineering design process. While these functions aid the design process, they also increase complexity that further affects both user interaction and UX.

Table 1 Current CAD functionality

Main features	Additional features
• Keeps track of design dependencies • Design figures and curves in 2-D • Design surfaces, curves, and solids in 3-D • View of design from any angle - Rotate • Zoom options for close-up or long-distance views • Simulation • 3D geometry input • Assembly Modelling • Digital Prototyping • Electronic Database • Easy Reproduction • Savings in Cost • Access Control - Secure file handling • Parametric Drawing • Parametric Design • Parametric Programming	• Annotation| Scaling | Rendering | Measuring • Sheet Set Manager (organize your drawings and link sheet set information) | Data logging | Report generation | Data Extraction (output object's property data) | document management | Data translation • Customized user interface | Programming Interfaces • Surfacing tools | Sheet metal design | Plastic parts design | Tube and Pipe design | Cable and Harness design | • Analysis design; structural, vibration, durability, heat, and motion performance analysis | Interface Detection Errors | Help assistance | Tracking tools for geometric information against specification | Intelligent design analysis (run possible scenarios) Automation features; Highlighting and tagging of dimensions, Rapid dimensions, Feature recognition | Assembly memory management | Manufacturing patterns recognition | Automatic tool path generation | • Dynamic Assembly Motion | Physical Simulation | Simulation of nonlinear large deformation, hyper-elasticity, assembly connectivity, friction-added surfaces, temperature, vibration, dust, humidity | pre-defined animation paths • Print 3D models |Knowledge capture / process database | Conceptual design tools | Reverse engineering | Part libraries | Design communication – collaboration capabilities | Synchronous technology | CAM • Welding Application | Mold /Casting Application

Recently, research has been directed towards making CAD more engaging [25] [13]. To better understand how engineers' interact with CAD, background literature studies and stakeholder (engineer) interviews were conducted to identify areas of CAD complexity, the importance of game design elements and user preferences in a game-based CAD context. The following steps were undertaken:

- **Literature review**: Outline the current research on engineering design with CAD and their impact on the user experience of the engineer.
- **Game engineering research**: Establish game analogies between game rules and productive application rules, to provide guidelines for future research.
- **Stakeholder interviews**: Understanding the engineers' relationship with game elements by identifying their preferences within a commercial CAD environment enhanced with an addition of a programmed game-based interface.

2.2 Background research

2.2.1 Literature review

Waern [26] [27] reported that CAD users could not remember all possible alternative methods in a CAD design task and also the difficulty they had in remembering menu items and other necessary design conditions to be applied. The author concluded that users would benefit from the system's feedback during the design modelling process. Cooley (in Parletun et al [28]) suggested that users are tempted to use sub-assemblies from stored drawings instead of spending their cognitive resources dealing with operating the CAD effecting possibly their creative process (focusing on set routines). Luczak et al [29] looked at the efficiency versus system complexity of CAD systems. He studied designers at different manufacturing firms and concluded that, even when they were highly trained, the high complexity of CAD commands, due to the many input parameters, restrictions, and requirements, led to low performance, reduced creativity, friction, and frustration.

Bhavnani et al [30] revealed suboptimal use of CAD systems with the use only of primitive commands. They concluded that the lack of designers' motivation to explore and find more efficient methods and commands for designing was due to repetitive design routines and the system's passive assistance through online help and other information resources. They recommended active assistance (feedback) while the user interacts with the CAD package. Similarly, Stacey et al [31] concluded that designers are pushed into creating designs which the tools make relatively easy to create. They also mentioned that the biasing effects of some CAD systems are due to inadequate human computer interface design.

Petre [32] observed that while CAD systems were sophisticated systems with powerful graphical editors, they did not support the conceptual design phase of a design process. This issue is similarly reported by Sung et al [33]. Lee et al [34] studied 10 state-of-the-art CAD systems and concluded that such design systems have become overly complex with several hundred menu items that cognitively stress the user. They summarized 179 issues and categorized them into seven problem areas, proposing a set of UI principles for 3D parametric modelling applications including, visibility, feedback, graphical richness and assistance. Robertson et al, [35], [36] also supported by Charlesworth's proposition [37], concluded that CAD had little or no value as a stimulus for ideas. Both carried out industrial case studies amassing a survey of 200 CAD practitioners from 32 different countries and found that the negative influences of CAD are premature fixation, circumscribed thinking and bounded ideation.

Four important issues stand out from the literature of current CAD systems:

- Many of the methods and commands used in these systems have not permeated into the designers' design modelling process and often are not used.
- The techniques or design strategies deployed by designers are constrained due to CAD systems being poorly evaluated from any type of cognitive behavioural studies of designers designing or systematic studies of their use.
- The designer's workflow is compromised due to an increased number of menu items embedded within CAD's GUIs making user-system interaction complex and unattractive.

- The designer's motivation to use these systems has been reduced by their own perception of the system's purpose; their lack of understanding of CAD as a tool within the context of the dynamic requirements (goals) of the engineering design process (Figure 3).

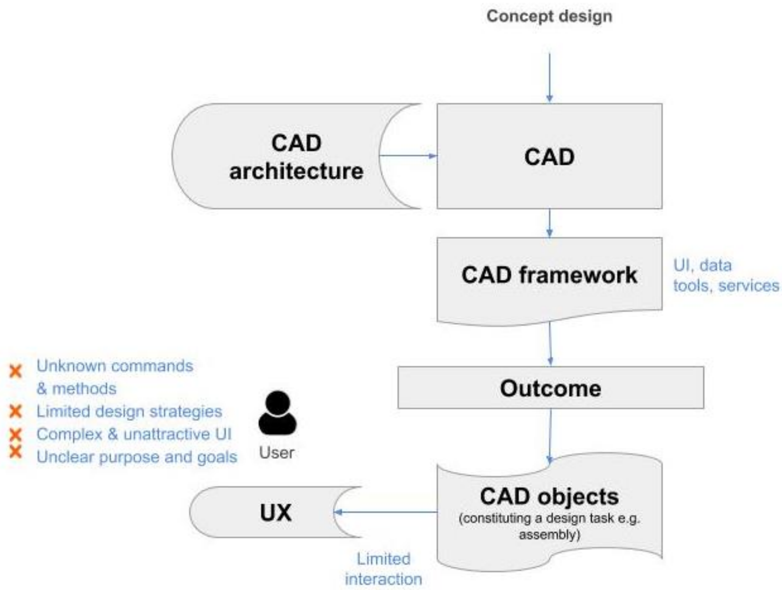


Figure 3 Overview of limited CAD user interaction.

These articles reveal the negative effects of CAD and its implications. An engineering design process involves many creative problem-solving processes and is non-linear; there are iterations across all stages of the design involving high levels of uncertainly. Thus, enhanced feedback and interaction as proposed in this game-based research could have significant benefits for engineers and their design processes.

In summary, advances in CAD systems have come at a cost producing CAD systems that have become too complex to use. Usability studies in engineering design within CAD have revealed a plethora of issues regarding efficiency, usability, motivation, and interaction within these systems (Table 2).

Table 2 Summary of CAD user issues

Research area	Authors
Efficiency limits in CAD	Waern [26] [27], Luczak et al [29], Lee et al [34]
Limited creativity in CAD	Waern [26] [27], Cooley (cited by Parletun et al [14]), Petre [32], Robertson [35], [36], Charlesworth [37]

Lack of user's motivation in CAD (suboptimal use)	Bhavnani et al [30], Charlesworth [37]
Limited interaction	Stacey et al [31]

2.2.2 Gaming for Engineering

The previous sections have identified issues regarding the efficiency, usability, motivation and interaction of users within CAD systems, including several implications to the engineering design process. Although Knowledge Based Engineering (KBE) stands at the crossroad of intelligent design paradigms, the drive to explore alternatives to better user-centric and engaging interaction with CAD would allow for the development of customised systems that can impact positively the user experience (UX) of the engineers and their design process. One growing trend is the use of gaming principles for engineering design processes. Recently, the serious games genre has emerged as a more engaging way within engineering problem-solving [38]. Games allow players to create meaning within the game context, i.e. experience of play, success of the play. A game anticipates players' responses to different situations and uses that to provide a good experience for the players by incorporating a variety of challenges ranging from decision-making and problem solving strategies through to action reflexes [39].

Inevitably, the question arises; can games potentially effect – in a positive way - the engineer's performance and user experience working with engineering design applications, e.g. CAD?

Further understanding is required regarding how games can positively impact on engineering design and the problem-solving process of engineers. For this reason, games and game design are factored into two domains: (i) games as systems and (ii) their interaction with the player and game elements.

All games use rules to determine what players can do and how the game will react. The underlying goal of a game is to generate positive experiences for the players engaged in a gaming activity [40], [41], [42] where interactive play (consisting on what the player does) is also referred to as “gameplay” [43]. Gameplay emerges from the way a game is constructed around internal or external goals [38] (structural qualities of games as ruled-based systems) and supports the psychological aspects of gaming, such as the user experience (UX) which can define a player’s behaviours during the gameplay due to the fact that this evolves from it - gameplay [43].

The nature of game playing is defined by the users’ actions that need to be performed to reach an explicit goal. A failure can provide the basis for a new attempt, while success is acknowledged through feedback on how well the user has done [2], e.g. by providing rewards or indication of progression. Both goals and feedback (failure or achievement) provide an engaging state with the game events accompanied by rich emotions as a result of game play [44]. Games engage users by presenting challenges that invoke emotions [45], [46]. Players are thus motivated to apply exploratory thinking and experimentation to achieve rewards [47]. Players feel “immersed”[48], [49], concentrated [50], in a state of flow [51], in sense of being there [52], inside the game. This engagement process provides users with compelling gameplay [40] leading to engaging interactions (Figure 4).

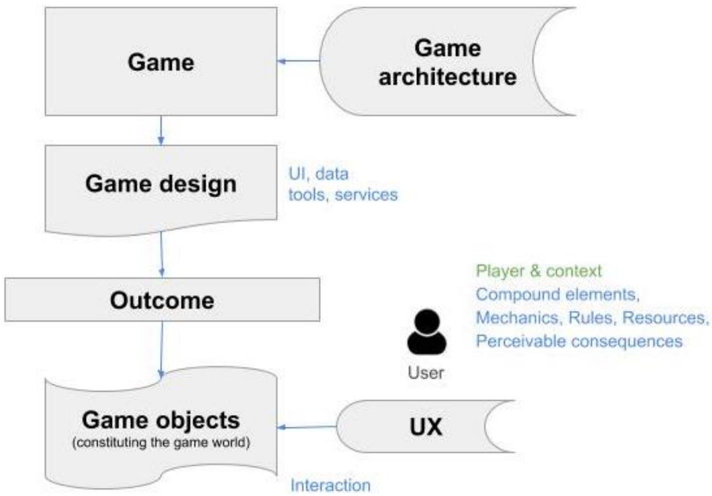


Figure 4 Overview of game systems and the UX

2.2.3 Stakeholder interviews

Implementing game approaches in productive applications such as CAD requires a very specific set of users' goals to be fulfilled to enable the engagement of interaction but in keeping with the professional/productive requirements of the application and allocated design task.

As an early stage in on the theoretical background, five (5) stakeholder interviews were conducted evaluating initial game-based CAD interaction-expectations. These stakeholders were engineers with different levels of experience in CAD design (for stakeholder scheduling details see Appendix E). The purpose of these interviews was to learn about the stakeholders' experience and expectations using a customised (programmed) gamified CAD dialogue / module within a commercial CAD system for parametric design. Specifically, interviewees were presented with a gamified dialogue window within the commercial Siemens NX CAD system [53], and answered questions including the significance on certain game elements within their engineering design process: scoring and rewards, progress bars and design stages/levels and feedback structures (Table 3).

Table 3 Stakeholder interview questions

Interview questions
Where there any game elements you liked to be applied in CAD?
What are your thoughts on the 'visual 'feedback given while working on the task?
Was performance affected with the 'scoring' mechanism?
What are your thoughts on leader-boards in engineering design with CAD?

All stakeholders identified two key themes: feedback and rewards.

Stakeholders expressed that to successfully use game approaches with commercial CAD, the focus should be on the engineers and their activities. In particular, immediate visual feedback must take into consideration the potential distractions it may cause in the long term. Feedback on errors with information describing the problem and possible approach to solve it would be beneficial particularly if integrated in 3D models.

They also offered specific feedback on rewards as a game approach. Rewards were understood to be performance-based or compensation mechanisms. Thus, challenging enough to be defined in the context of the engineering design without them intruding or distracting the more experienced or expert engineers. However, visualizations of step-by-step task completion bars or TO-DO lists during a routine parametric design, could offer a sense of current state and accomplishment/satisfaction.

Given the example of leader-boards, the stakeholders found this mechanism controversial. They suggested that it introduces misguided types of competition into the process and could possibly have a negative impact on the engineer and the team.

Overall, the integration of game elements in the processes of engineering design is unknown territory but is still seen as being of great interest. The assumptions of introducing games in professional/productive software such as CAD will systematically make the design process more engaging by:

- having a way of monitoring their current design process within a routine design
- having a better understanding on design opportunities (feedback) while designing a 3D model

The stakeholder interviews provided an initial view on the users' preferences on interaction with a gamified CAD.

2.3 Game design review

Games are designed to be dependent on the interaction between the player and the game:

- Game goals affect the player's *behaviour* [54].
- Game challenges (conflict) provide meaning to player's *actions* (to reach a game goal) [55].
- Game information provides a means of measuring a player's *decision making* to take strategic actions [56].

Games design frameworks differ from the design of applications such as CAD. Games actively encourage a variety of experiences. There have been a number of studies defining game design frameworks by representing its components, (Figure 5).

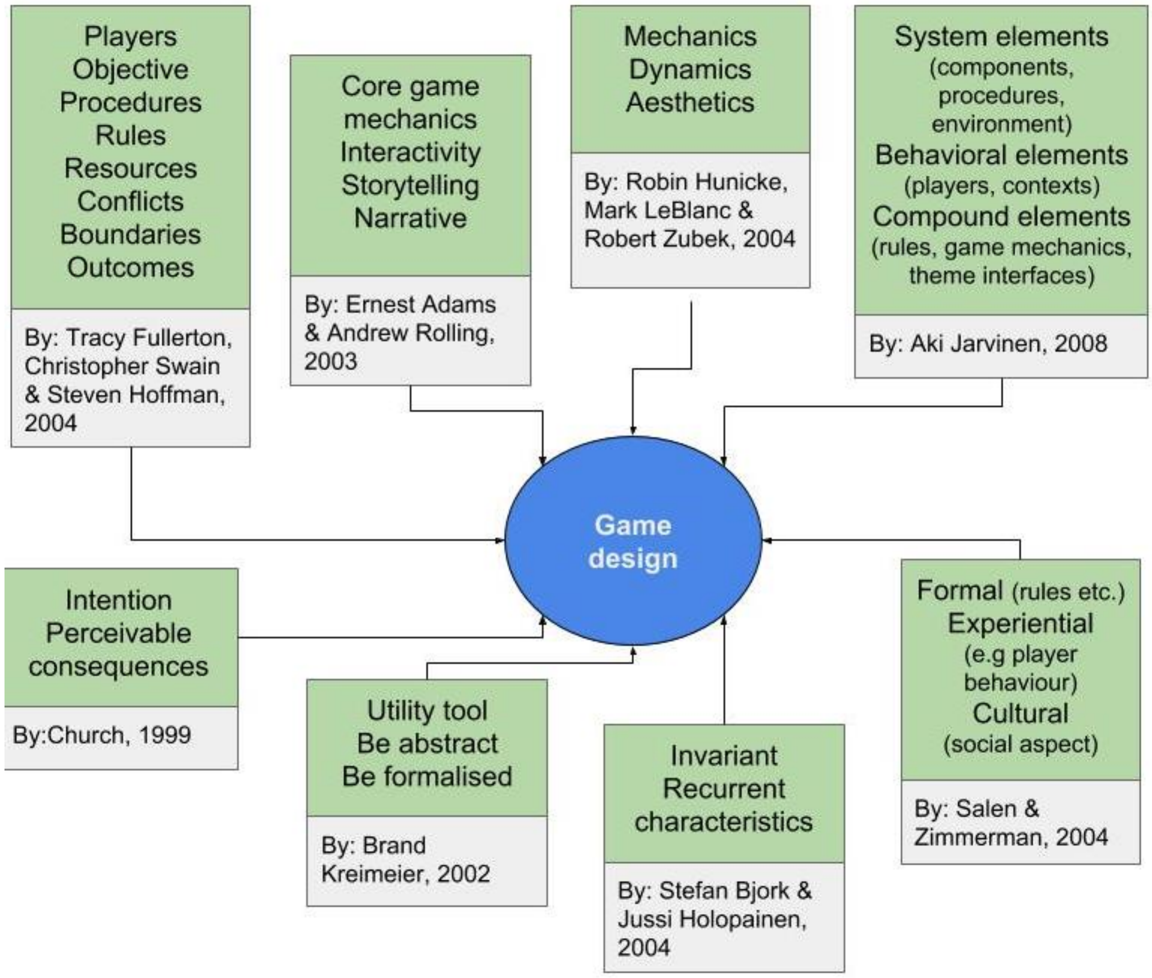


Figure 5 Summaries for the representation of game components by different authors

Game mechanics are the default component in any game design framework and, while often used as a synonym for rules, are usually closer to an implementation.

Game mechanics connect player's actions with the game goals and game challenges (e.g. variable difficulty level) and are part of the design and usability of a game [57]. There are many game mechanic definitions useful for the formal analysis of game systems that open up the possibility of connecting game mechanics to engineering design. In his study Sicart [58], listed various game mechanics definitions based on the formal structure of rules within a game. However, he suggested there is an ontological distinction between rules and mechanics; rules are normative while mechanics are performative [58]. Pulsipher [59] also argued that game rules are not game mechanics, however they include specifications of mechanics and a description of the context of the game: "how" and "what/why?" The author concludes that the mechanics are a result of rules and player actions [59]. Schell in his book "The Art of Game Design" describes the mechanics as abstract game events and rules as how these mechanics function, become manifest [60].

Distilled from the different approaches, Sicart [58] described game mechanics as "*...Methods invoked by agents, designed for interaction with the game state*"; where methods are behaviours, actions and functions, available to the agent (player, or AI of system) within the constraints of a game environment.

Thus, game mechanics can be described as:
"A single set of rules that dictate the outcome of interactions within the system (player's actions). They have an input, a process and an output ".

Some mechanics may be used more in a game than others. Fabricatore [61] briefly distinguishes game mechanics and core mechanics. He defines as core game mechanics the set of activities that the player will undertake more frequently during gameplay [62]. The term core mechanics also has been described as the mechanics that have the biggest impact on gameplay [63], [64]. Core game mechanics usually define the genre of the game, whether it is strategy, role-playing, simulation or action etc., based on gameplay challenges. For example the gameplay challenge of puzzle together with the features of story, player, character, object manipulation and exploration shape the core game mechanic base for the genre of an adventure game [65]. Other game mechanics deal with collecting game resources such as power-ups or coins [63]. Moving and jumping are core mechanics in most games compared to the game mechanic of collecting; however, this can change depending on the aim of the game.

Mechanics have also come to indicate many different types of rules in games are connected with physics engines. A set of different type of game mechanics are those of emergence mechanics [66] where simple rules describe a variation of different game states based on different game objects placements. The game of chess incorporates such a set of mechanics (tactical manoeuvring and economy mechanics) where different sets of movements driven by the player's strategy can change the state of the game from winning to losing or vice versa. Game mechanics can also be types of progression that structure gameplay into manageable levels to introduce player core concepts. Adams and Dormas in their book "Game mechanics: Advance Design" [67] provide examples of game mechanics by relating them to game patterns (Table 4).

Table 4 Sample of game mechanics and their patterns [69]

Game Mechanics		Patterns
Emergence Mechanics	Physics	Detailed physics for movement, shooting, jumping, fighting, simulation, challenges' generation etc.
	Internal Economy	Power-ups, collectables, lives, points, units building-upgrading, risking, units in combat, character and content customization, management resources or player's inventory.
	Tactical Manoeuvring	Units positioning to gain offensive or defensive advantages, tactics, managing resources.
	Social Interaction	Coordinated actions and alliances between players, cooperation-conflict.
Progression Mechanics	Progression	Predesigned levels with increasingly difficult tasks, competitions, missions, tournaments, quests, storyline/scenarios to drive user purpose and goal.

A collection of game mechanics has also been presented in the form of a play deck [68], where the game mechanics have been broken down into their constituent parts; such as “achievements,” “status,” and “virtual items.” Other game mechanics are time driven with gameplay and/or with cooperative player assistance. Few inherit the multiplayer mode incorporating game mechanics of coherence rewarding and collaborating play. Some are based on real-time editing, enabling players in creatively designing their own levels of their game world. Popular with the younger crowds are the game mechanics of procedural character creation, which provides the design and structure of creatures and their structures. Also there are the game mechanics of combat or physics-based building [69].

Recently, AI-based game mechanics have emerged with the ability of customising games and gameplay. Similar to AI-based story generators, AI game mechanics take form based on player’s input and game play events. They use optimization and evolutionary algorithms as tools [38]. One of the most popular of AI-based game mechanic is called Goal Oriented Action Planning (GOAP), originally designed as means of real-time control of autonomous character behaviour in games [70].

One of the most significant areas that games have been applied in a non-game context is Serious Games (SGs). SGs encourage active and critical learning through game environments where users enjoy the process of pursuing challenging tasks, achieving goals by making decisions, formulating strategies, constructing knowledge and trying different alternatives without worrying about the consequences in real life [2]. Moreover these environments involve some aspects of competition [71] where the user tries to influence the final outcome at the same time feeling attached to the outcome [66] [72]. Such behaviour can be described as intrinsic motivation, which has been recognised to be the one of the mechanisms of exploration and curiosity [73].

2.3.1 Critique of game mechanics through game patterns

Game mechanics are the building blocks for game systems. They can be equivalent with game design patterns [129]. In this study game patterns are explored as an extended interpretation of gameplay, which includes game mechanics [74]. Drawn previously from the literature (see sections 2.2.1 – 2.2.3), some of the most common game mechanics of predefined goals, and performance feedback are critiqued through the *game patterns* for their possible integration within an engineering activity and CAD:

- The game pattern of "predefined goals" followed by "levels or sub-goals", describes goals arranged in a hierarchy of levels which all player actions take place until the end conditions (certain goals) have been fulfilled [74]. Predefined goals require explicit boundaries to game states that are considered a success and how players can reach those states. The *perfect or complete information* describes the goals and how to achieve them within a gameplay [74]. The game mechanics derived from here are related to directed goals and progression.

- Performance feedback with score and rewards represent a player's success in the game. *Score* is an abstract value associated with the gameplay and how is played (tactics) [74]. The score be a *status indicator*. The *rewards* influence the player on completing the game; it encourages the players to do certain actions in a game. Rewards provide feedback and give players *perceivable margins* to learn *predictable consequences* and thereby achieve *game mastery* [74] (Figure 6). Game mechanics here are associated to performance feedback and rewards (or achievements).

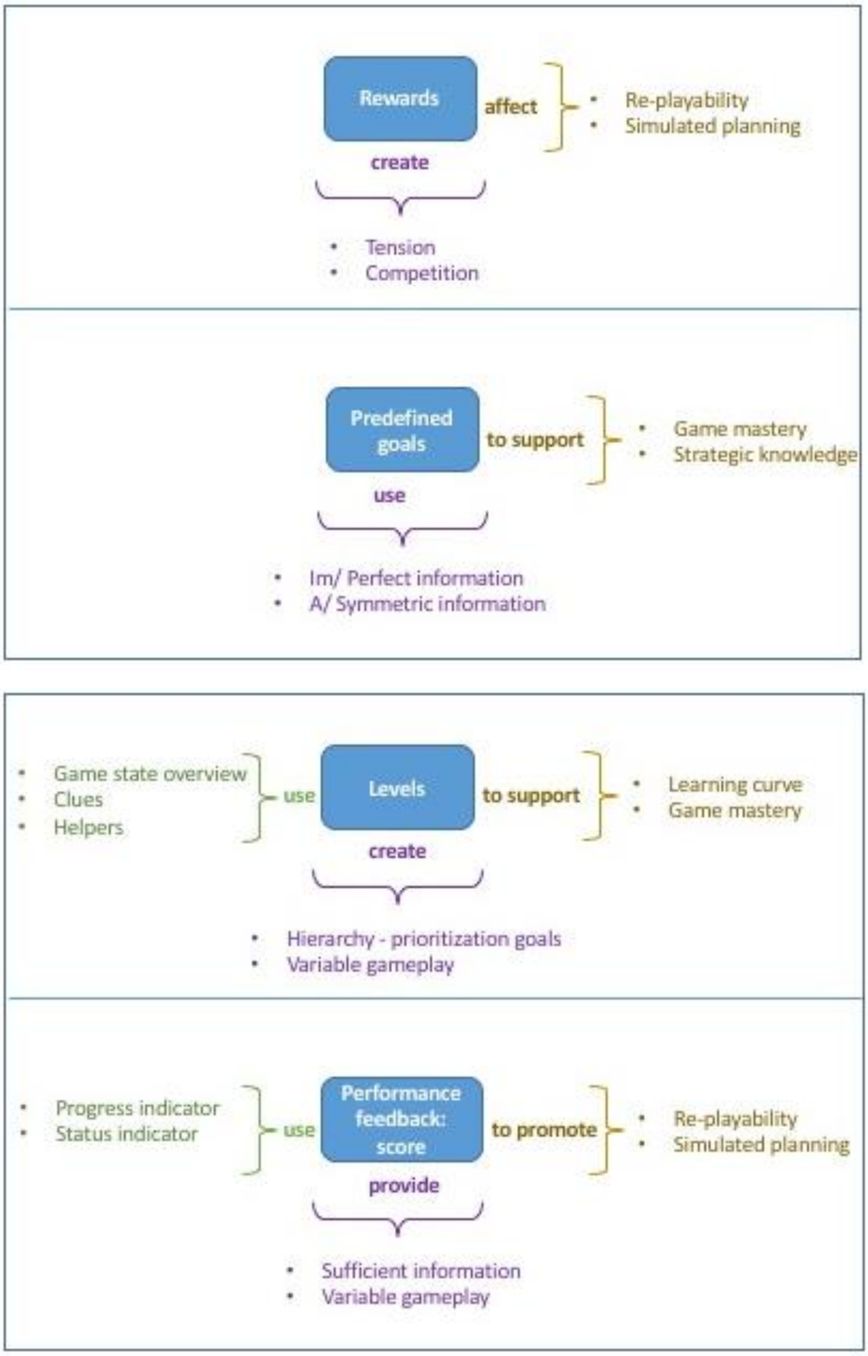


Figure 6 Game Design Pattern approach of Björk and Holopainen [129]

2.3.2 Game aesthetics

Gameplay interactivity is closely coupled to the visual aspects of the game experience, i.e. visual perception. The game component of aesthetics represents the front end of the game play experience and is directly associated with the UX; it is also referred to as the “aesthetic experience” [75]

Game aesthetics assist the mechanics of gameplay through form and content within the game interface. Game aesthetics targets players' goals and their activity within the gameplay as well as maintaining player's attention and engagement [76]. Thus, as an extension of game design, incorporates both the usability of the interface and the aesthetic game elements to immerse player. The usability or functional information enabling the player to understand and perform the activities required to play the game, thus closely connected to the playability of the game [76]. The aesthetics [55] allow the player to pay attention to visual and auditory cues for interpreting the game world and to feel engaged/immersed within it [77]. These types of game UI design elements describe the game's more subjective parts, such as the setting and narrative and are usually conveyed via graphical channels [55].

To transit the boundaries of games in CAD requires that the game mechanics and their pattern (of use) should have an effect on the engineers' experience and performance while working in CAD. It should address issues regarding efficiency, usability, and motivation as well as provide an enriched user interaction and experience. What has been notable from investigating game patterns are the ubiquitous game mechanics related to goals, feedback, progression, status and rewards; these are both directly visible to users and have underlying motivational mechanisms.

2.4 Game components in CAD and Engineering Design

A recent example of game mechanics in CAD is the "gamified" tutorial system of Autodesk, called GamiCAD [78]. GamiCAD uses game mechanics associated with progression such as feedback guidance, progressive disclosure, time pressure and rewards in a guided training task to facilitate learning [78]. The study revealed a "gamified" interactive tutorial system produced faster completion times for each task. Moreover, users mentioned that the gamified condition was more enjoyable, fun, engaging and effective. For future work, the authors suggested incorporating additional game design aspects to facilitate guided instructions and investigate the minimal level of gamification that can affect positively the performance and the learning.

A clever use of game mechanics and game components for CAD is demonstrated in a game called “The Monkey Wrench Conspiracy” (MWC) project by Thinkdesign Company (Figure 7). This first-person shooter style game aims to train design engineers to learn and use the Think3D CAD system [79]. The marketers of Think3D CAD observed young engineers (20-30 years old) working in CAD having difficulty in learning how to operate the environment and they suggested a game approach to reduce the steep learning curve of their system [80]. In the MWC game, the game mechanics of emergence and progression are presented within CAD as design activities of modelling configuration in the form of design quests (Figure 7) to defeat traps. The game’s aim is to engage engineers to move from 2D CAD systems into learning complex 3D CAD while having fun and being able to use Think3D CAD competently [80].

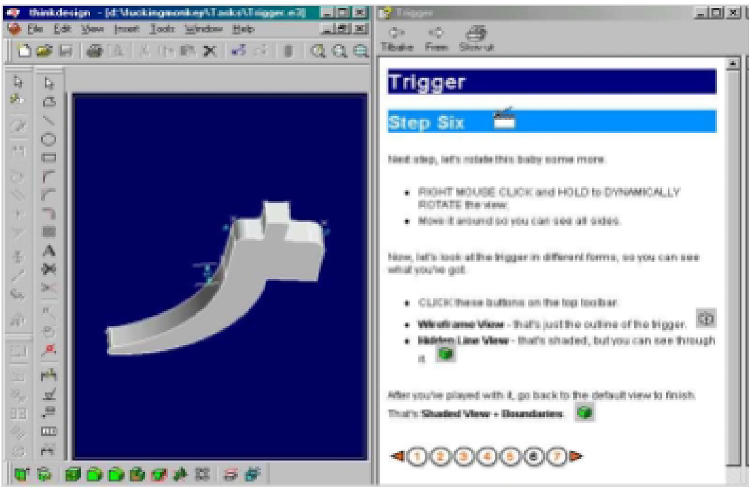


Figure 7 The Monkey Wrench Conspiracy CAD-game interface [119]

The use of game mechanics in engineering design and CAD is still in its infancy; however, there have been a few studies already demonstrating the opportunities of game-based approaches in engineering design process:

Tideman et al. [81], studied product design methods for supporting designers’ design processes. The authors established a design environment combining VR simulation, scenarios and gaming principles for a lane change support system. The gaming principles with scenario modelling allowed for the designer to seamlessly generate designs, provide insights and feel emerged / focused within problem-solving process. The game mechanics prominent in that interaction were associated with progression and feedback.

Game mechanics and game-based approaches in engineering design have a potential to positively impact on engineering domain by presenting engineers with an immediate insight to understanding the design process in a superfluous and engaging way [82]. What remains unclear are how and which game mechanics and game approaches affect engineering systems.

2.5 CAD & Games Systems: Similarities, Differences & Gaps

Identifying similarities between games and CAD systems is not a straightforward process. In games the user may operate a character/avatar which can be dynamic and can respond based on the user's inputs and the level-points (rules) of the system [83]. In CAD, there are different event structures that users have to deal with; however, the system still responds to user's inputs based on its features to support the user's defined task and produce an outcome.

Although CAD and games are very different as productive systems they still share many traits. Lazzaro et al [45] suggested, games and productive systems have features which support tasks, common graphical user interface (GUI) elements such as menus, dialogs, control cursors and text entry supporting goals.

Games are rule-based systems [84] with a variable and quantifiable outcome [66]. There are different outcomes assigned to different values and the user exerts effort to influence the outcome i.e. attachment to the outcome. Playing then becomes accepting and learning from the system-based message embedded in the game. This is how procedural mechanics in games works. The rules of the game provide the different possible outcomes/meanings depending on the user actions/strategies [66].

CAD systems are designed to *accept* user's input with the user defining the rules in contrast to a game system where the *system* is set to *react* in user's inputs based on its (already defined) rules. CAD is comparable to games as abstract rules-based systems. The important difference lies within the interaction and usability between the two systems, which further impacts on the UX of its users [45]. The underlying goal of a game is to generate positive experiences for the players engaged in a gaming activity while in use whereas CAD focuses on the results of the process and particularly on delivering a functional output.

Even though games and CAD are ruled-based systems they have different UX outcomes. UX has to incorporate not just explicit interactivity but meaningful choice, meaning that a player makes a choice in a game and the system responds in some way [85]. CAD users have many functional design tools; however, interaction with the actual design process is limited. In Figure 8 bellow, a visual comparison between CAD and game systems is presented with user experience being limited for CAD, whereas for games being the main driver.

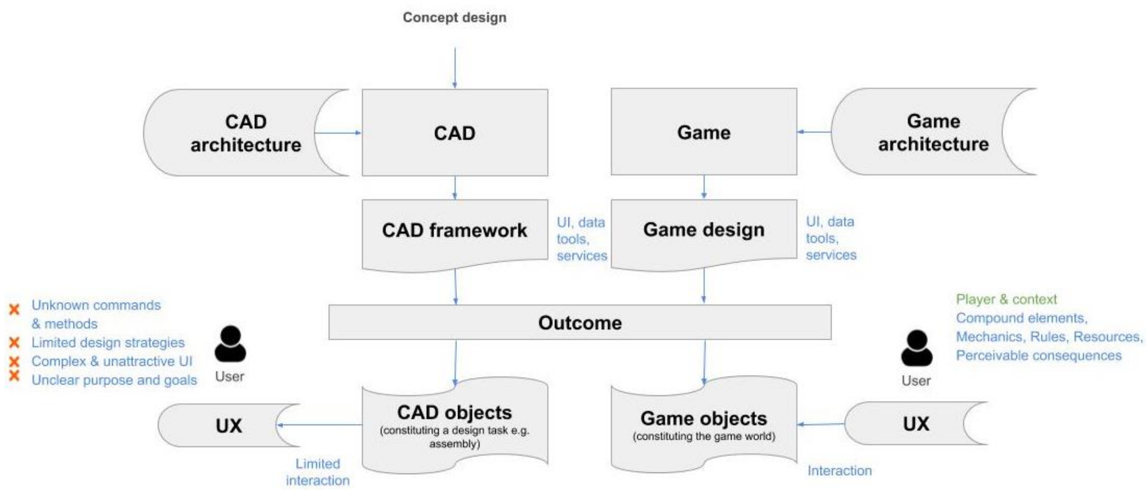


Figure 8 Overview of Games and CAD as rule-based systems

2.5.1 Game opportunities for engineering design with CAD

CAD systems have enabled the communication of design through to analysis. On the other hand, CAD's sophistication has impacted on engineers' design performance, usability and interaction experience. Studies on interaction problems in CAD are plentiful, however, very few suggest how to resolve them. It seems that game approaches have the potential to alleviate interaction issues. Although user experience research in CAD is extremely limited, in game systems it has been the focus since the 1990s when the first game engines were developed. Games are an extremely influential form of computer software and have provided a promising approach to impact different interaction aspects of any system across different domains. The core definition of success for a game is that a person enjoys the game enough to keep playing, rather than it helps a person achieve a task. The game has a crafting and compelling "feel" to it, a moment-by-moment interaction as the system responds to the player; not an end-use experience such as within CAD.

With this in mind, Table 5 summarises the general game patterns [86] and game mechanics obtained via the theoretical background research including the literature review and stakeholder interviews and which can be further investigated for their effect on the UX of the engineers while using CAD. These are compared with the key characteristics found in current CAD systems and highlight the potential for possible "gaming" effects, which could potentially be embedded in the latter and are worth researching.

Table 5 Gaps and game opportunities in CAD and engineering design identified

Game Patterns	CAD Mechanisms	Limited CAD Aspects	Opportunities
Process of use; gameplay: challenges, rewards and achievements	Model definition and manipulation, picture generation	Results of the processes	Improve interaction between user-CAD in style of conversation (process of use)
Goals defined by game world & System's performance feedback	Design - Data management Parametric CAD using parametric programming	Goals defined by task requirements & Manager's performance reports	System / Task identified goals Goals divided to sub-goals and levels
Variable Difficulty Level (e.g. for score keeping); GUI has successive layers of complexity	Applications for evaluation, analysis, simulation, and manufacture	No Difficulty Levels; GUI organized on design tasks	Challenges, Rewards & Achievements Instantaneous Feedback & Different representation of useful information (Graphical Richness)
Use of communications strategies: Introduce new information when knowledge is incomplete and inconsistent	Common basic services and system environment	Limited Assistance and constructive Feedback	

The potential CAD-relevant game mechanics requiring further investigation are (Table 6):

Table 6 Game mechanics and aesthetics for CAD

Directed goals (AI-based game mechanic)	Games state their goals clearly, so users will know what task is to be completed and so stay engaged with the system.
Progression	Games provide levels of progressive difficulty and challenge to sustain a user's state of flow or frustrate and stagnate the user on purpose to enhance the engagement and experience.
Performance Feedback	Games provide feedback immediately to users to assess on their progress and goals. This way user' engagement levels by indicating they are in the correct truck on reaching their goal.
Rewards & Achievements	Games state their goals clearly, so users will know what task is to be completed and so stay engaged with the system.
Aesthetics:	
Different representation of useful information (Graphical Richness)	Games use a variety of graphics and aesthetics to be emotionally appealing

2.6 Evaluating User Experience for game-based CAD

Given that there is no clear set of UX relevant measures that describe both a gaming experience and a productive experience (in this case, CAD) a combined UX approach needs to be defined.

The usual focus of game is on creating an engaging experience, while standard productivity applications such as Microsoft Office or, in this case, CAD systems are task-oriented.

There are many quantitative and qualitative studies providing a useful list of traditional and game-relevant approaches and cognitive models that measure the outcome of the experience (Table 7):

Table 7 Qualitative and quantitative measures of UX in games and productive systems

Game-based UX	Productive systems UX
Self-report data: Using the Game experience questionnaire (GEQ) [87]	**Holistic approaches**: Dividing UX into a number of factors or processes such as cognition – sub consciousness – storytelling – narrative or pragmatic – hedonic attributes [88], [89], [90]
Usability metrics: Translated into a context of player metrics with "requirements gathering" for effectiveness, system learn-ability for efficiency and satisfaction including motivation and socialization [91]	**Usability metrics:** Efficiency, effectiveness, satisfaction [92], [93], [94]
Flow theory and "flow experience"[95]; For example the Presence-Involvement-Flow Framework (PIFF) [44], the Dispositional Flow Scale-2 (DFS-2) [96] or GameFlow [97]	**Flow theory:** Flow transients as a structural model for customer experience [98]
Psychological measures using emotional states and brain activations [99], [100]	**Emotion-based approaches:** Rating specific emotions such as satisfaction or boredom [48], [101], [102], [103]

For both game and interactive-productive system domains UX factors that overlay are the ones related to the "impact of use". What can be adopted from the game-based UX measures are factors related more to the psychological outcome of the player/user interaction in context with the player's/user's goals that need to be achieved. Bernhaupt [104] described UX in games:

"UX in games describe a specific phenomenon; the process which is influenced by interaction techniques and format of the game elements and then the psychological outcome (derived from user psychology)."

This definition seems to lie well with both the game and the interactive system's UX components profiling the concept of flow [44] defined by goals and feedback [105] control [106], concentration with task completion and balance of challenge/skills of the task [107], immersion [47], temporal distortion – engagement [108]. Based on the research covered in this chapter the definition of UX in games by Bernhaupt [104], the model of UX for game-based engineering design can be shaped as following:

The engineer's performance (measured by performance metrics) describes the process of interacting with the system [109] *which can be enriched by game mechanics which then can influence the emotional response in terms of engineer's engagement. These combined can describe the user experience (UX).*

2.7 Summary

CAD remains an irreplaceable tool in the product design lifecycle but due to its high-level operational functionality and specialization driven by current engineering design needs, it has become difficult to use. Gaming principles, methods and their mechanics are potentially emerging as an alternative to a more engaging way (engaging UX) of problem-solving in product design. They have opened the possibility of being applied in engineering design with CAD so can take advantage of their positive effects. Limited studies of applying game mechanics in engineering within a design process poses an interesting field of research that could lead to a positive impact on the design and the UX of the engineers.

The literature has indicated opportunities and identified potentially useful game mechanics for CAD (see opportunities Table 5); aspects related to system/identified goals and sub goals divided into levels, challenges, rewards and achievements, and graphical representation of information.

To transit the boundaries of games in engineering design with CAD, requires that the game mechanics should have a positive effect but also a non-distracting impact on the engineers' design thinking process within CAD. It should address the issues regarding usability and provide enriched user interaction and experience. For example, the rewards-achievements mechanic can offer a mechanism to evaluate an engineer's design (or with a set of defined optimal designs within the CAD database) at the end of their design process.

The game mechanics of Directed goals, Progression, Performance-Feedback, Rewards-Achievements are ubiquitous game mechanics across games. Even though this selection is not an exhaustive one, it represents some of the game elements highlighted from the literature. Their procedural nature and integration simplicity may allow interruption free in an engineering design processes with careful implementation as well as be, a good fit across different possible design approaches, an engineer may follow on solving an engineering design problem.

In the next chapter, we will focus on capturing the impact of those game mechanics.

Chapter 3: Exploring game mechanics through an empirical approach

To begin to address RQ2-RQ4 this chapter applied an empirical approach to explore game-based opportunities and their potential to enrich the engineering design experience and performance when compares to traditional CAD [15]. More importantly, it provides a basis in formulating a methodology to implement further empirical studies.

Within this study, the aim is twofold: an initial understanding of a common game mechanic (such as performance) and its impact in engineering design and CAD as well as its assessment through biometric logging with the introduction of a basic emotional capture and analysis framework. Their interlinked cause (game mechanics interaction) and effect (emotional response) would allow an effective analysis and investigation of game approaches in this context within this simple setting, which would further lead to more complex empirical studies.

3.1 BAMZOOKI case study

BAMZOOKi [110] is an online educational toolkit with an elementary component library to enable the creation of 3D rendered graphics which can be simulated in a real-time environment. It is used as part of a BBC game-based learning programme for children to build virtual creatures. This case study was designed to compare and contrast user performance and responses for a given engineering design task in both a game-like CAD environment (BAMZOOki) and a conventional CAD environment, (Solid Edge V20 CAD system [111]). The BAMZOOki was ideal for working on simple parametric design as its functionality mirrored many conventional parametric CAD packages.

For the evaluation and comparison of both CAD systems for impact on the engineering design process, the UX of the engineers was reviewed with respect to their design process in both environments. As highlighted from the literature review, there is very little knowledge on the evaluation of UX when comparing game-based productive systems and CAD, as the research area is particular new. Therefore, this explorative study attempts to establish whether game-based approaches, particularly the game mechanics, can influence the engineering design strategy and UX of the engineers when compared with traditional CAD.

3.1.1 Neurophysiological insights of UX in a gamified design space

Capturing users' physiological responses for the purposes of evaluating interfaces of design software has been proposed in the past. Shackel [112] emphasised the need to assess user experience resulting from interacting with a system together with task performance and user satisfaction. Cockton [113] states that *"Experience is an important outcome in some contexts, whereas in others it may be all that matters"*. Methodologically, UX in games relies on the evaluation of emotional and cognitive experiences in a gameplay [100], [114].

Applying psycho-physiological assessments and measures to deduce emotional responses is gaining ground. Until recently, UX assessments relied almost exclusively on subjective, after the event, data. However, these can never directly present what a person has experienced. When a person's attention is directed at a specific point in their interaction with an application, this can be perceived as a distracting/interfering event, which could influence their overall experience. Memory biases can also enhance or impair the recall of a memory and so alter the actual experience. Therefore, psycho-physiological measures can give real time objective feedback on the UX and participant's internal state.

Changes in the physiological indicators of arousal are known to be sensitive in emotional reactions. Andreassi [115] reported that Galvanic Skin Conductance (GSR), a measurement of resistivity as a result of electro-dermal activity in the palms, and the electrical brain activity through electroencephalograms (EEG) respond differently when factors such as levels of difficulty, attention, frustration, surprise, etc. vary.

The relationship between EEG and neurophysiological changes, indicate states of consciousness. In particular, research has established that certain EEG frequency bands indicate activity on different hierarchical levels [116]. For example, alpha waves in the frequency between 8 and 13Hz [117] are related with positive feelings such as relaxation and awareness without any attention or concentration. Beta waves (13 to 30 Hz) indicate active thinking but also at its higher levels can indicate an anxious, stressed state associated with negative emotions. Theta waves (4 to 7 Hz) are generally associated with creative inspiration and deep meditation [105], [118].

Picard [119] reports changes in the muscle electrical activity (EMG - Electromyography) of game players when software does not react correctly to its controls. GSR measures has been found to indicate stress levels as well as cognitive activity [100]. These physiological indicators can be an important evaluation tool. However, this can involve difficulties in the analysis of the signals and their interpretation. Signals can be inconsistent within individuals on different occasions. Given that they are also highly variable there is difficulty on deciding the latency, duration and magnitude of the responses. Interpretation without having a repeatable and robust experiment protocol will be impossible. There can be also identical responses to different psycho-physiological events making categorising frustration, stress, enjoy or other kinds of experience difficult.

Implementing a Design of Experimentation (DoE)

To study the factors that influence games for engineering design and the emotional response it creates, a comparative study between a game-based CAD (CADG) against traditional CAD (CADT) is needed.

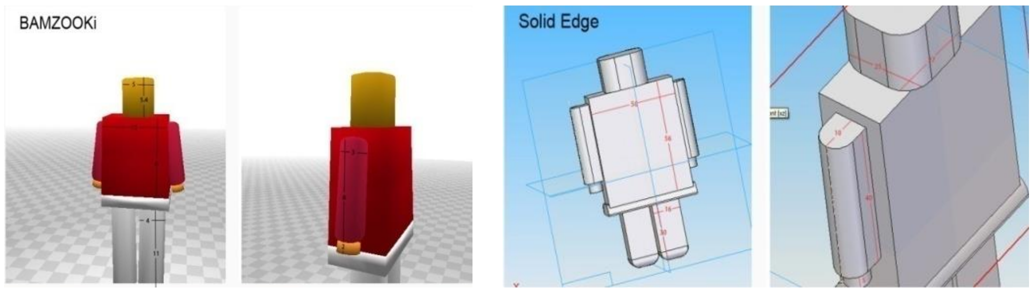
The empirical process comprises three steps:

1. design task and user trial procedure (3.2.1),
2. data capture (3.2.2),
3. data analysis and conclusions (3.2.3)

3.1.2 Design task and user trial procedure

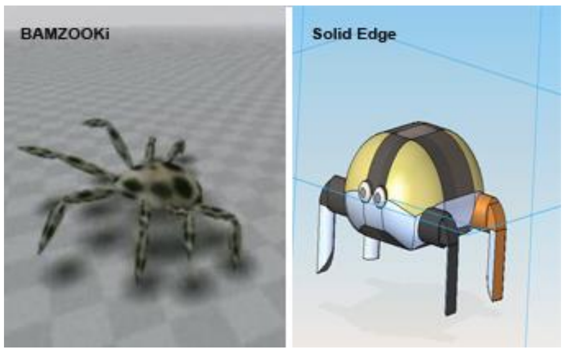
Participants performed the same design task in two different design environments; BAMZOOKi (CADG) and Solid Edge (CADT), a conventional CAD system. On the completion of the task, they were interviewed about their experience with the environments. To ensure a level playing field, all participants received an introductory tutorial on each environment. They were then divided into groups A and B. Group A designed using CADT while Group B used CADG. Both groups were given 30 minutes to complete each individual design task comparisons with approximately the same number of geometric objects as follows:

- Group A participants designed a robot according to given dimensions as shown in Figure 9. The performance goal was to create a dimensionally exact model according to tasks instructions in both CADT and CADG
- Group B participants designed a spider-model similar with what given in Figure 10. The performance goal was to create the exact model, but their task requirement included meeting the performance goal also by\ simulation (game mechanic of performance) in both CADT and CADG.



(a) (b)

Figure 9 Group A were given a task in both (a) BAMZOOKi or CADG and (b) in Solid Edge or CADT



(a) (b)

Figure 10 Group B were given a task in both (a) BAMZOOKi and (b) in Solid Edge

3.1.3 Data capture

To conduct the explorative case study three main types of data are collected:

- Psycho-physiological measurements, EEG and GSR for indicators of mental effort as well as positive and negative emotional indicators (see Figure 11)
- Interviews to review participants' engineering design process, preferences, and expectations in game and conventional environments

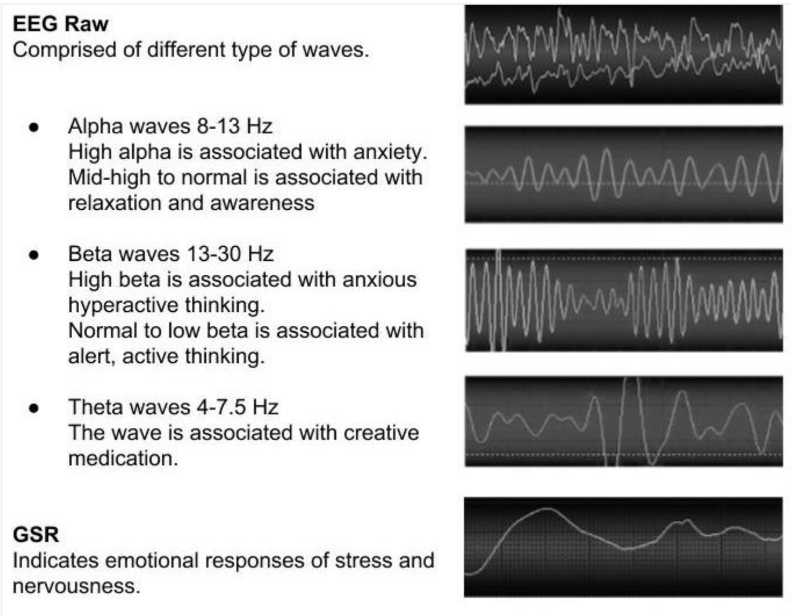


Figure 11 Brain waves frequencies from the top to bottom: EEG Raw, Alpha waves, Beta waves, Theta waves and GSR as extracted from Biotrace [120]

Two sensors placed on either side of participants' forehead measure the EEG activity. The GSR is monitored with two sensors; one on the index finger and one on the ring finger of the participant's non-dominant hand (see Figure 12). All the psycho-physiological data were captured with a NeXus-10 [120] biofeedback device.

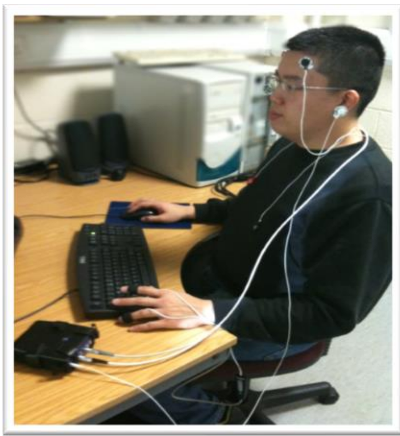


Figure 12 Participant connected with the sensors

3.1.4 Data analysis

The protocol of analysis for the psycho-physiological data is based on the experimental hypotheses:

1. If GSR is high (based on an individual's relax state- baseline) then the arousal is high and when arousal is low, GSR is low [121].
2. When the peak frequency of Alpha is very high (A>11Hz), negative emotions are dominant (anxiety); when the peak frequency of alpha is mid-high (A< 10Hz) then positive emotions are dominant (relaxation) (see Table 8) [122].
3. When the peak frequency of Beta is very high (B>19Hz), negative emotions are dominant (stress, anxiety); when the peak frequency is mid-normal (15Hz >B>12.5Hz) then positive emotions are dominant (active thinking, attention, focus) (see Table 8) [117].
4. When peak frequency of Theta is high (T>5.3Hz) then positive emotions of creativity are high (see Table 8) [117].

The EEG signals are processed through a 1024-point Fast Fourier Transform (FFT) to subtract Alpha, Beta and Theta wave with a sample rate of 256 samples/sec. Thus, a frequency spectrum with 0.25Hz resolution is obtained using frame of 4 seconds. After the FFT the frequency corresponding to the peak power of every 4 seconds can be found and then the peak frequency normalized. Due to the variances among the participants both the EEG and GSR signals from each participant were normalized on a scale between 0 and 100 as follows:

Taking as an example the peak GSR:

$$Normalized\,\mathrm{GSR}(i) = \frac{GSR(i) - GSR_{\min}}{GSR_{\max} - GSR_{\min}} \times 100$$

Finally, the data were evaluated through a series of conditional rules to describe the user response in terms of linguistic outputs and more specifically, to positive and negative emotions.

The conditional statements are as shown in Table 8.

Table 8 Conditional rules for describing emotions

For the EEG	
Alpha Frequency:	If A>11Hz then Alpha is very high, so user is anxious (negative emotions) Else A < 10Hz then Alpha is mid-high, so the user is relaxed (positive emotions)
Beta Frequency:	If B>19Hz then Beta is very high, so the user is stressed (negative emotions) Else if 15Hz >B>12.5Hz then Beta is mid-normal, so the user is alert, focused, attentive, (positive emotions)
Theta Frequency:	If T> 5.3Hz then Theta is high, so the user is creative (positive emotions) Else Theta is low, so the user is not highly creative and in state of wakefulness
For the GSR	
GSR:	If GSR> baseline the user is stressed (negative emotions) Else the user is relaxed (positive emotions)

3.2 Experimental results and analysis

Four mechanical engineering students were involved in the experiment, two creating a 3D model of a robot and two creating a model of a spider using BAMZOOKi and Solid Edge during which their psycho-physiological responses were recorded with the NeXus-10 biofeedback device.

Table 9 shows the EEG percentages for group A.

Table 9 Brain frequencies group A

Group A	Normalised EEG Percentages (%)					
	Alpha		**Beta**			**Theta**
	High > 11Hz	10Hz > Mid-High	High > 19Hz	15 Hz > Mid-High > 12.5 Hz	High > 5.3 Hz	Low < 5.3 Hz
Participant 1 BAMZOOKi	13.541	19.444	22.569	61.458	59.375	40.625
Participant 1 Solid edge	13.242	26.484	23.287	62.557	59.360	40.639
Participant 2 BAMZOOKi	12.5	22.826	37.5	55.978	47.282	52.717
Participant 2 Solid edge	13.215	30.176	-	-	49.118	50.881

Table 10 shows the EEG percentages for group B.

Table 10 Brain frequencies Group B

Group B	Normalised EEG Percentages (%)					
	Alpha		**Beta**		**Theta**	
	High > 11Hz	10Hz > Mid-High	High > 19Hz	15 Hz > Mid-High > 12.5 Hz	High > 5.3 Hz	Low < 5.3 Hz
Participant 1 BAMZOOKi	21.621	29.279	26.576	61.261	57.207	42.792
Participant 1 Solid edge	18.421	18.421	42.10	52.631	47.368	52.631
Participant 2 BAMZOOKi	16.541	26.315	32.330	64.661	52.631	47.368
Participant 2 Solid edge	24.229	24.669	29.955	62.995	59.471	40.528

Finally, Table 11 shows the GSR percentages for both groups.

Table 11 GSR data

	Normalised GSR percentage (%)	
	Mean	**Mean STDEV**
Group A		
Participant 1 BAMZOOKi	18.397	19.778
Participant 1 Solid edge	11.253	7.146
Participant 2 BAMZOOKi	17.415	6.196
Participant 2 Solid edge	73.588	7.228
Group B		
Participant 1 BAMZOOKi	17.839	14.740
Participant 1 Solid edge	49.562	11.501
Participant 2 BAMZOOKi	16.499	11.366
Participant 2 Solid edge	62.088	10.447

Group A with the design task of the robot:

Users liked the Solid Edge professional design interface. However, they found BAMZOOKi fun, with a simple interface but criticised the lack of precision. The GSR levels were varied, with one participant being on average levels and the other high during the task in Solid Edge. With regards to the EEG frequencies (**Figure 13**), the users showed no significant changes between the two environments, other than the increased percentage on mid-high beta frequency while working in Solid Edge compared to BAMZOOKi. For the theta, only one participant showed higher percentage on the lower theta frequency in Solid Edge.

Overall, the increased percentage of mid-high beta (15Hz > B > 12.5Hz), indicates a positive experience for the users while working on Solid Edge. However, the varied percentages of the theta frequency and GSR can be an indication of intense focus and information processing. This can be due to the number of menus and tools on Solid Edge compared to BAMZOOKi, as also commented by users during the interviews. More specifically, the visibility of the buttons (submenus) affected their concentration but overall, they found Solid Edge easy to work on. All the users suggested they liked BAMZOOKi's grouped view of tools and the UI that allowed them to focus more on creating the robot with only the essential components on view. It is worth mentioning that users found the "EEG cap" and the monitoring process intrusive.

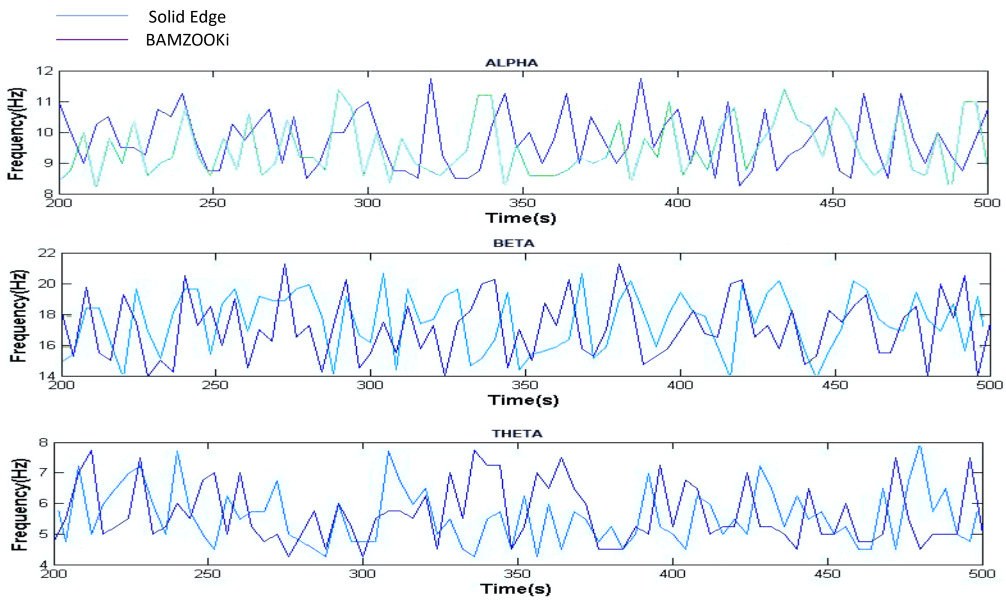


Figure 13 EEG signals showing no significant differences between Solid Edge and BAMZOOKi interfaces for group A participants

Group B with the design task of the spider:

The users responded that their design experience with Solid Edge was stressful compared to BAMZOOKi. It was observed that participants working with Solid Edge were unable to finish their task. They also paused several times during the design process to explore tools that could help them to finish the task. The GSR measured in Solid Edge was higher in comparison with BAMZOOKi (Figure 14). Participants had a high percentage of high theta, indicating increased creativity in the task within the BAMZOOKi environment. The beta and alpha frequencies varied in term of percentages between users; Participant 1 had increase mid-high alpha and mid-high beta whilst Participant 2 had low high alpha frequency while working in BAMZOOKi. This indicates users were having a positive experience in the game-based environment.

User interviews indicated that the performance goal game mechanic helped them concentrate even as they followed a more trial and error approach. They also suggested that they had a very enjoyable time while working in the game environment and would have liked to have spent more time using it.

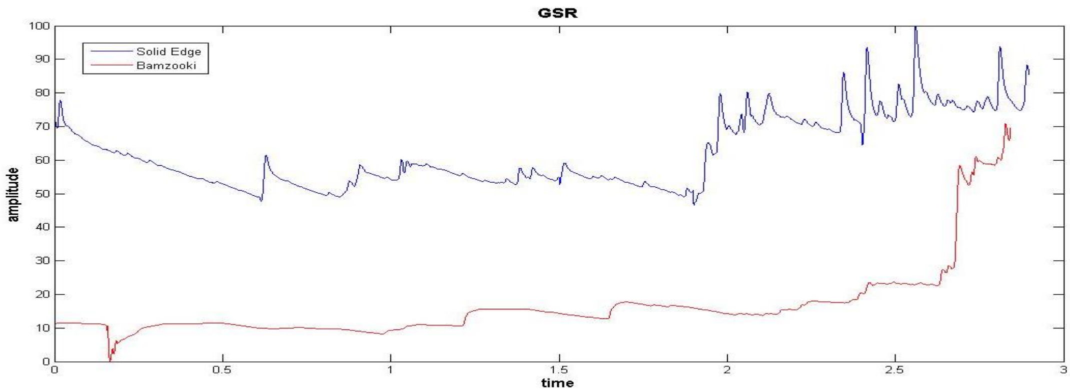


Figure 14 Example of participant in Group B showing significant difference in GSR levels while designed in both interfaces; the top line is the GSR in Solid Edge and the bottom in BAMZOOKi

The results of this study show:

- A positive response of the users to a game-based CAD interface and its game mechanic of performance goal for an engineering task. The users felt immersed in the task, having a clear, visual and animated approach to reaching a goal within the context of an engineering design related task, as well as having an enjoyable time throughout. This is good indicator for further exploring this and other game mechanics embedded in CAD environments.

- Objective, real-time psycho-physiological data can help distinguish between positive and negative emotions. However, more sophisticated protocols are needed to combine and correlate psycho-physiological measures, such as EEG and GSR, in one emotional outcome. EEG monitoring has the potential to affect the users' comfort (user perceived it as intrusive) thus potentially impacting their user experience (this was the case for both design environments).
- Interview questions can be further structured with more quantitative data in the form of an emotional rating questionnaire. This will aid the review and correlation of subjective emotional responses to objectives measures of the psycho-physiological emotional outcome (EEG).
- Simplifying the user interface and its menu are to be further explored for their impact on users' experience.
- The order of the CAD environments affects the emotional response. This can be further explored with a larger group of users divided into two groups alternating the CAD design environment for a defined task.

3.3 Summary

This explorative study suggests that the engineering design experience in a CAD environment can potentially be enriched through game-based mechanisms. The use of psycho-physiological measures offers a means to consolidate qualitative and quantitative measures to better evaluate the game-based approach when compared to traditional CAD.

While inconclusive this case study did indicate potential for game mechanics to influence the engineering design strategy. It also identified the possibility of using psycho-physiological data to evaluate and measure behavioural and emotional responses during engineering design. Based on these explorative case study results, furthermore detailed empirical studies in this research were carried out will follow (Chapters 5, 6 and 7).

Chapter 4: DeReFrame - A design-research framework to evaluate gamified CAD

The explorative study in Chapter 3 provided some evidence of the effect of game mechanics in engineering design and the use of potential psycho-physiological data as indicators of emotional response. Based on these early findings, this chapter proposes an experimental design research framework (*DeReFrame*) to gain further insights into the role and impact game mechanics may have on engineering design and CAD systems while fully addressing RO 2, 3 and 4 with a view to answering RQs 2-5.

4.1 DeReFrame design

DeReFrame is specifically designed is to address the impact of specific game mechanics in engineering design with CAD. Since games and game design encompasses so many different game mechanics and their application, it is difficult to study every possible facet of it. The following experiments focus on the game mechanics of: Directed Goals, Progression, Performance-Feedback, Rewards-Achievements, and the game element of Aesthetics as identified in Chapter 2 section 2.5.1.

In order to study the above game mechanics within a CAD system it is proposed that the framework will measure their impact on:

- The effectiveness and efficiency of the engineers' design strategy when carrying out given tasks (goals) while improving performance (RQ4).
- The type of interactions and features when tracking progress to identify any changes to the main emotional responses and overall UX (RQ5).

The framework is composed from four phases covering the understanding of the problem space (Chapter 2, 3), defining the evaluation metrics (Chapter 4), developing a game-based CAD (Chapter 4) and analysing the results (Chapter 5). Questionnaires throughout the phases can be seen in Appendix E. Chapters 2-4 form the theoretical basis for constructing the game-based CAD system, which is used to further evaluate the framework. A model the framework can be seen in Figure 15.

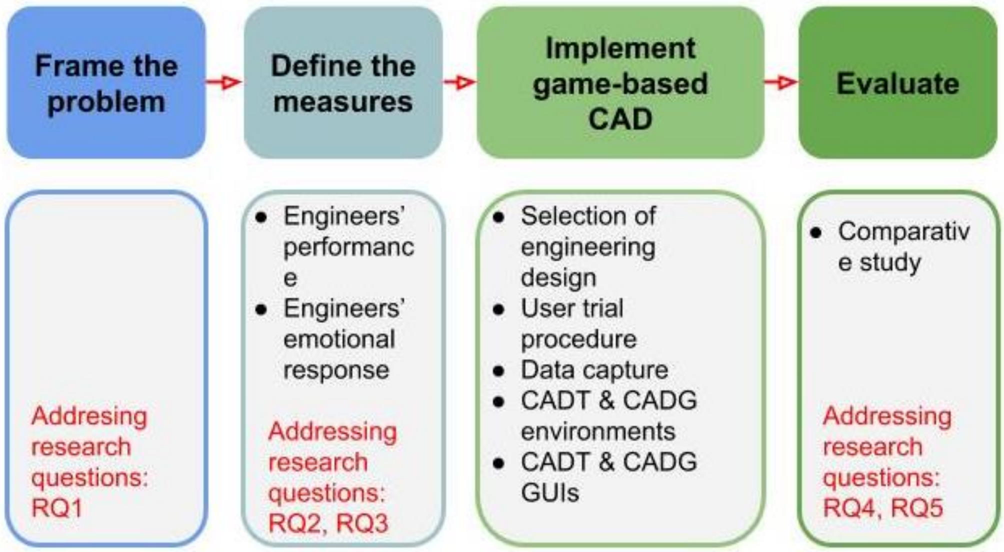


Figure 15 DeReFrame framework for game-based CAD

4.1.1 Game mechanics evaluation metrics

For the purpose of the experimentation, the game mechanics impact on an engineers' design performance and design strategy (RQ4) and their associated emotional responses (RQ5) can be broken down to defined qualitative and quantitative metrics.

Engineer's performance metrics

Measuring a user's performance on a task in a given system through usability metrics, is a common approach [123], [115]**.** Usability metrics can help evaluate the "productivity" in the gameplay and cover the effectiveness, efficiency and satisfaction of a user [124], [125] (Table 12). Reviewing the process of completing an engineering task also contributes to the understanding of an engineers' performance. Task analysis models such as GOMS (Goals, Operators, Methods, Selection rules) [126] give predictions about usability evaluations [125], [127] and learning and further identify user's task flow i.e. design strategy at the functional level of a task. The GOMS process includes a hierarchy of goals to be created for a defined task, which then is broken down to user's executable actions called Functional Level Operators (FLOs). Based on the defined FLOs users' strategy can be consistently understood and evaluated for its optimal state.

Delving deeper into engineers' performance, cognitive underpinnings can indicate the internal abilities of a user to complete a task. Cognitive workload is a metric related to the mental effort require to perform tasks [125]. NASA TLX [128] is a tool to aid the capture of subjective measures of cognitive workload assessment. This tool provides a rating system of the users' processing resources and effort indicative of their internal abilities and can be measured through the five dimensions of mental demand, temporal demand, performance, effort and frustration.

Combining the usability metrics, GOMs and cognitive load, a holistic profile of the engineers' performance and interaction with a game-based CAD (CADG) can be provided (Table 12) enabling insights to RQ4.

Table 12 Engineer's performance metrics

Engineer's performance metrics
Usability metrics • Efficiency or "time on task" referring to task completion time (TCT) **[129]**. • Effectiveness or "error rates" referring to the frequency of a specific set of actions – number of iterations to reach and end goal/finish the task **[129]**. • Satisfaction, referring to the extent to which an interaction can be satisfying; It can be measured by satisfaction rating questionnaire **[129]**.
Design strategy or task flow • GOMS (user task flow)
Cognitive workload • NASA TLX (mental demand, temporal demand, performance, effort and frustration)

Engineer's emotional responses

Emotional outcomes, including engagement, are associated with feelings, thoughts and behaviours and are therefore involved in decision making, perception, learning and thinking [130].

Flow or user emotional rating questionnaires and interviews are common approaches used to measure the subjective experiences of a person's emotions [131], [132]. As seen in Chapter 3 in the BAMZOOKi experiment, physiological activity is integrally related to emotional responses [133]; different stimuli evoke different subjective experiences [134]. A fuzzy model with affect grid was applied to reveal the relationship between psycho-physiological signals, electroencephalogram (EEG), electrocardiogram (ECG) or Galvanic Skin Response (GSR) and emotions of satisfaction, frustration, challenge and engagement as detected during the operation of the CAD system [135]. The fuzzy logic approach has been proven to effectively evaluate the emotional response of the engineers in CAD environments [135], [136] across the whole design process.

Combining subjective emotions, behavioural data, and fuzzy logic the emotional response can provide a complete set of objective and subjective psychological results (Table 13), enabling for the review of RQ5:

Table 13 Emotional response measures

Emotional response
Subjective emotions and flow • Subjective emotions or users' emotional responses are evaluated with the use of emotional rating questionnaires (Appendix E) **Objective Measurements** • Phyco-physiological measures using Fuzzy logic to analyse EEG readings for emotional measures (frustration, challenge, satisfaction and engagement) [135]

4.2 Implementation

To analyse the impact of game mechanics in CAD and the engineering design process a CAD application embedded with game mechanics (CADG) will be compared against a traditional CAD (CADT) for the same engineering task. The design process of the experiment can be broken down in to the following steps:

- Selection of engineering design problem (4.2.1)
- User trial procedure (4.2.2)
- Data capture (4.2.3)
- CADT & CADG environments (4.2.4)
- CADT & CADG GUIs (4.2.5)

Each step is outlined in the following sub-sessions.

4.2.1 Engineering design problem setting

The BAMZOOKi study suggested that a parametric CAD task was an ideal for CAD experimentation comparing CAD users due to:

- A constrained task repeatable by a large number of users
- Familiarity with the potential subject population.
- A short duration task (30-60 minutes).
- No need to train the participants on a high-level CAD interface
- Short learning curve.

The design task chosen was a welded bracket exercise. Adapted from the tutor resource pack "Engineering applications, a project-based approach" [138], the problem set compromises of tensile and shear stress requirements for a standard welded bracket with the relevant weld throat specification to carry a defined load [138]. Outline notes for the calculating different modes of tensile and shear failure of the bracket, including the fillet weld size (Table 14) were provided.

Table 14 Information for modelling a bracket

Bracket Design	
Tensile Stress	Applied Pin Force (P) / (breadth –diameter) * thickness
Shear Stress	Applied Pin Force (P) / 2*(thickness*effective shear height)
Weld Join Parameters	Throat (A) = Applied Pin Force (P) / ((0.828*0.3*Allowable Shear Stress&*Length) * 2)

The goal was to design a mild steel bracket via parametric CAD interface provided equations such that the designed bracket can sustain a required load (pin force) (Figure 16).

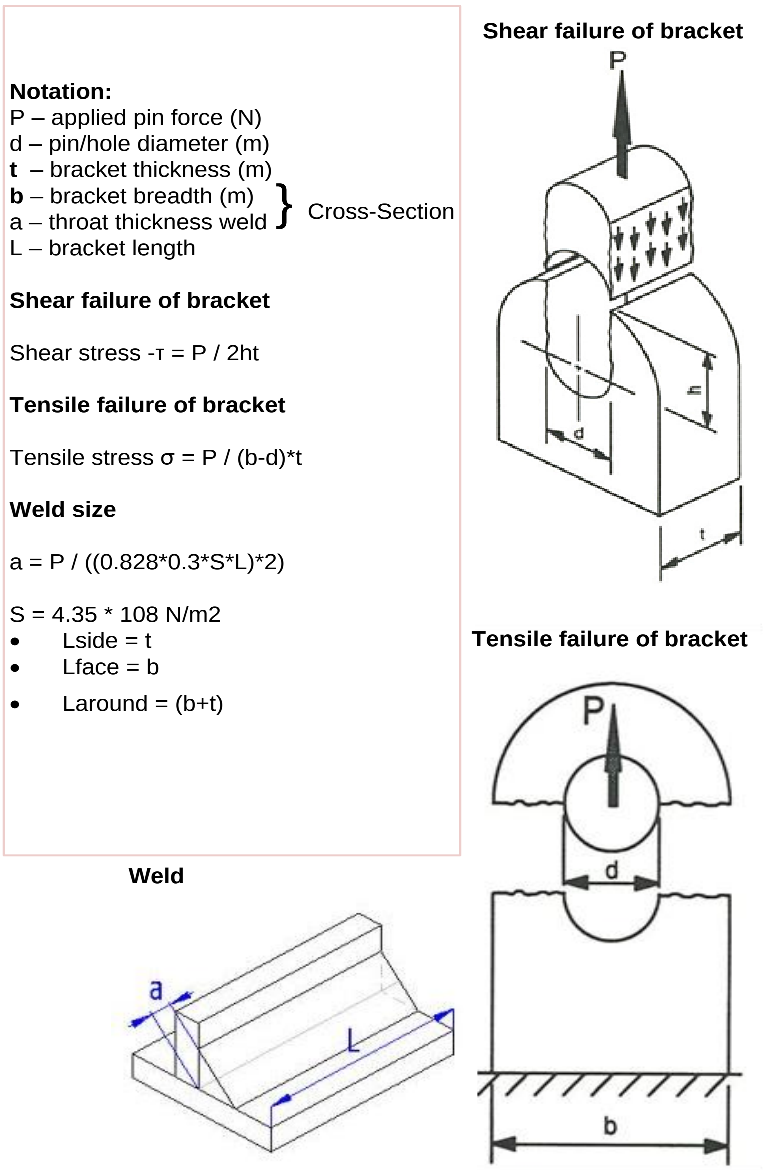


Figure 16 Shear, Tensile failure modes and weld throat graphs and equations [138]

The purpose of this exercise was to evaluate the role and impact of game mechanics in engineering design with CAD. The game mechanics of Directed goals, Progression, Performance-Feedback and Rewards-Achievements fit well within this design problem and was implemented in UGS NX [53]; the welded bracket follows a parametric linear design set of operations where game mechanics can be easily embedded for CADG. Through the bracket parameterization process, progress would be monitored (Progression), un/successful attempts logged (Rewards-Achievements), design steps clustered (Directed goals) and feedback given to aid the user in the next step of the process (Performance Feedback) (Figure 17). Note that the participants will use both traditional CAD bracket design parametric interface (CADT) and the game-based CAD bracket design parametric interface (CADG). The design process flow for each approach is given in Figure 17.

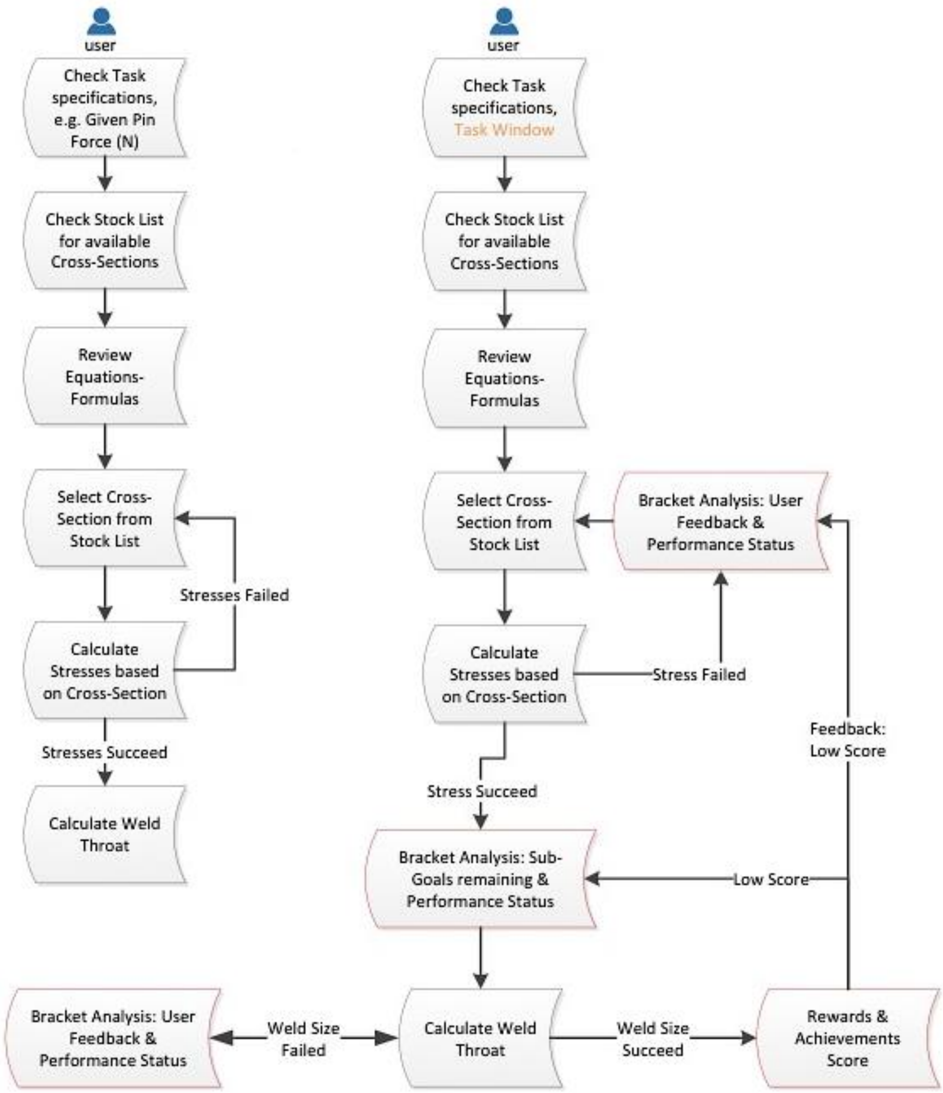


Figure 17 Process flow for configuring a welded bracket (CADT) (left) with no standard form of feedback on the success of the design and a game-based welded bracket (CADG) (right) with a broken-down design feedback mechanism

This engineering design problem setting uses parametric constraints that forces users to consider design strategies. Being a controlled design process, it allows design steps to reviewed, monitored and analysed in a more structured manner. It is also a well-established exercise coming from a standard tutor resource pack.

4.2.2 *Experimental procedure*

Figure 18 shows the high-level organisation of the CADT and CADG trials.

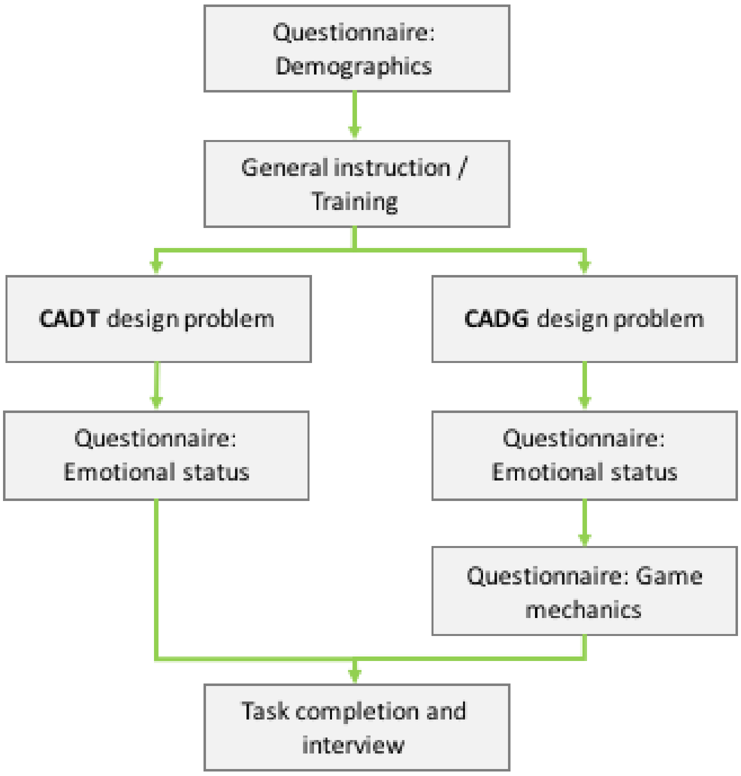


Figure 18 User trials procedure

The comparison between the two organised as follows:

Step 1. A general anonymous questionnaire completed to collect the demography of the user, i.e. personal details, engineering background and CAD experience.

Step 2. Each participant was given some general instruction and practice on the stress analysis of a bracket to familiarise themselves with the equations required for the experiment.

Step 3. Each user allocated either the CADT or CAD GUI to complete the bracket design.

Step 4. The participant fills in an emotion-ranking questionnaire related to the CAD GUI used using the rating system on a scale of 0 (low) - 10 (high) for each of the selected emotional responses: frustration, satisfaction, engagement, and challenge.

Step 5. Repeat Step 3 for the remaining CAD GUI, i.e. CADT or CADG

Step 6. Repeat Step 4.

Step 7. Answer questionnaire on the relevant GUI design and if appropriate how the set of the game mechanics affected the solution as well as design process and their design experience.

Step 8. End session with an interview on the design process experienced and the emotion changes participants experienced during the process.

Each user trial lasts approximately 30-60 minutes with 2 stages over two levels of difficulty. The participants were presented with a CAD model of a bracket and worked through the design problem. The aim was to optimise objective of meeting the functional requirements detailed in the design specification. Each level increases with difficulty.

Level 1: Optimise the bracket size, i.e. form factor, to meet the stress requirements using a standard material stock list. Each participant calculates the tensile and shear stress based on the bracket material and then uses the interface to configure the bracket cross-section.

Level 2: Design a welded joint configuration to meet different load requirements. The participants must select the weld types and calculate their size.

To minimise the possibility of the participants performing better on CADG due to having practiced on CADT first or vice versa, resulting in influencing the actual effects of game mechanics in the engineering design process, participants were divided into two groups:

- Group A: Participants worked on the CADT first following by the CADG.
- Group B: Participants worked on the CADG first following by the CADT.

4.2.3 *Data Capture*

Section 4.1.1 identified metrics for the evaluation of users' performance and interaction in CADT and CADG (Figure 19):

- Engineers' performance: usability metrics, design strategy (GOMs) and cognitive load.
- Emotional responses: objectively via fuzzy logic and EEG, ECG, GSR and subjectively via emotional questionnaires.

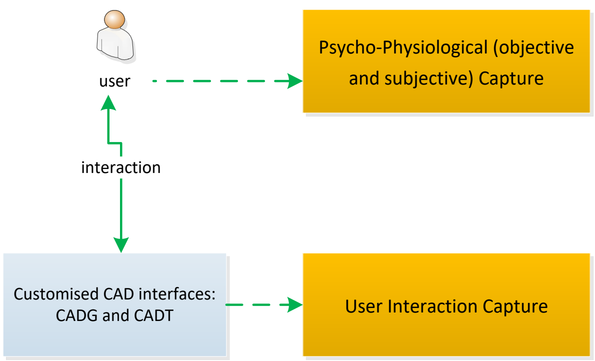


Figure 19 Game mechanic evaluation measures

Each of these and their associated metrics can be captured by continuous, synchronous, chronological, time-phased logging of multiple click inputs providing a rich data source which can be analysed to evaluate the chosen metrics and cause and effect relationships. This is a new approach to analyse design processes and a construction to knowledge.

a. Performance

- **Mouse /Keyboard events**

The effectiveness (number of errors of number of iterations) and efficiency (total tasks completion time -TCT) of an interaction with the UGS NX CAD system is recorded against CAD events with timestamp. These data are input into the history file of the system in a time-phased sequential manner, enabling users' design strategy to be reviewed (GOMs). Additionally an external mouse / keystroke logger recorded the overall activity and was synchronised with the EEG data sets using the ubiISA framework [139]

- **Eye Tracking and Video**

Eye tracking and user screen recording (video) was through a TOBii eye tracking device [140]. An additional C# interface was used to communicate data from the TOBii software to ubilSA framework enabling these data to be synchronised with all other data inputs

b. **Psycho-physiological responses**

- **EEG, ECG, EOG and GSR**

A Nexus 32 device [120] was selected to capture the psychological signals. The EEG, ECG, EOG and GSR data were logged and synchronised using the ubilSA. Figure 20 shows the GSR, ECG and EOG sensor placements. A 21 electrodes cap based on the 10-20 system [141] records the EEG.

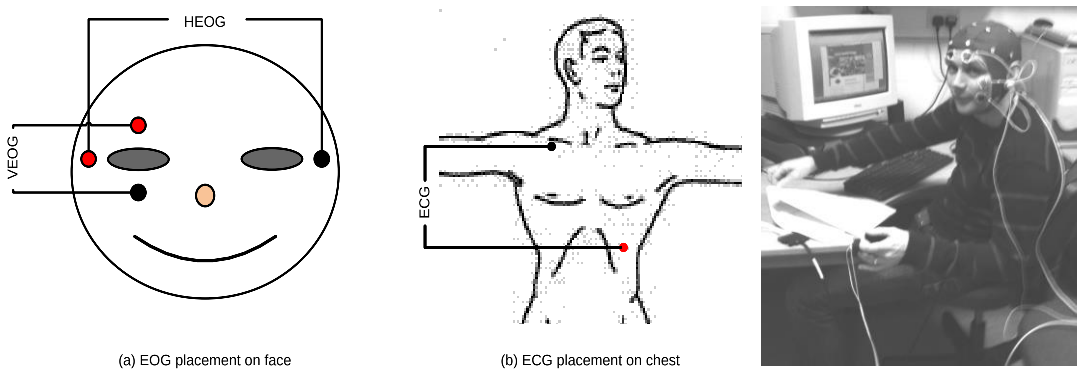


Figure 20 Sensors Placement for the EOG (a) ECG (middle) and EEG cap with GSR sensor fingers (right)

The fuzzy logic system [135] used outputs of four valences associated to emotions which are also rated by the participants supplementing emotional rating questionnaire for further correlation: Satisfaction, Frustration, Engagement and Challenge.

c. Data Capture and Synchronisation

The setup (Figure 21) compromises of a recording device described as "C# log" which monitors and records CAD activity as a history file with timestamps. The 3D representation of the set-up is shown in Figure 22.

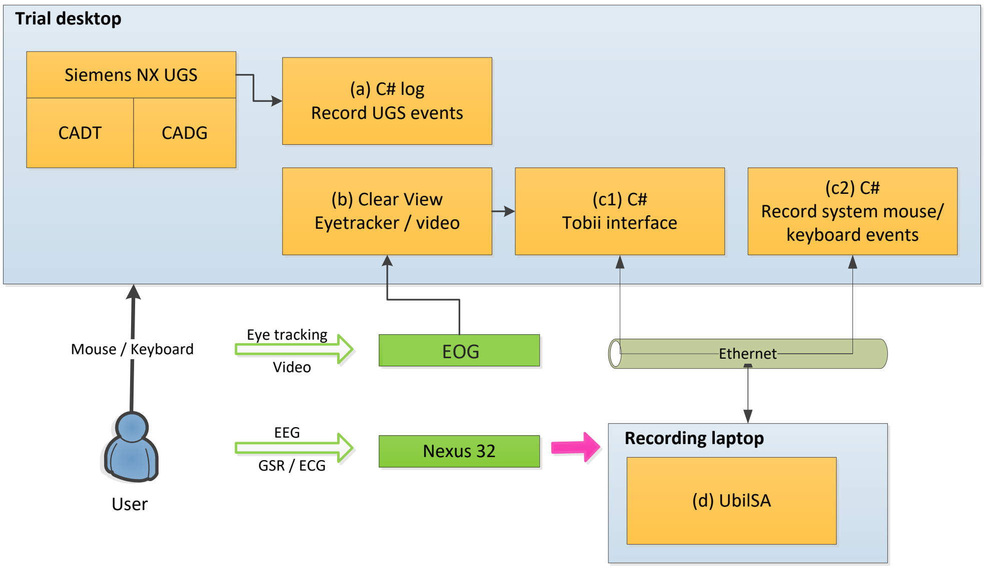


Figure 21 Overview of experimental setup

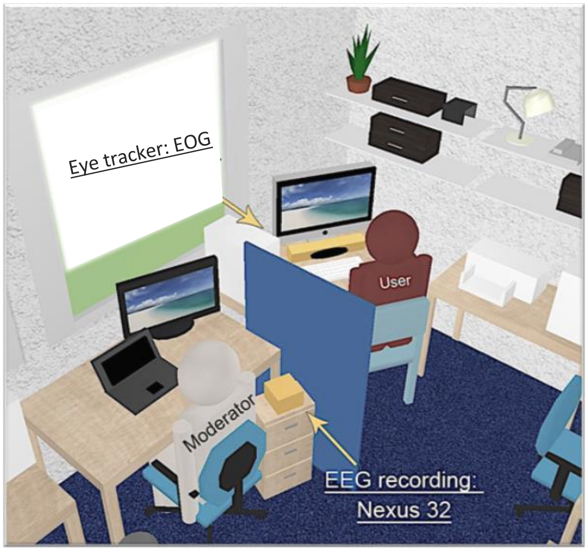


Figure 22 3D representation of the experimental setup

The link connecting the psychological signals and CAD activity is through the keyboards mouse events files. MATLAB [142] routines were created to format the psychological signals against the CAD activity.

Figure 23 shows an example of CAD activity against emotional input.

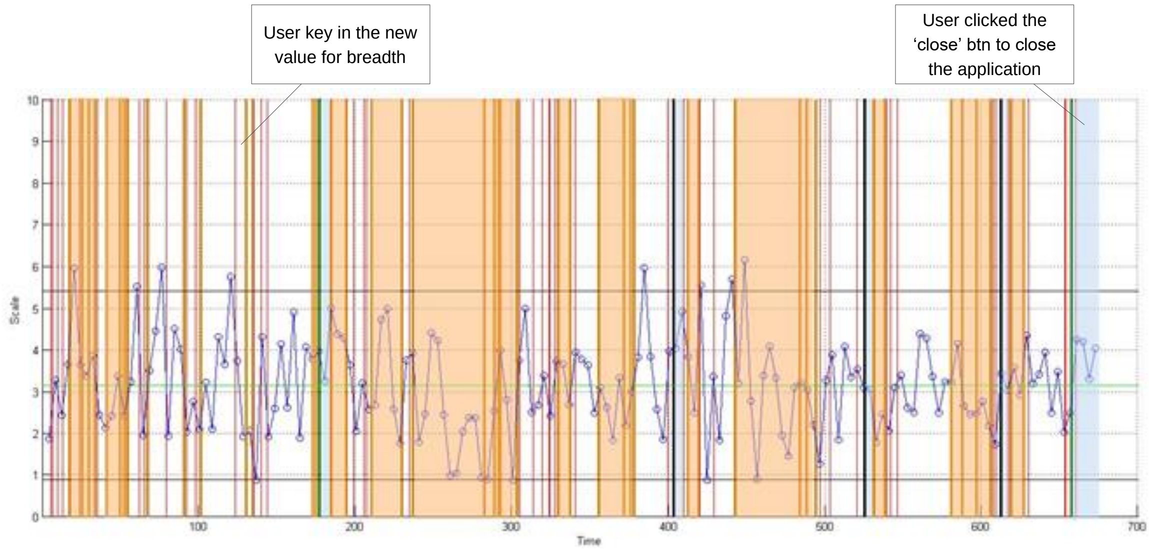


Figure 23 Example-graph showing the psychological input (vertical line) against the CAD activity in form of keyboard/mouse events – clicks (horizontal lines)

Both CADG and CADT interfaces incorporated all the relevant APIs for connecting to the customised GUIs to the model data.

d. Data Analysis

Within groups, paired and independent (unpaired) TTESTs [123] and ANOVA [144] were used to identify whether CADG and CADT interaction process are statistically significant.

The engineers' performance metrics, usability, and cognitive load will be analysed using within groups paired or independent TTESTs [143], [145], which compares the means within the same or different set of users working on the two different versions of the CAD. The paired TTEST allows for evaluating whether or not individual user's performance is statistically different over two conditions in CADG and CADT whereas the independent TTEST allows for evaluating two groups of users using different versions of the CAD (CADG or CADT) is statistically different. A subsequent ANOVA analysis [144] will be used to compare any statistical significance between means, as it offers the advantage of comparing more than two conditions or group of variables at the same time.

For the psycho-physiological and fuzzy logic data, a Lillie test [146] was used to evaluate the normality of the data prior to statistical analysis. If the datasets are not distributed normally then the use of statistical tests derived from normal distribution such as TTESTs and ANOVA are invalid [147]. For small samples, TTESTs would enable a means, of establishing a comparison of the resultant emotions between game-based CAD (CADG) and traditional CAD (CADT).

4.2.4 CADT & CADG environments

Siemens UGS NX 7.5 [53], a commercial CAD package, was selected for the implementation of the CADT and CADG environments. UGS NX APIs [53] (Figure 24) was used to programmatically create bespoke interactive parametric design application modules. The APIs provide access to core functionality through compliant languages: Visual Basic .NET and C#. UGS NX was chosen particularly due to the detailed documentation of the

NX APIs for the creation of customised applications and the familiarity of the environment to the experiment's potential participants i.e. university students and industrial candidates.

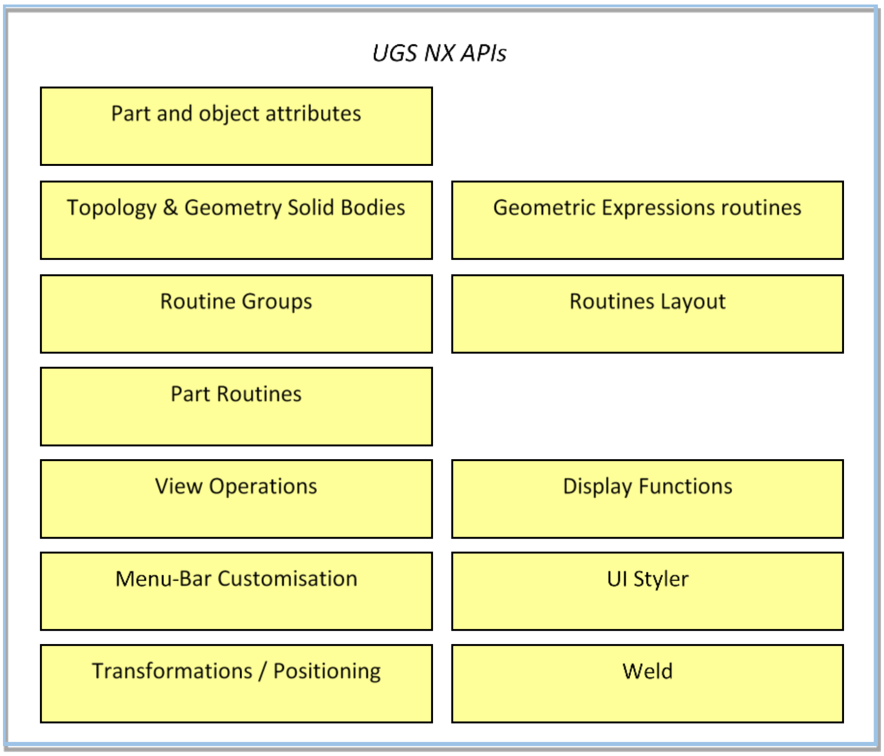


Figure 24 UGS NX APIs

The CADT and CADG interfaces were designed as two different application versions, which can be selected and executed from a single profile window or toolbar. The bracket parameters are defined in a look-up table in the form of expressions, which link the bracket's geometry, topology and features in the main CAD environment. Depending on the CADT or CADG input variables, the expressions are processed by a knowledge base compromising of a set of rules for the defined engineering task. This knowledge–base is programmed with conditional rules related to structural analysis of the bracket, defined by the failure modes of shear stress, tear stress and weld size.

During CADG or CADT use, the bracket's current table of expressions is evaluated against a coded look-up table of rules directing the game mechanics. The expressions are updated through the CADT or CADG GUI and controlled by the knowledge-base rules that define the interaction with game mechanics (for CADG). Figure 25 shows the relationship between the design knowledge base and the bracket parameters (CAD-data).

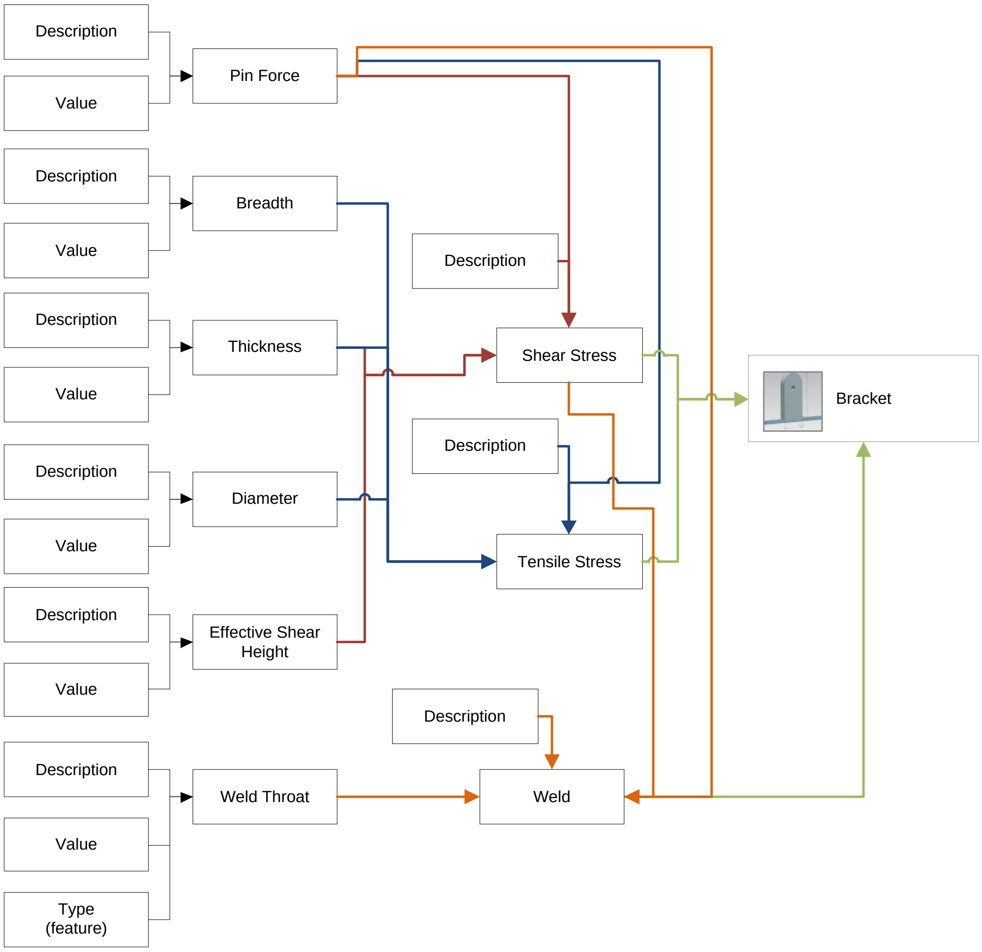


Figure 25 Knowledge base defined by rules related to the stress and weld equations

An evaluation process is initiated whenever the user enters a value to configure the bracket. This process uses the design knowledge-base (Rules) inside the system to guide the user (Direct Goals) through the levels (Progression) through feedback messages (Performance Feedback) specific to failure or success (Rewards & Achievements). It further provides recommendations or next steps towards completion of the final goal (Directed Goals).

4.2.5 CADT and CADG GUIs

The CADG GUI includes a profile window in the top-level interface, which used to navigate through the design task and its levels. The CADG comprises of several features for example, read-only information such as the pin force, material and maximum allowable stresses illustrated by a colour wheel and feedback messages (Figure 26).

The participant performs one task at a time (other task are locked), ranging from a basic parametric design task of shear and tensile stress (Level1) to a more advanced task with shear and tensile stress with weld features (Level2). Participants work on the tasks progressively, analogous to a goal game mechanic. For each level completed, the participant's best score and highest number of stars achieved will be displayed as Rewards & Achievements. The design window has areas reserved for instructions (material table, formulas), help information (diagrams), and task goals. Tasks goals are divided into sub tasks, framing the game mechanic of directed goals (Figure 26). During the parametric design task (an engineering design problem) of the bracket, feedback in a form of messages are incorporated within the main window. The GUI has also additional graphical context in the form of a colour wheel and checkboxes which provides the participant an alternative visual aid in self-evaluating their performance (Graphical Richness, Performance Feedback).

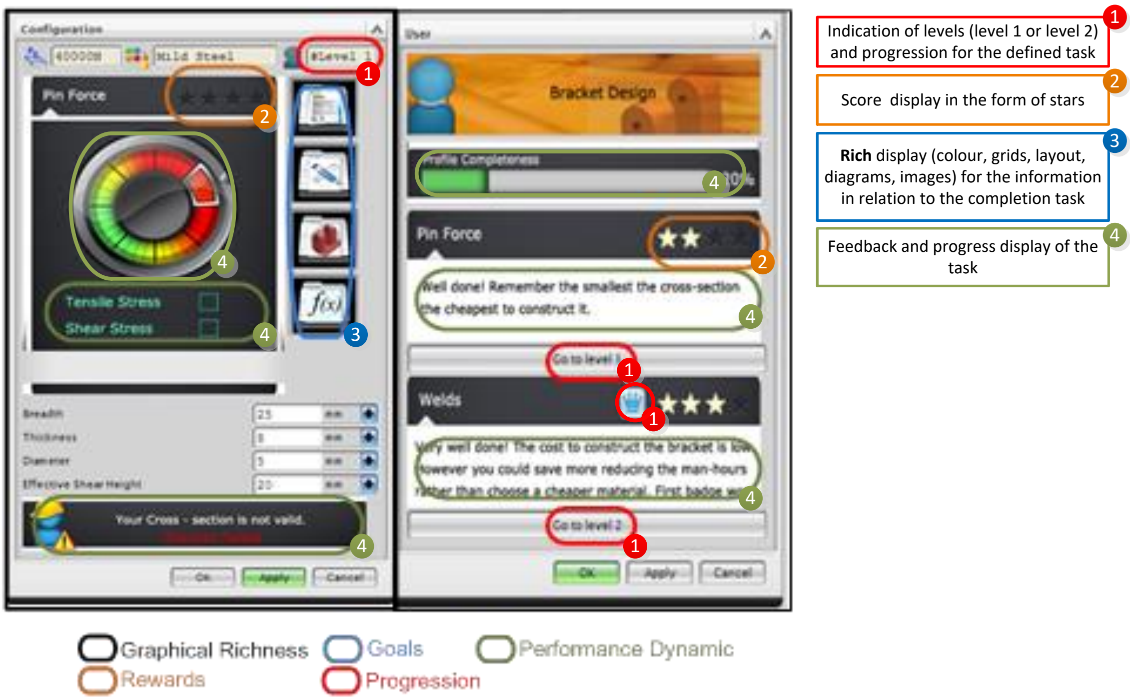


Figure 26 User interface for CADG or game-based CAD with the additional profile window (levels).

To further extend the task evaluation visual aid; the actual bracket model changes colour (Figure 27): green for acceptable, red for wrong and white when the parameters used are not part of the material list provided. Taken together these visceral outputs make up the performance-feedback mechanics.

Figure 27 Bracket configurations; green for acceptable, red for wrong and white for unknown parameters

For CADT GUI the entry parameters are the same as to CADG (e.g. inputs for breadth, thickness, diameter etc) as well as the content of instruction (task descriptions, material table, and formulas) for the direct comparison of the two, however there is no structured interaction in the form of feedback or any type of aesthetic element embedded (Figure 28).

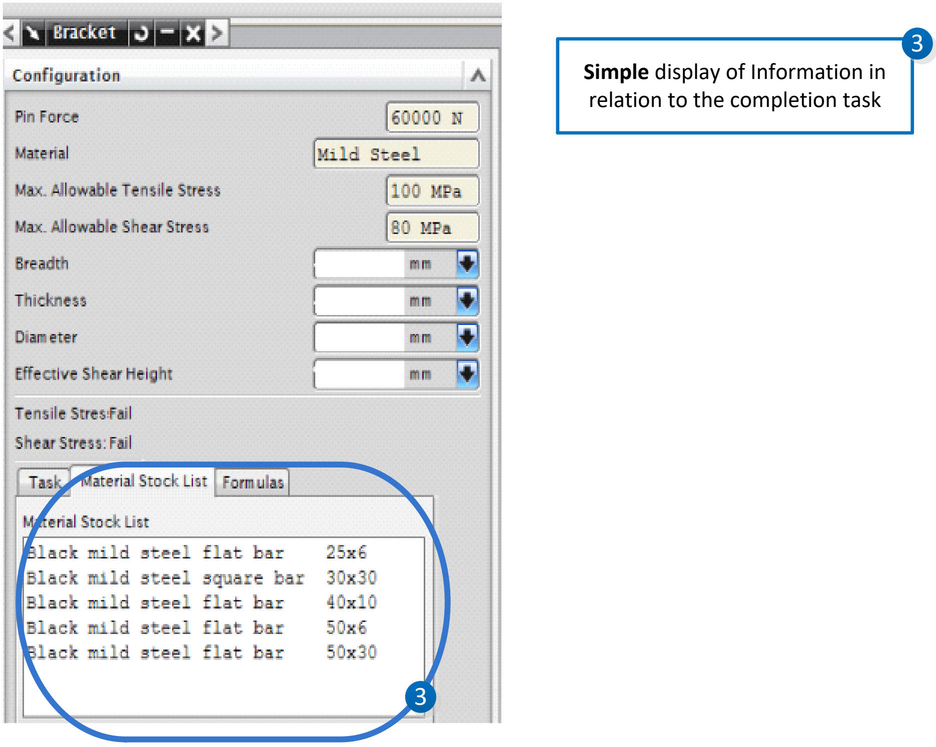


Figure 28 User interface of traditional CAD or CADT

4.3 Summary

DeReFrame is a framework to support and evaluate the impact of game mechanics on engineering design with CAD. It includes parametric phases of framing the problem (Chapters 2, 3), constructing the framework (Chapter 4) and phases of implementation and evaluation of game-based CAD (CADG). It also supports traditional CAD UI for comparative purposes.

The framework's defined measures are engineer's performance and psychological outcome. The metrics of usability, design strategy and emotional response are measured through mouse/keyboard events, eye motion and video recording, trough EEG, GSR/ECG and EOG and questionnaires. Data capture and synchronisation was via the ubilSA [139] framework. During the experimental trials, users are required to fulfil the goals of the parametric engineering design task, which are based on the bracket failure modes of tensile and/or shear stress with welded featuring. The data are analysed comparatively with TTESTs and ANOVA to evaluate the defined measures between CADG and CADT.

Chapter 5: Establishing the role and impact of game mechanics in CAD

This chapter examines whether the game mechanics of Directed Goals, Progression, Performance Feedback, Rewards & Achievements and CADG aesthetics positively impacts an engineer's performance, task flow and emotional responses when compared with a traditional CAD equivalent.

Sixteen (16) final-year engineering students participated, with each rating their level of expertise within CAD and expectations of the task's difficulty (Table 15).

Table 15: Sample demographics

Participants rated as	Number of samples	Average ratings on expectations on task difficulty 1(low)-5(high)
Moderate (intermediate)	5	1.5
Accomplished or Expert	11	2.9

The following sections report the findings of the bracket design experiment. All datasets and statistical outputs can be found in the Appendix A.

5.1 Engineers' performance results

The analysis was conducted using each CAD environment in turn (CADT then CADG or vice versa) and divided per task level: Level 1 (L1) pertains to the calculation of tensile and shear stress; Level 2 (L2) focuses on tensile and shear stress of a welded joint. Additionally, data was analysed per group of participants to evaluate the impact of game mechanics based on the order of CAD use.

- Group A: Participants worked on the CADT first following by the CADG.
- Group B: Participants worked on the CADG first following by the CADT.

a. **Effectiveness**

As defined previously, the ***Effectiveness*** constitutes the number of times users try and modify the bracket while designing it within the CAD environment (i.e. the number of design iterations). Since the same participants were involved in trials in both environments, two stages of TTESTs were carried out to compare this variable against each specific CAD interface (CADT and CADG). Test 1 was carried out across the whole sample within groups to determine the overall effect of the CAD environments on ***Effectiveness***. Test 2 was carried out within each separate group to determine if any potential bias was present due to using on CAD interface before the other.

In this case the following TTEST definitions apply:

- Dependent variable: ***Effectiveness*** (number of iterations).
- Independent variable: **CAD Environment** (CADT and CADG)

Test 1: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Effectiveness (number of iterations) when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Effectiveness (number of iterations) when using different CAD environments"*

Test 2: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Effectiveness (number of iterations) when using a specific CAD environment first."

The general **alternative hypothesis (H1)** is: *"There is a difference in participants' Effectiveness (number of iterations) when using a specific CAD environment first."*

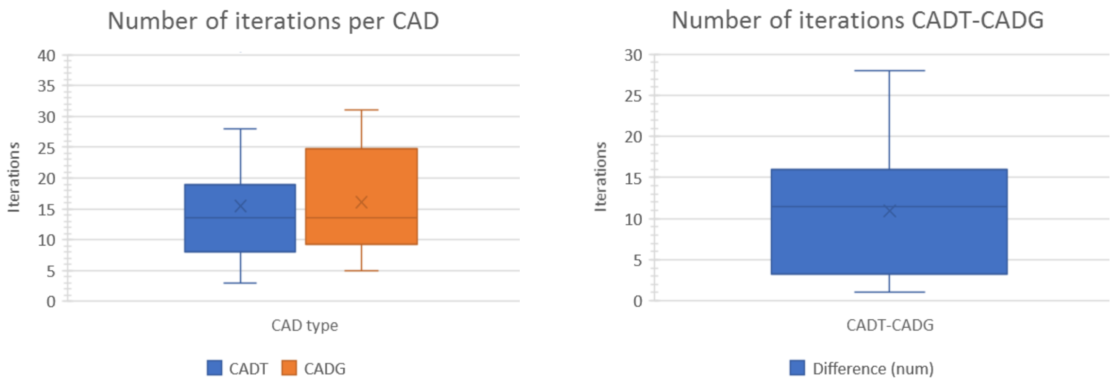
Table 16 shows the TTEST results for ***Effectiveness***.

Table 16 TTESTs output for difference in effectiveness or num. iterations per CAD type and per group

Test	Paired Differences			
	Means	Std. Dev.	t	p < 0.05
Test 1: Effectiveness CADT vs CADG	10.94	7.870	0.20	0.84
Test 2 (CADT-CADG): Effectiveness CADT first vs CADG second (Group A)	CADT: 14.57 CADG: 10.00	-	0.93	0.39
Test 2 (CADG-CADT): Effectiveness CADG first vs CADT second (Group B)	CADG: 20.89 CADT: 16.11	-	1.03	0.33

Table 16 indicate in both tests the results failed to reject each relevant null hypothesis (***H0***); therefore, the alternative hypotheses (***H1***) were both rejected with each TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers' effectiveness (Test 1 t(30) = 0.2, p < 0.84, Test 2 (CADT-CADG) t(30) = 0.93, p<0.39, Test 2 (CADG-CADT) t(30) = 1.03, p< 0.33).

Figure 29 however shows an increased number of iterations when participants used CADG as opposed to CADT. This may highlight that CADG influences users' behaviour in supporting a more 'sampling' type of approach for achieving a more optimised result. This was also observed in the BAMZOOKi experiments when users, after reaching a successful result, kept iterated their design until they reached a more optimised solution.



(a) (b)

Figure 29 Effectiveness or num. iterations per CAD type (a) and CADT-CADG median (b)

Figure 30, shows that for both Groups less iterations were required after their use of one or other of the CAD environments, which points to carry over terms of the design problem awareness and learning associated with system operation. However, this was not statistically significant.

Group B began with CADG followed by CADT. This group appears to show an increased number of iterations in both CADG and CADT, indicating that their trail-and-error problem-solving process used in gamified CAD was transferred to traditional CAD (see CADT-Group B-second). This is an indication that gamified CAD does influence design behaviour and the problem-solving process. However, when CADT was used first in Group A, the iterative nature of the design solution process used subsequently in CADG was not as apparent. Any benefits appeared to be based around problem familiarity and system operation carry over.

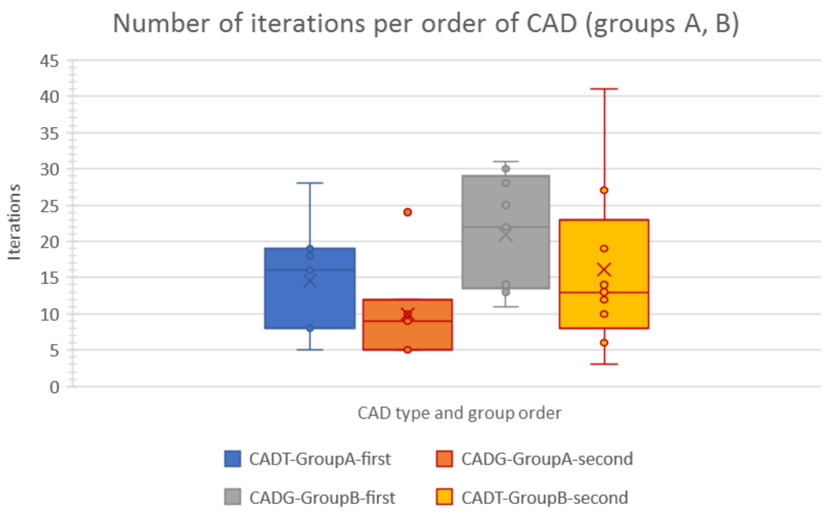


Figure 30 Effectiveness or num. iterations per CAD and per group

Therefore, although CADG was shown statistically to have no significant impact on user, these results do show that the game mechanics had some influence on engineers' behaviour and problem-solving approach; especially when the engineers work on gamified CAD first (Group B).

b. **Efficiency**

As defined previously, ***Efficiency*** constitutes the Task Completion Time (TCT) or Time completion, for users, to reach a solution for the design task of the bracket within the CAD environment. Similar to the Effectiveness testing structure in the previous section, two stages of TTESTs were carried out to compare this variable against each specific CAD interface (CADT and CADG). Test 1 was carried out across the whole sample within groups to determine the overall effect of the CAD environments on ***Efficiency.*** Test 2 was carried out within each separate group to determine if any potential bias was present due to using on CAD interface before the other.

In this case the following TTEST definitions apply:

- Dependent variable: ***Efficiency*** (time completion).
- Independent variable: **CAD Environment** (CADT and CADG)

Test 1: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Efficiency (time completion) when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Efficiency (time completion) when using different CAD environments"*

Test 2: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Efficiency (time completion) when using a specific CAD environment first."

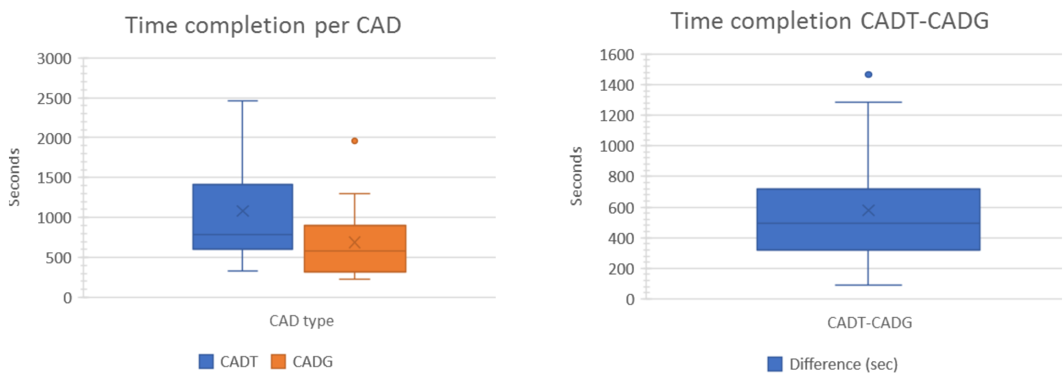
The general **alternative hypothesis (H1)** is: *"There is a difference in participants' Efficiency (time completion) when using a specific CAD environment first."*

Table 17 shows the TTESTs for ***Efficiency***.

Table 17 TTESTs output for difference in efficiency or time completion (sec) per CAD type and per group

	Paired Differences			
	Means	Std. Dev.	t	p < 0.05
Test 1: Efficiency CADT vs CADG	578.62	379.12	1.99	0.06
Test 2 (CADT-CADG): Efficiency CADT first CADG second (Group A)	CADT: 1152.00 CADG: 676.57	-	2.34	0.06
Test 2 (CADG-CADT): Efficiency CADG first CADT second (Group B)	CADG: 699.89 CADT: 1030.33	-	1.55	0.16

Table 17 indicate in both tests the results failed to reject each relevant null hypothesis (***H0***); therefore, the alternative hypotheses (***H1***) were both rejected with each TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers' efficiency (Test 1 $t(28) = 1.99$, $p < 0.06$, Test 2 (CADT-CADG) $t(6) = 2.34$, $p < 0.06$, Test 2 (CADG-CADT) $t(8) = 1.55$, $p < 0.16$). Though the TTESTs results indicate no statistical significance ($p< 0.05$), the means efficiency in all three tests showed that participants working on CADG spent less time working in the task compared to the participants using CADT. Figure 31a show a reduced time completion for participants when used CADG compared to CADT, highlighting the possible impact of game mechanics in reaching a solution quicker.



(a) (b)

Figure 31 Efficiency or time completion per CAD type (a) and CADT-CADG median (b)

Figure 32 shows Group A finished faster than Group B indicating that the game mechanics influenced the time invested on completing the task.

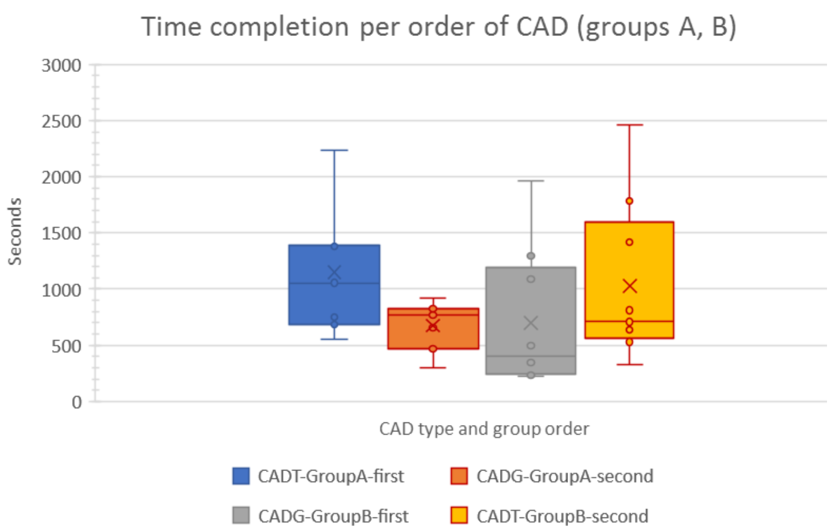


Figure 32 Efficiency or time completion per CAD and per group

c. Satisfaction

Satisfaction describes a positive emotional response related to fulfilment. Users rated their ***Satisfaction*** of their interactions with the CAD environments in a scale 1-10. Similar to the previous metrics of effectiveness and efficiency testing structures, two stages of TTESTs were carried out to compare this variable against each specific CAD interface (CADT and CADG). Test 1 was carried out across the whole sample within groups to determine the overall effect of the CAD environments on ***Satisfaction.*** Test 2 was carried out within each separate group to determine if any potential bias was present due to using on CAD interface before the other.

In this case the following TTEST definitions apply:

- Dependent variable: ***Satisfaction***
- Independent variable: **CAD Environment** (CADT and CADG)

Test 1: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Satisfaction when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Satisfaction when using different CAD environments"*

Test 2: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Satisfaction when using a specific CAD environment first."

The general **alternative hypothesis (H1)** is: *"There is a difference in participants' Satisfaction when using a specific CAD environment first."*

Table 18 shows the TTESTs for ***Satisfaction***.

Table 18 TTESTs output for difference in satisfaction ratings per CAD type

	Paired Differences			
	Means	Std. Dev.	t	p < 0.05
Test 1: Satisfaction CADT vs CADG	1.31	1.35	0.29	0.77
Test 2 (CADT-CADG): Satisfaction CADT first vs CADG second (Group A)	CADT: 6.71 CADG: 6.71	-	0	1
Test 2 (CADG-CADT): Satisfaction CADG first vs CADT second (Group B)	CADG: 6.67 CADT: 6.33	-	0.45	0.65

Both tests the results failed to reject each relevant null hypothesis (***H0***); therefore, the alternative hypotheses (***H1***) are both rejected with each TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers' satisfaction (Test 1 $t(30) = 0.29$, $p < 0.77$, Test 2 (CADT-CADG) $t(6) = 0.0$ $p < 1.0$, Test 2 (CADG-CADT) $t(8) = 0.45$, $p < 0.65$).

Figure 33 and Figure 34 shows very similar trends. The game mechanics do not influence engineers' emotional response with respect to satisfaction. This may be due the level of design differentiation between the gamified CAD and the conventional CAD.

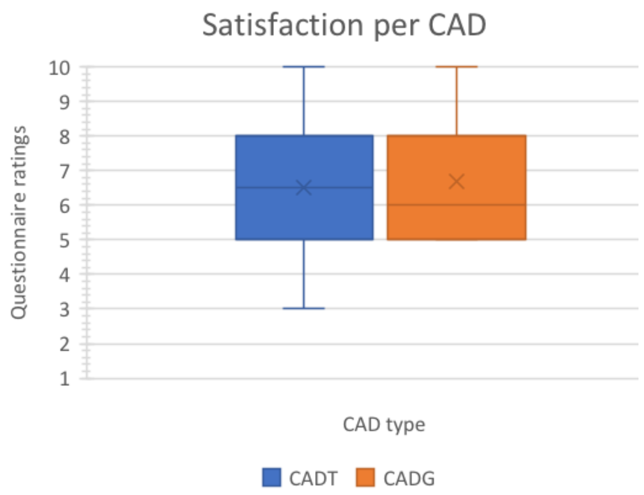


Figure 33 Satisfaction ratings per CAD type

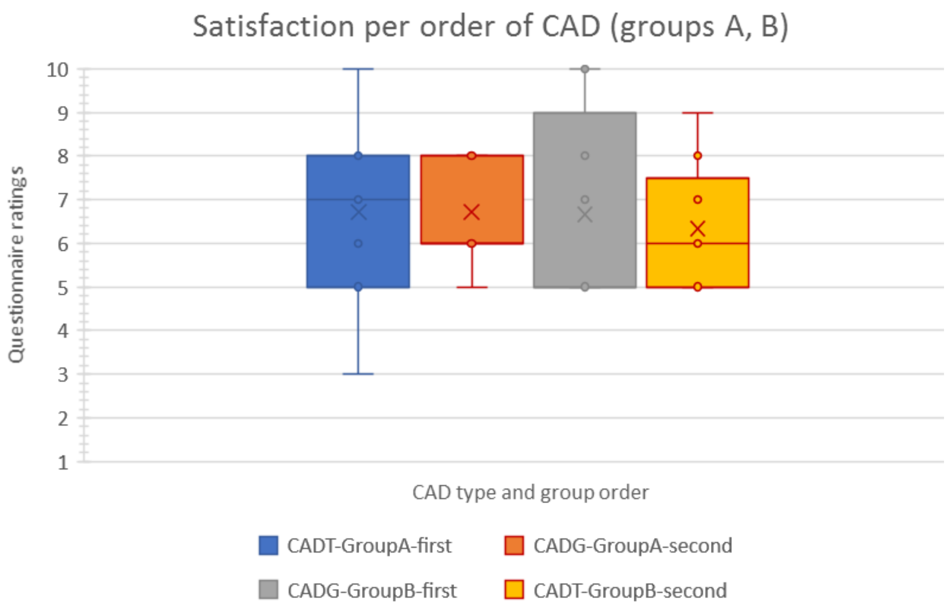


Figure 34 Satisfaction ratings per CAD and per group

d. Cognitive load

Cognitive load describes the level of mental demand, temporal demand, performance, effort and frustration of users within a context of an interaction. Users rated their ***Cognitive load*** for their interactions with the CAD environments in a scale 1-20. The scoring of cognitive are though the NASA TLX framework and its questionnaire. The questionnaire can be found in the Appendix E.

Following the testing structure of the previous metrics (effectiveness, efficiency, satisfaction, in above sections), two stages of TTESTs were carried out to compare this variable against each specific CAD interface (CADT and CADG). Test 1 was carried out across the whole sample within groups to determine the overall effect of the CAD environments on ***Cognitive load.*** Test 2 was carried out within each separate group to determine if any potential bias was present due to using on CAD interface before the other.

In this case the following TTEST definitions apply:

- Dependent variable: ***Cognitive load***
- Independent variable: **CAD Environment** (CADT and CADG)

Test 1: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Cognitive load when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Cognitive load when using different CAD environments"*

Test 2: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Cognitive load when using a specific CAD environment first."

The general **alternative hypothesis (H1)** is: *"There is a difference in participants' Cognitive load when using a specific CAD environment first."*

Table 19 shows the TTESTs for ***Cognitive load***.

Table 19 TTESTs output for difference in cognitive ratings per CAD type

	Paired Differences			
	Means	Std. Dev.	t	p >= 0.05
Test 1: Cognitive load CADT vs CADG	10.81	8.7	0.64	0.53
Test 2 (CADT-CADG): Cognitive load CADT first vs CADG second (Group A)	CADT: 36.3 CADG: 30.23	-	0	0.20
Test 2 (CADG-CADT): Cognitive load CADG first vs CADT second (Group B)	CADG: 40.44 CADT: 42.52	-	0.45	0.70

Both test results failed to reject each relevant null hypothesis (***H0***); therefore, the alternative hypotheses (***H1***) are both rejected with each TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers' cognitive load (Test 1 $t(29) = 0.64$, $p < 0.53$, Test 2 (CADT-CADG) t($t(6) = 1.42$ $p < 0.20$, Test 2 (CADG-CADT) $t(8) = 0.39$, $p < 0.70$).

Figure 35 shows the users' ratings between CADT and CADG are very similar. Participants in the CADT experienced slightly higher cognitive workload but neither of the two CADs imposed high workload as the mean scores for both were below the median value (50/100).

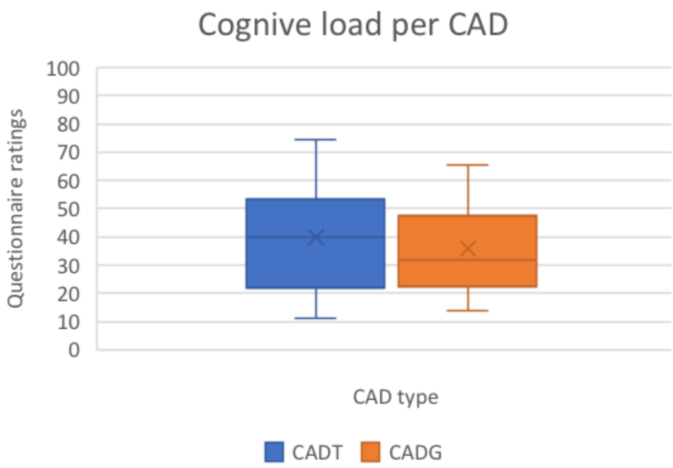


Figure 35 Cognitive load ratings per CAD type

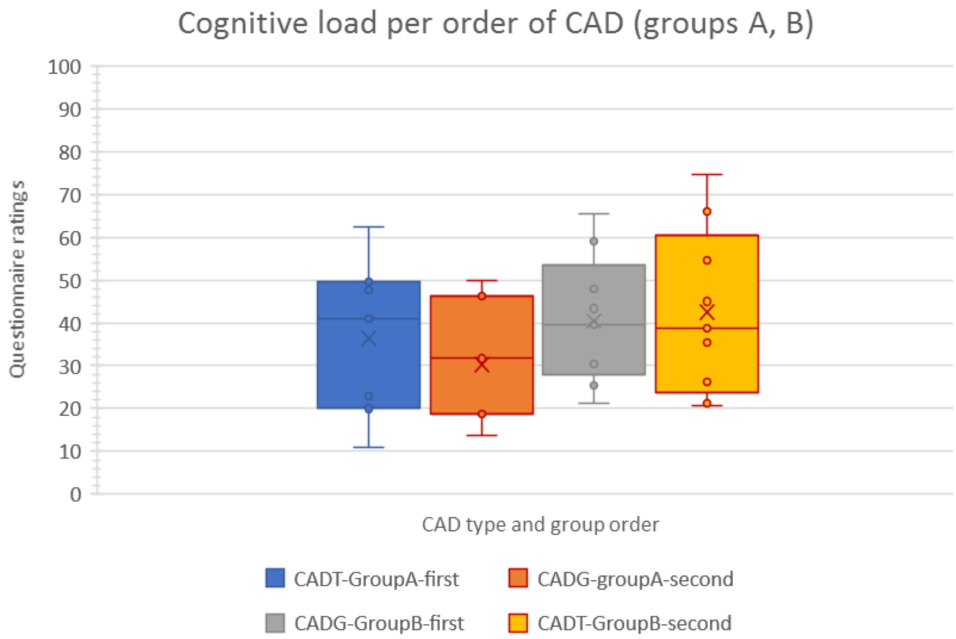


Figure 36 Cognitive load ratings per CAD and per group

The defined list of game mechanics has no impact on the workload of the engineers for the given task of the bracket. One possible explanation is the actual goal description of the task. Both CADs have the *same* description of goals and its division to sub-goals for the task involving similar associated steps to a solution resulting in statistically similar low- level cognitive load (Figure 36). Also, is worth noting the possibility of the task maybe being too easy for the current users.

e. GOMs

With regards to the design strategy for both CADG and CADT, the analysis was carried out within the two groups A & B:

- Group A: Participants worked on the CADT first following by the CADG
- Group B: Participants worked on the CADG first following by the CADT

The task goal was to effectively configure the bracket such that it will not fail under the applied load. Within that task's goal the main methods or functional descriptions to achieve that goal, otherwise called functional level operators (FLOs) [126] are:

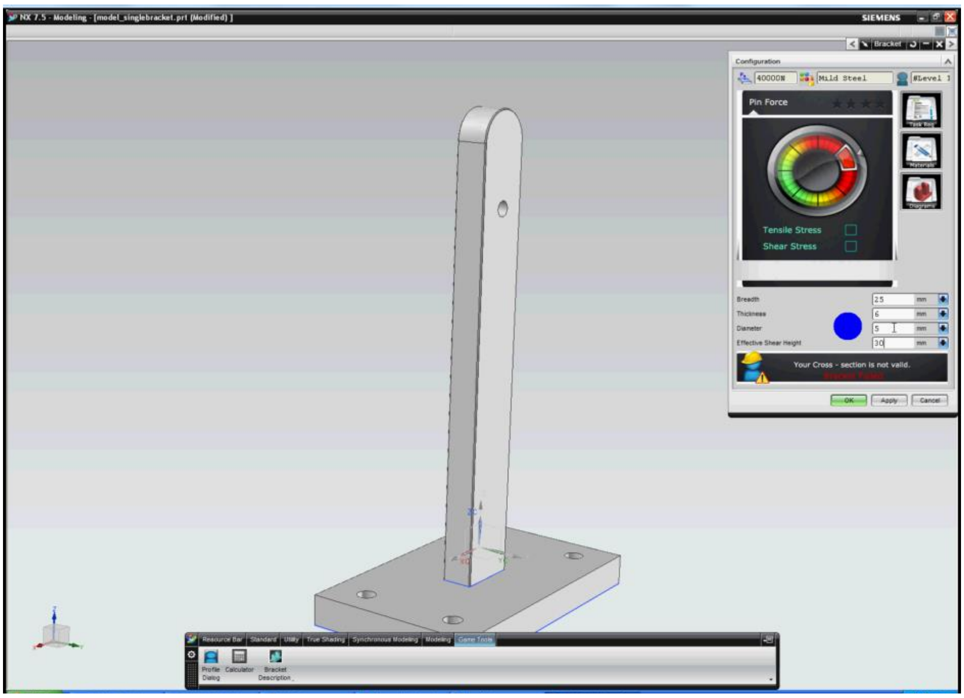
- Check resources
- Entering cross–sections / weld type–size
- Test

Table 20 shows the optimal FLO order for the task of parameterising the bracket. The text highlighted represents the individual FLOs (Check resources, Entering cross-sections / weld type-size, Test).

Table 20 Optimal order of FLOs for the parameterization of the bracket

GOAL: Finish task (both levels, L1, L2)	
..GOAL: Pass L1 ...GOAL: Check resources .... Task / Material Stock List / Formulas .... Material Stock List / Task / Formulas .... Formulas / Task / Material Stock List ...GOAL: Locate cross-section parameters to configure .... Breadth .... Thickness ...GOAL: Check resources .... Material Stock List .... Formulas ...GOAL: Calculate selected cross-section from Material Stock List ...GOAL: Enter cross-section values .... Breadth .... Thickness ...GOAL: Click test	GOAL: Pass L2 ...GOAL: Check resources .... Task / Material Stock List / Formulas .... Material Stock List / Task / Formulas .... Formulas / Task / Material Stock List ...GOAL: Locate cross-section and weld parameters to configure .... Breadth .... Thickness .... Weld type .... Weld size ...SUB GOAL 1: Check resources .... Material Stock List .... Formulas ...SUB GOAL 1: Calculate chosen cross-section from Material Stock List ...SUB GOAL 1: Enter cross-section values .... Breadth .... Thickness ...SUB GOAL 1: Click test ...SUB GOAL 2: Check resources .... Formulas ...SUB GOAL 2: Calculate weld size based on cross-section and chosen type/types ...SUB GOAL 2: Enter cross-section values .... Weld type .... Weld size ...SUB GOAL 2: Click test ..GOAL: Exit main design window

The CAD event logs (Figure 37) for both CADT and CADG indicated that the participants' design strategies or task flows for configuring the bracket deviated from the optimal approach presented in Table 20.



(a)

	E	F	G	H	I	J	K	L	M
1	Subject	Task&Level	Mouse Action	Value	Time Stamp (s)	Calc	Extra Info	Note	Score satisfaction
2	6	CADG-1	CADG		1.640	N			
3			Level 1		5.824	N			
4			Click On	ss Section Error Mess	8.392	N			
5			Stock Tab		14.392	N			very high/decreasing
6			Click On	Cross Section 25x6	22.888	N			
7			Fold	Stock Tab	25.844	N			
8			Unfold	Stock Tab	26.642	N			
9			Close Stock Tab		28.079	N	Double Click		
10					28.476	N			
11			Breadth	25	33.855	N			
12			Thickness	6	36.248	N			
13			Click On	Background	38.505	N			
14			Click On	Shear Height	39.592	N			
15					39.952	N			
16			Click On	Diameter	40.520	N			
17			Apply	Fail	42.572	N	All		
18			Click On	"Mild Steel"	59.917	N			
19			Formula Tab		69.088	N			very high/decreasing
20			Close Formula Tab		71.832	N			
21			Stock Tab		72.718	N			*very low/increasing*
22			Close Stock Tab		73.863	N			
23			Click On	"Mild Steel"	76.765	N			
24			Click On	"Mild Steel" Icon	77.216	N			

(b)

Figure 37 Video recording of user's interaction (a) along with a typical participant's log (b)

Depending on their knowledge and experience, participants followed either two strategies:

- Sampling or probability approach: participants alternated between checking resources, material stock list, entering cross–sections, weld type–size and then testing them to see if they are successful. If the selected cross-sections, weld size and type were successful, the task was considered completed. The use of the formulas with related stress and weld calculations was typically minimal (Figure 38).

- Methodological & optimising approach: As with above, however the difference was that participants were able to judge the feedback and find a way to optimise the bracket to achieve best possible results for the task. The use of the formulas with related stress and weld calculations was also minimal (Figure 38).

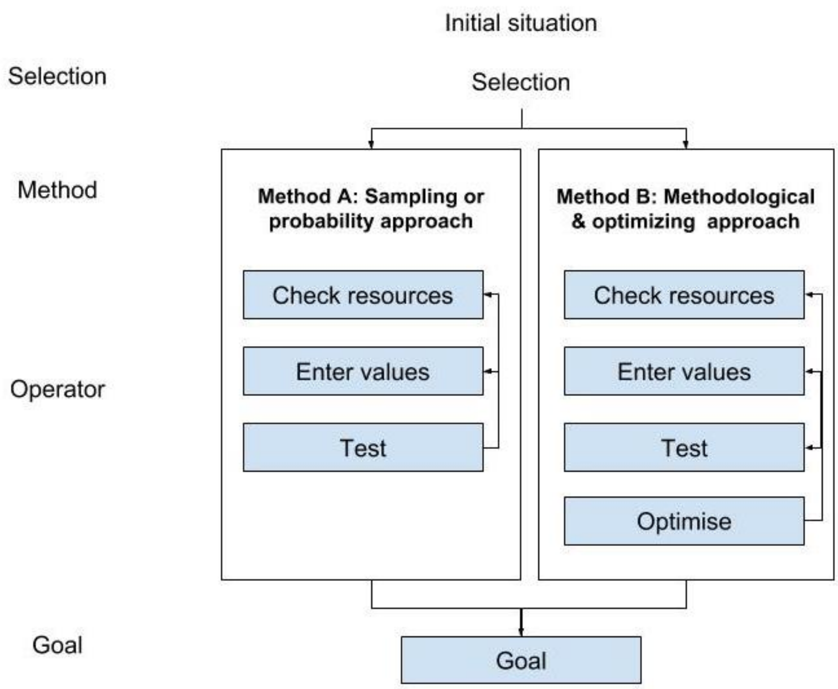


Figure 38 Participants' used two strategies: a sampling approach and a methodological and optimization approach

All but two participants in group A (CADT-CADG) used the sampling approach of checking resources, entering values, and testing them until they found a successful set of values fulfilling the task. For Group B (CADG-CADT), two participants followed a methodological and optimised approach by checking the task goals, task resources, entering values and testing them until they found a successful set of values fulfilling the task prior to design optimisation.

Multiple variables influence the design strategy of the engineers: effectiveness, efficiency, satisfaction ratings, cognitive load and the description of goals for the task as well as the feedback mechanics and rewards. Group B participants had on average 2-3 additional iterations after completing both levels' goals indicating that the incentive of scoring, 'have a better score' and the mastery of the 'desired' actions or design strategy to reach that end goal of the game, motivate them to continue.

Game mechanics do have some influence on engineers' behaviour and problem-solving approach. As seen Effectiveness metric in Figure 29, Figure 30 participants in Group B who experienced CADG first followed by CADT had more design iterations compared to Group A. This indicates a positive use of performance-feedback game mechanic which encourages users to do certain actions and learn from its consequences, thereby achieving game mastery, agreeing with [74].

Based on the participants' questionnaire (see Table 21) Performance-Feedback (C, E) and their design representations were mostly selected for their potential to be implemented in future CADs.

Table 21 Participants questionnaires (RQ1-RQ4) answers on game mechanics (g.m.)

Users	g.m. influence performance (RQ1)	g.m liked (RQ2)	Satisfaction User Feedback (RQ3b)	g.m. applied CAD (RQ4)
1	C	C, E	Quite satisfied, yes	C
2	B, C	all	Only at the end	B, C
3	E	A	Was only at the end, so no	E
4	B, C, A	B, C, A	Was only at the end, so no	B, C, E, F
5	A	C, A	yes	E
6	A, C, E	C, E	yes	C
7	B	E	yes	E
8	B, C, E	B, C, E	yes	A, B, C
9	"Resources"	A	"Rewards coming only from boss"	-
10	C	E, C	"Irrelevant"	E, C
11	A	A	"Not really"	A, C, E
12	B	B	yes	B
13	A, C	A	no	A
A: Round Interface (graphical richness - aesthetics), B: Progress: Check Boxes, C: Feedback: info window D: Progress: levels, E: Feedback: Colour, F: Rewards: Achievements				

5.1.1 Engineer's performance results summary

The results indicate that game mechanics have not a significant impact on the engineer's performance. However, they do show some influence; the effectiveness and efficiency results with GOMs indicated better solutions on the gamified system with participants being better engaged in the process through more design iterations and optimised calculating design strategy. In Group B (CADG first followed by CADT) the participants' approach is influenced by their interaction with CADG by increasing the amount of design iterations to reach an optimal result (see Figure 30). Thus, moving from the gamified system to the conventional one, it was observed that were certain expectations of interaction (e.g. feedback). This signifies the game elements' influence (on approaching the task) and is transferability in a non-game context.

The cognitive load was the same for gamified and conventional system, possibly due to the goal-oriented nature of the parametric task, which lead to similar mental loads for both versions of CAD.

There is the possibility that the same description of the task's goals within CADT and CADG (clear presentation of information and goals and sub-goals) seem to influence participants into having similar experience in both CAD environments.

5.2 Emotional response

The emotional responses were captured using a 1-10 scale questionnaire and analysed per CAD environment and per group (only for the emotional questionnaire):

- Group A: Participants worked on the CADT first following by the CADG
- Group B: Participants worked on the CADG first following by the CADT

The emotion of satisfaction, being part of the usability metrics within the engineer's performance will be referenced here but its analysis can be found in 5.1 Engineer's performance.

a. Emotions questionnaire

Engagement, Frustration, Challenge (and ***Satisfaction***) are a set of district emotional responses defined by the dimensions of arousal and valance. These emotional responses are chosen to align and be comparable to the fuzzy model emotions, referenced in [135] and seen in the next section.

Users rated their ***Engagement, Frustration, Challenge*** of their interactions with the CAD environments in a scale 1-10. Similar to the metrics of satisfaction, two stages of TTESTs were carried out to compare this variable against each specific CAD interface (CADT and CADG). Test 1 was carried out across the whole sample within groups to determine the overall effect of the CAD environments on ***Engagement, Frustration, Challenge.*** Test 2 was carried out within each separate group to determine if any potential bias was present due to using on CAD interface before the other.

In this case the following TTEST definitions apply:

- Dependent variable: ***Engagement, Frustration, Challenge***
- Independent variable: **CAD Environment** (CADT and CADG)

Test 1: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Engagement, Frustration, Challenge when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Engagement, Frustration, Challenge when using different CAD environments"*

Test 2: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Engagement, Frustration, Challenge when using a specific CAD environment first."

The general **alternative hypothesis (H1)** is: *"There is a difference in participants' Engagement, Frustration, Challenge when using a specific CAD environment first."*

Table 22 shows the TTESTs for ***Engagement, Frustration,*** *and* ***Challenge***.

Table 22 TTESTs output for difference in engagement, challenge, frustration, and satisfaction (for reference) ratings per CAD type

	Paired Differences			
	Mean	Std. Dev.	t	p < 0.05
Test 1: Engagement CADT vs CADG	CADT: 6 CADG: 5.81	CADT: 2.6 CADG: 2.5	0.20	0.84
Test 2 (CADT-CADG): Engagement CADT first vs CADG second (Group A)	CADT: 6.57 CADG: 6.42	-	0.25	0.80
Test 2 (CADG-CADT): Engagement CADG first vs CADT second (Group B)	CADG: 5.33 CADT: 5.55	-	0.45	0.66
Test 1: Challenge CADT vs CADG	CADT: 5.12 CADG: 4.93	CADT: 3.0 CADG: 2.3	0.19	0.84
Test 2 (CADT-CADG): Challenge CADT first vs CADG second (Group A)	CADT: 5.71 CADG: 6.0	-	0.44	0.67
Test 2 (CADG-CADT): Challenge CADG first vs CADT second (Group B)	CADG: 4.11 CADT: 4.67	-	1.47	0.18
Test 1: Frustration CADT vs CADG	CADT: 3.93 CADG: 4.12	CADT: 3.4 CADG: 3.0	0.16	0.87
Test 2 (CADT-CADG): Frustration CADT first vs CADG second (Group A)	CADT: 5.0 CADG: 5.0	-	0	1.00
Test 2 (CADG-CADT): Frustration CADG first vs CADT second (Group B)	CADG: 3.44 CADT: 3.11	-	0.23	0.82

Table 22 indicate test results across the emotional responses Engagement, Challenge and Frustration failed to reject each relevant null hypothesis (***H0***); therefore, the alternative hypotheses (***H1***) are both rejected with each TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers' given emotional responses (Test 1 Engagement $t(30) = 0.20$ $p < 0.84$, Test 2 Engagement $t(6)= 0.25$ $p < 0.80$, Test 2 Engagement $t(8) = 0.45$, Test 1 Challenge $t(30) = 0.19$ $p < 0.84$, Test 2 Challenge $t(6)= 0.44$ $p < 0.67$, Test 2 Challenge $(8) = 1.47$, $p < 0.18$, Test 1 Frustration $t(30) = 0.16$ $p < 0.87$, Test 2 Frustration, $t(6)= 0$ $p < 1.0$, Test 2 Frustration $t(8) = 0.23$, $p < 0.82$).

Figure 39 and Figure 40 show very similar trend, implying that game mechanics are not an influencing factor in the emotional responses of the participants for the given task.

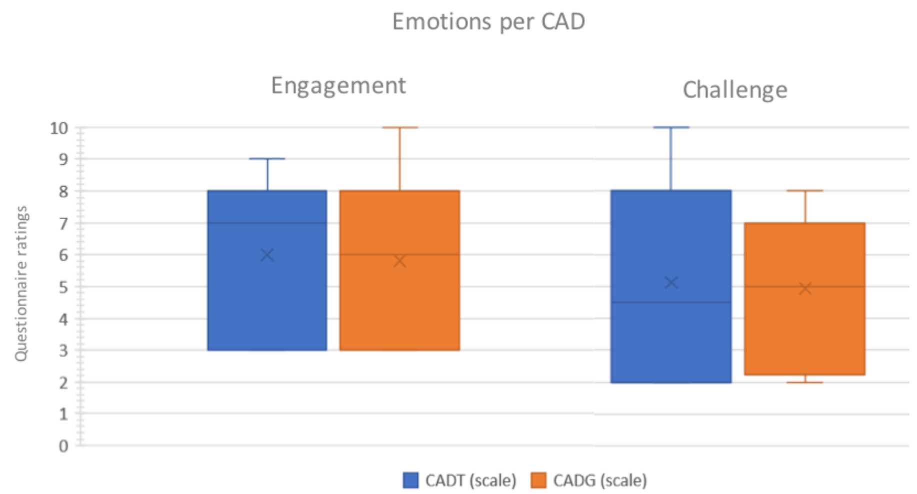


Figure 39 Engagement and challenge per CAD type and per group

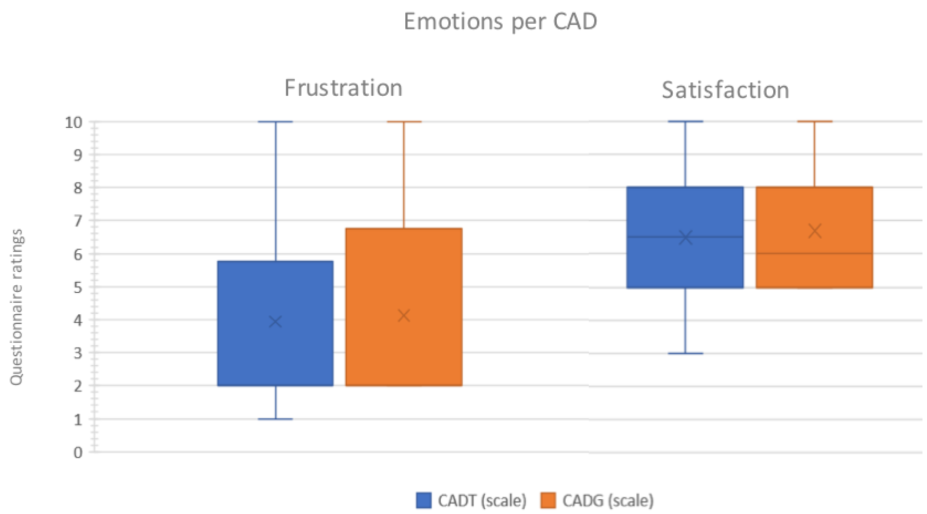


Figure 40 Frustration and satisfaction (for reference) per CAD type and per group

The TTEST results indicate no statistically significant difference also seen in Figure 41, and Figure 42. However, is worth pointing out in Figure 42 that the emotional response of frustration for group A is higher rated compared to Group B. This suggests emotional responses in the gamified CAD could set positive interaction expectations for the engineers.

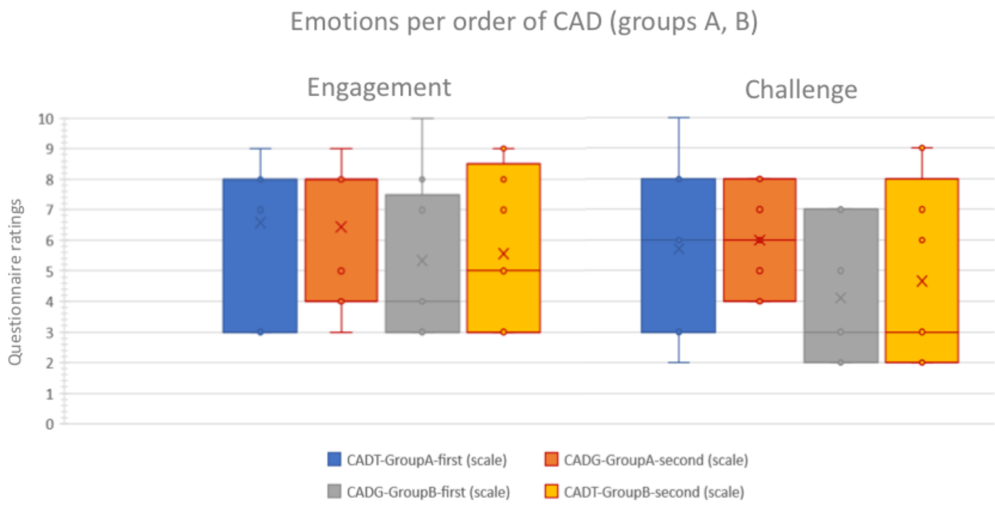


Figure 41 Engagement and challenge ratings per CAD and per group

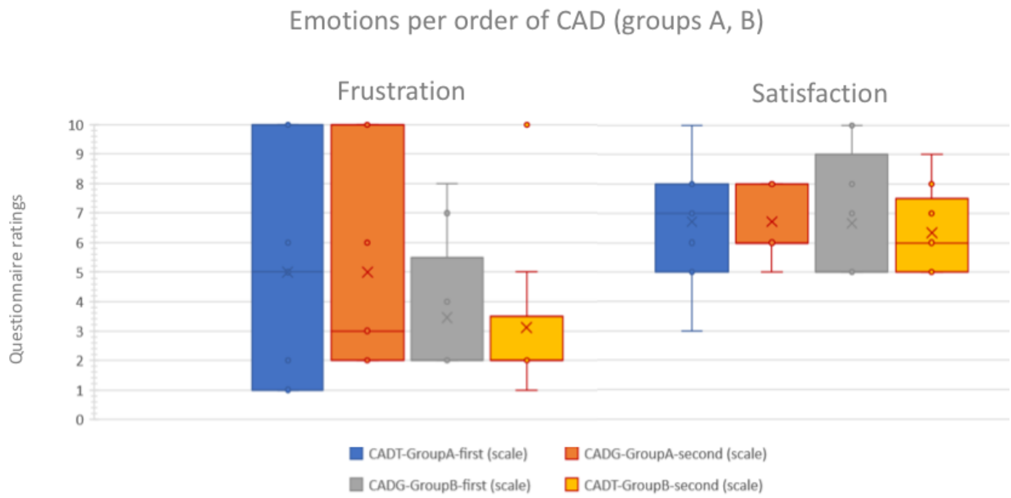


Figure 42 Frustration and satisfaction ratings per CAD and per group

Overall CADG had no impact on emotion responses associated to engagement, challenge, frustration, and satisfaction as rated by the participants (emotional questionnaire). Regardless of the CADG frustration ratings, the overall association of gamified systems and the serious activity of engineering design needs further tuning.

b. **Fuzzy logic**

To evaluate the emotional responses to interaction with CADG and CADT more objectively, fuzzy logic was used to separate the four emotions of Engagement, Challenge, Frustration and Satisfaction into its valance/affect. More information on the process is seen in [135]. Using MATLAB [142], the outputs were compared with TTESTs to identify any statistically significant differences between the two environments of CADG and CADT.

Figure 43 shows the formula used in MATLAB for the TTESTs.

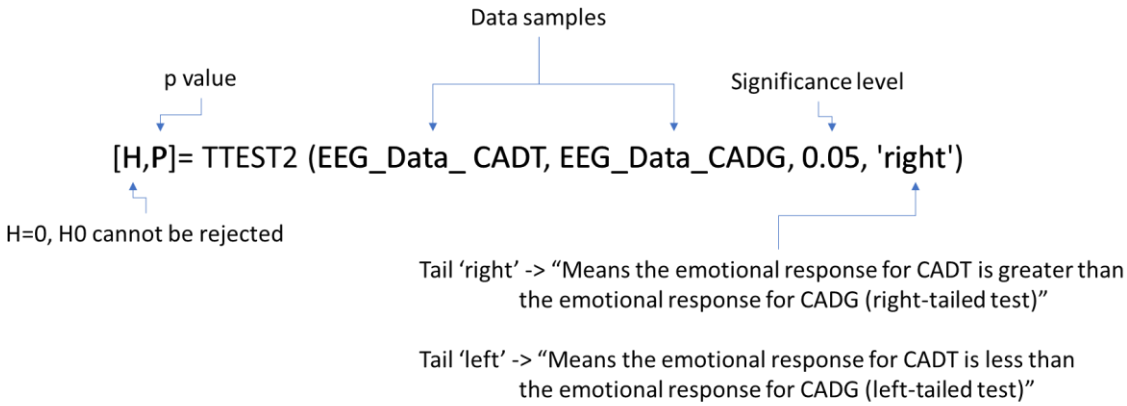


Figure 43 TTEST formula for MATLAB

For this part of the analysis, four (4) participants were removed due bad quality/noisy/partly recorded (corrupted) set of EEG data, bringing the sample to twelve (12).

In this case the following TTEST definitions apply:

- Dependent variable: ***Engagement, Frustration, Challenge, Satisfaction***
- Independent variable: **CAD Environment** (CADT and CADG)

Test 1: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Engagement, Frustration, Challenge and Satisfaction when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Engagement, Frustration, Challenge and Satisfaction when using different CAD environments"*

Table 23 shows the TTEST results of the fuzzy logic on Engagement, Challenge, Frustration and Satisfaction.

Table 23 Fuzzy TTESTs outputs for Engagement, Challenge, Frustration, and Satisfaction per CAD environment

	Paired Differences	
	H	p < 0.05
Test 1: Engagement CADT vs CADG	0	0.81
Test 1: Challenge CADT vs CADG	0	0.86
Test 1: Frustration CADT vs CADG	0	0.95
Test 1: Satisfaction CADT vs CADG	0	0.88

Table 23 indicate all test results across the emotional responses Engagement, Challenge, Frustration and Satisfaction, failed to reject each relevant null hypothesis (***H0***). Each TTEST showed no significant statistical difference regarding the influence of the CAD environment on the engineers' emotional response (Test 1 Engagement H = 0 p < 0.81, Test 1 Challenge H=0 p < 0.86, Test 1 Frustration H = 0 p < 0.95, Test 1 Satisfaction H = 0 p < 0.88).

The EEG recordings and emotional responses mappings to Engagement, Challenge, Frustration and Satisfaction do not show that the game mechanics have an impact CAD interaction. One possible explanation is that the gamified CAD in this current implementation does not meet engineers' expectations as a design system in a professional setting.

5.2.1 Emotional responses results summary

The emotional response results provide a positive view of the aspects of the game mechanics but have no significant impact. The novelty of the gamified system seems to have appealed the participants but shown not increased engagement or satisfaction. The game mechanics of Performance-Feedback and Progression were the most impactful and preferred among the game mechanics (per user ratings and their translation of their impact on the metric of effectiveness). However, overall the gamified experience seems to be distracting from the familiar engineering design approaches promoted in an engineering course curriculum.

A further focused approach may be required to determine which combination of game mechanics are most impactful on the emotional experience of engineering design with CAD.

5.3 Discussion and lessons learned

The usability metrics of effectiveness and efficiency, and the measure of design strategy with GOMS were no statistically significant, however they did show some influence of the gamified approach on the engineer's performance. Participants showed a better problem-solving approach to the task on the gamified system with a 'methodological and optimised' strategy compared to 'sampling approach; they were able to judge the CADG feedback and decide on the way to optimise the bracket. Within this context they highlighted the goal-oriented nature of the game mechanics.

The cognitive load was similar between the CAD environments. It has been also shown that the engineers' design behaviour was influenced after they interacted with the game elements, reinforcing similar interactions in non-game context on similar tasks (see Figure 30, Group B)

The emotional responses do not indicate significant change based on the game mechanics used. Participants found the experience disconnected from the processes currently taught/followed. A possible explanation is that the novelty of the gamified CAD did not feel authentically connected with the seriousness of real-world tasks. Additionally, could be the goal-oriented nature of the parametric task and the provision of the same detailed information and task requirements in both CAD environments, discouraged participants to engage in the process of approaching and understanding the problem within the relevant context, thus eliciting different emotional responses.

Lessons learned:

1. The combined game mechanics of performance-feedback and rewards-achievements showed were more influential among the game mechanics but need further tuning to balance the serious activity (of engineering design) based on users' expectations.
2. The presentation of goals on CADT and game mechanics of directed goals in CADG need to be less detailed to provide the participants the opportunity to be more challenged and define for themselves essential aspects of the problem structure of the task.
3. Based on moderator's observations and participants comments, the EEG cap raised an issue of comfort and feeling of intrusiveness that should be taken as an influencing factor on their emotional responses' results.

5.4 Summary

Overall, the results are statistically insignificant, but the game mechanics indicate a positive influence in the performance of engineers for a simple parametric task; Within CADG, engineers worked with a more optimized strategy (see Figure 38) for the given task. In this context, CADG is linked geometry to performance of the design thus allowed for the engineers a deeper understanding of the connections between parameters (e.g. breadth, thickness, weld size etc.) leading to an optimised design.

The impact of game Aesthetics and the game mechanics of Performance-Feedback and Rewards-Achievements did not influence their interaction significantly other than possibly providing a more appealing interface.

One key finding from the cognitive load was that the goal-oriented nature of the parametric task exaggerated by the impact of 'clear goals' and task description, provided a similar problem-structure in both CADT and CADG. There was no opportunity for the engineers to interpret the problem in their own way (i.e. breakdown the task to their goals and sub-goals) and allow the game mechanics to have any impact.

Further experimentation is needed to understand and balance the goal-oriented nature of the parametric task with the level of instruction given and the selected game mechanics with particular interest on Directed Goals (which by default is connected to ‘clear goals’).

Chapter 6: Game mechanics' goal-orientedness and its effects

The exaggerated goal-oriented nature of the parametric task essentially created a zero-sum effect for the game mechanic of Directed Goals as evidenced in Chapter 5 - similar user experience (performance and emotional responses) when working in both CADs. Thus, posed a challenge on engineers' experiencing the rest of the game mechanics (Progression, Performance-Feedback, Rewards-Achievements) during the design process.

Based on this observation, Chapter 6 details a revised experimentation balancing the goal-oriented-nature of the parametric task and the impact of game mechanics.

6.1 Experimental design

Prior experiments indicated that participants were influenced by the task's goals exacerbated by the game mechanic of goals. In the given parametric task, the clearly stated end goal and task's decomposition into sub-goals or achievable states drove a similar goal-oriented behaviour (goal-oriented cognition [70]) for users working in both CAD environments (as seen by the no statistical significant results on the usability metrics and similar outcomes with GOMs).

Further investigation into the engineers' goal oriented behavioural strategies, showed that they were composed pre-existing knowledge entities, which can be associated with the context of a set of game goal states and their pre-conditions. Using the GOAP (Goal, Action, Plans and Formulate) framework the engineer's behaviour can be identified as a plan/strategy based on a goal's structure with actions attached to pre-conditions and effects. When that plan/strategy is formulated then the goal-directed mechanism to activates a behaviour satisfying the most relevant goal at that particular instance [148].

In this context, parametric design or GOAP can both be described as a goal-oriented cognitive information processes, where knowledge is assumed to be predictable (parameters or defined actions) [149]. Consequently, both CADG and CADT were inadvertently driven by the same goal-oriented nature of the parametric task very much minimising the effect of the other game mechanics.

A design iteration was conducted based on these findings to:

- ✓ Minimise the goal-oriented effect, i.e. game mechanic of Directed Goals
- ✓ Focus on emphasizing the game mechanics of Performance-Feedback, and aesthetics with graphical richness.

6.1.1 *Game mechanics evaluation metrics*

The game mechanics evaluation metrics remain the same and can be seen in Table 24 and Table 25.

Table 24 Engineer's performance metrics

Engineer's performance metrics
Usability metrics • Efficiency or "time on task" referring to task completion time **[129]**. • Effectiveness or "error rates" referring to the frequency of a specific set of actions - iterations to reach and end goal / finish the task **[129]**. • Satisfaction, referring to the extent to which an interaction can be satisfying; It can be measured by satisfaction rating questionnaire **[129]**.
Design strategy or task flow • GOMS (user task flow)
Cognitive workload • NASA TLX (mental demand, temporal demand, performance, effort and frustration)

Table 25 Emotional outcome measures

Emotional outcome:
Subjective emotions and flow • Subjective emotions or users' states are evaluated with the use of emotional rating questionnaires
Objective Measurements • Fuzzy logic outputs [135]

6.2 Implementation

Most of the parts in the design process for this experiment remain the same with:

- Selection of the engineering problem being the parametric task of the bracket as seen in 4.2.1
- Data capture metrics (Usability metrics, GOMs, cognitive load, fuzzy logic, and emotional questionnaires), synchronisation (synchronous logging framework ubilSA) and analysis (Paired and unpaired TTEST and ANOVA) as defined in 4.2.3
- CADT and CADG environments implementations with UGS NX as seen in 4.2.4

The modified experimental settings for this iteration are:

- CADT & CADGnoGOAP environments (6.2.1)
- User trial procedure (6.2.2)

6.2.1 CADT and CADGnoGOAP environments

For this set of experiments the design changes focus on balancing the game mechanics of Directed Goals, i.e., limiting the effect of GOAP and addressing the exaggerating goal-oriented structure of the game mechanics. A more game-like version of CADG was created (with a focus on Rewards-Achievements, Performance-Feedback), named CADGnoGOAP for further comparison with the CADT results from the previous experiment (Chapter 5) (see Figure 44).

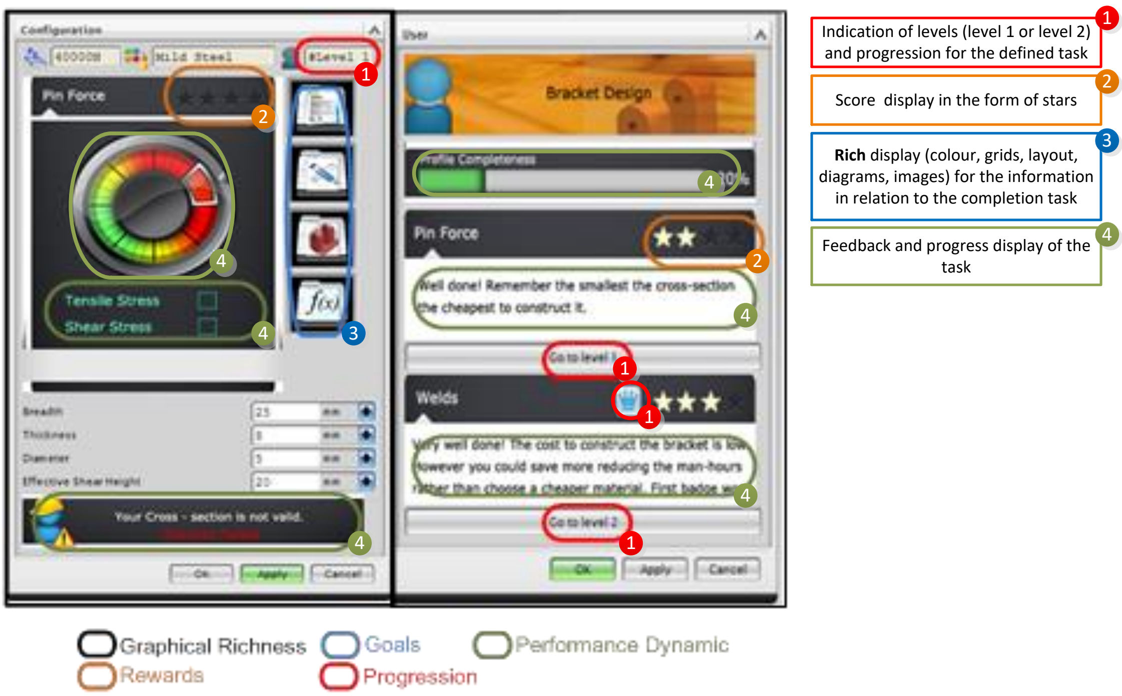


Figure 44 First design of CADG (Chapter 5)

The CADGnoGOAP environment differs from the previous CADG environment in the following areas (Figure 45):

- The top-level interface profile window has been modified to have a single advance design task.
- The tasks' goals design pattern (colour wheel), removed to change the focus of the interface to the task variables.
- Design pattern of Performance-Feedback and Rewards-Achievements modified to have more visual impact to increase the aesthetic richness of the game interface.

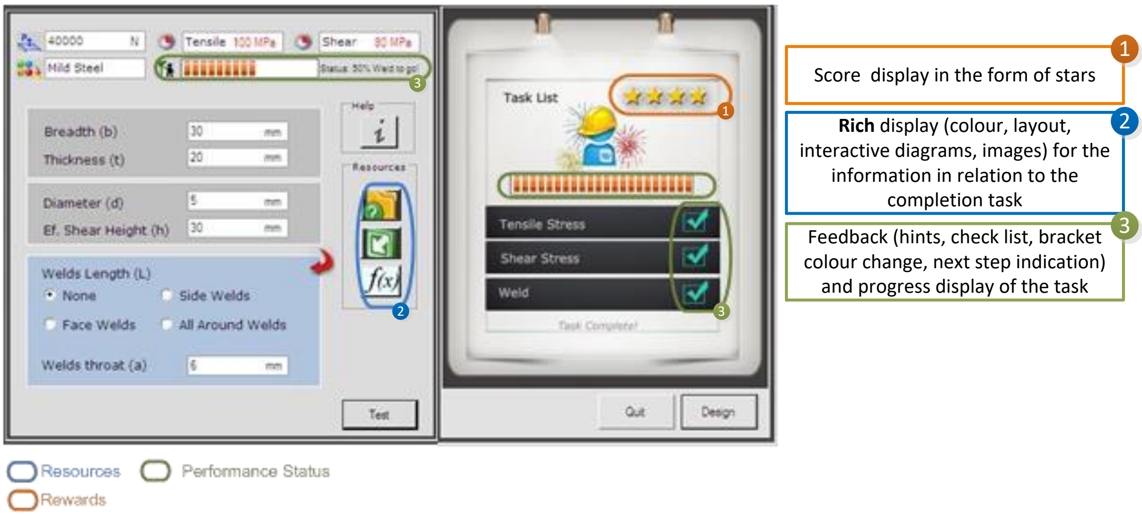


Figure 45 Previous experiment GUI – Main window and Profile window (top) Vs. Current Game-based CADGnoGOAP GUI – Main window and Profile window (bottom)

- The areas reserved for resources (material table, formulas and diagrams, bracket design information) and help information (description of the parameters) was altered to provide general instructions on how to use the system instead of breaking down the task into action steps (Figure 46).

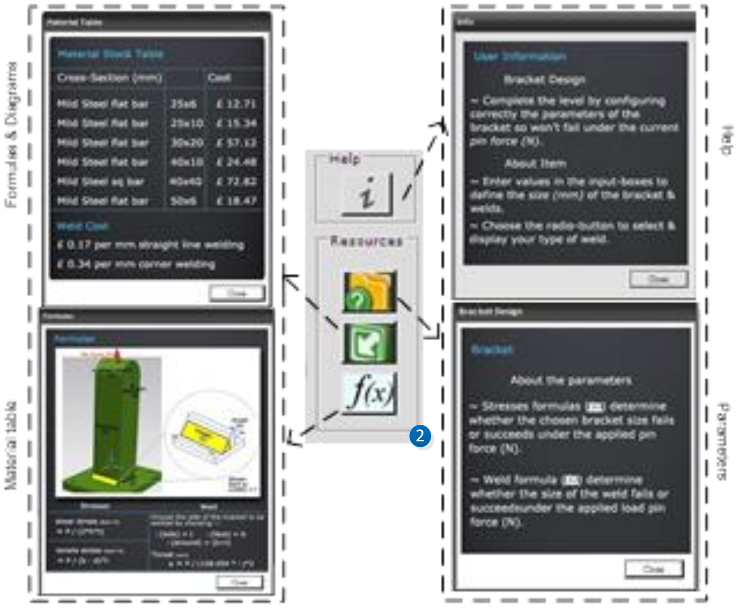


Figure 46 Task's resources

- The Performance-Feedback with guiding information (clues, hints) is emphasised with screens in red for fail and green for success (**Figure 47**).

Figure 47 Performance-feedback with cascading information game mechanics (hints) (far left) and scoring of 2-4 stars

6.2.2 User trial procedure

The experimental steps are as follows (also see Figure 48):

1. A general questionnaire to collect user demographic on engineering background and CAD experience.
2. Each participant is given some general instruction to practice stress analysis and to familiarise themselves with the design engineering equations required.
3. Use the new version of the CADG environment, called CADGnoGOAP to complete the bracket design.
4. The participant fills in an emotion-ranking questionnaire on CAD GUI using a scale of 0 (low) - 10 (high) for each of the following emotional responses: frustration, satisfaction, engagement, and challenge.
5. Answer questionnaire on the GUI's design and how the set of the game mechanics affected the solution as well as design process and their design experience.
6. The session ends with an interview involving the participant on the design process experienced and the emotion changes they experienced during the process.

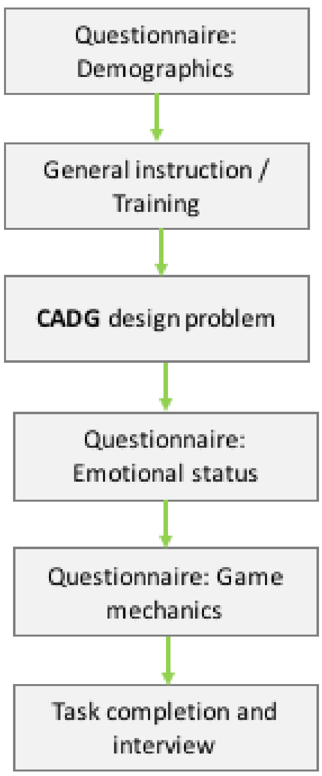


Figure 48 User trials procedure

The experiment similarly lasts between 30-60 minutes with the participant working through the bracket design problem. As before, the aim is to optimise the design with the objective to meet the functional requirements detailed in a design specification.

6.3 Experimental results and analysis

Eleven (11) experienced mechanical engineering students were tasked to design a bracket by configuring it to withstand an applied pin force. The following sections report the findings. All datasets and statistical outputs can be found in Appendix B.

The analysis is a comparison between the previous experimental CAD trials; Group A CADT and Group B CADG vs. CADGnoGOAP. Independent (unpaired) TTEST [123] identify whether the different versions of CAD's interaction processes are statistically significant.

As before, the engineer's performance was evaluated through the usability, GOMs and cognitive load, with the usability and cognitive metrics analysed with TTESTs. To understand the effect of emotions, psycho-physiological data are captured (brain signals frequencies) and fed to the fuzzy logic to elicit emotional responses. These responses are then further reviewed for their distribution with Lillie tests [146] followed by TTESTs. Emotional questionnaires are also analysed with TTESTs.

Engineers' performance results

A cross-case analysis with previous CADG and CADT results against CADGnoGOAP was conducted. Since both the CADT or CADG in earlier trials (Chapter 5) are significantly goal-oriented, only the user's first CAD experience is needed for the CADGnoGOAP comparisons:

- Participants in Group A with CADT first were compared with participants using the new version of CADG, CADGnoGOAP.
- Participants in Group B used CADG first were compared with participants using the new version of CADG, CADGnoGOAP to review the impact of the new gamified version, against the older one.

a. **Effectiveness**

As defined previously, the ***Effectiveness*** constitutes the number of times users modify the bracket (i.e. the number of design iterations). Participant data for Group A and B were compared to participants' data from CADGnoGOAP, thus two stages of unpaired TTESTs were carried out to compare the CADT and CADG data against CADGnoGOAP. Test 1 for Group A CADT data. Test 2 for Group B CADG data.

In this case the following TTEST definitions apply:

- Dependent variable: ***Effectiveness*** (number of iterations).
- Independent variable: **CAD Environment** (CADT, CADG and CADGnoGOAP)

Test 1: Unpaired TTEST within participants from Group A

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Effectiveness (number of iterations) when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Effectiveness (number of iterations) when using different CAD environments"*

Test 2: Unpaired TTEST within participants from Group B

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Effectiveness (number of iterations) when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Effectiveness (number of iterations) when using different CAD environments"*

Table 26 shows the TTESTs for ***Effectiveness***.

Table 26 TTESTs output for difference in effectiveness or num. iterations per CAD type

	Paired Differences			
	Means	Std. Dev.	t	p < 0.05
Test 1 (CADT-CADGnoGOAP): Effectiveness CADT first vs CADGnoGOAP (Group A)	CADT: 14.57 CADGnG: 7.81	CADT: 8.08 CADGnG: 7.61	1.73	0.1
Test 2 (CADG-CADGnoGOAP): Effectiveness CADG first vs CADGnoGOAP (Group B)	CADG: 20.89 CADGnG: 7.81	CADG: 7.98 CADGnG: 7.61	3.64	0.002

For Test 1 the results failed to reject the null hypothesis (***H0***); therefore, the alternative hypothesis (***H1***) is rejected, with TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers; effectiveness (Test 1 $t(13) = 1.73$, $p < 0.1$). However, for Test 2 the results rejected the null hypothesis (***H0***); therefore, the alternative hypothesis (***H1***) is accepted (Test 2 $t(17) = 3.64$, $p< 0.002$). CADGnoGOAP has significantly less iterations compared to CADG (Figure 49). It was observed that during the experiment participants approached the given task by reviewing and calculating the best possible solution on paper before proceeding on changing the parameters in the interface. This is evidence that the 'noGOAP' design appears effective in eliminating GOAP mechanic and subsequently reduced the 'sampling' approach.

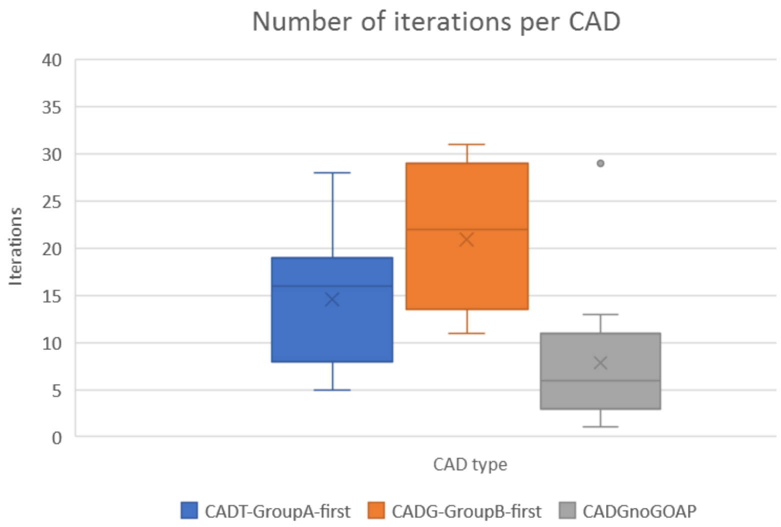


Figure 49 Effectiveness or num. iterations per CAD type

Limiting the effect of GOAP and the game mechanic of Directed Goals while emphasising the game mechanics of Performance-Feedback and Rewards-Achievements had a direct impact on the effectiveness of engineers within the CAD interface. Observations indicated that engineers approached the engineering problem differently given the task description. The game mechanic of Directed Goals and participants' engineering knowledge were the two influencing factors on their ability to solve the task. This can be further elaborated through on the participants' strategy – GOMs in the following sections.

b. Efficiency

As defined previously, ***Efficiency*** constitutes the Task Completion Time (TCT) or Time completion, for users, to reach a solution for the design task of the bracket within the CAD environment. As with ***efficiency***, two stages of unpaired TTESTs were carried out to compare the CADT and CADG data against CADGnoGOAP. Test 1 for Group A, CADT data. Test 2 for Group B, CADG data.

In this case the following TTEST definitions apply:

- Dependent variable: ***Efficiency*** (time completion).
- Independent variable: **CAD Environment** (CADT, CADG and CADGnoGOAP)

Test 1: Unpaired TTEST within participants from Group A

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Efficiency (time completion) when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Efficiency (time completion) when using different CAD environments"*

Test 2: Unpaired TTEST within participants from Group B

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Efficiency (time completion) when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Efficiency (time completion) when using different CAD environments"*

Table 27 show the TTESTs for ***Efficiency***.

Table 27 TTESTs output for difference in efficiency or time completion (sec) per CAD type

	Paired Differences			
	Means	Std. Dev.	t	p < 0.05
Test 1 (CADT-CADGnoGOAP): Efficiency CADT first vs CADGnoGOAP (Group A)	CADT: 1152 CADGnG: 808.39	CADT: 580.83 CADGnG: 391.21	1.36	0.2
Test 2 (CADG-CADGnoGOAP): Efficiency CADG first vs CADGnoGOAP (Group B)	CADG: 699.89 CADGnG: 808.39	CADG: 612.27 CADGnG: 391.21	0.45	0.65

Both test results failed to reject each relevant null hypothesis (***H0***); therefore, the alternative hypotheses (***H1***) are both rejected with each TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers' efficiency (Test 1 $t(10) = 1.36$, $p < 0.2$ and Test 2 $t(14) = 0.45$, $p < 0.65$). Limiting the effect of GOAP did not impact time completion or efficiency regardless of the different approaches the engineers took, e.g. calculating possible solutions on paper first (Figure 50).

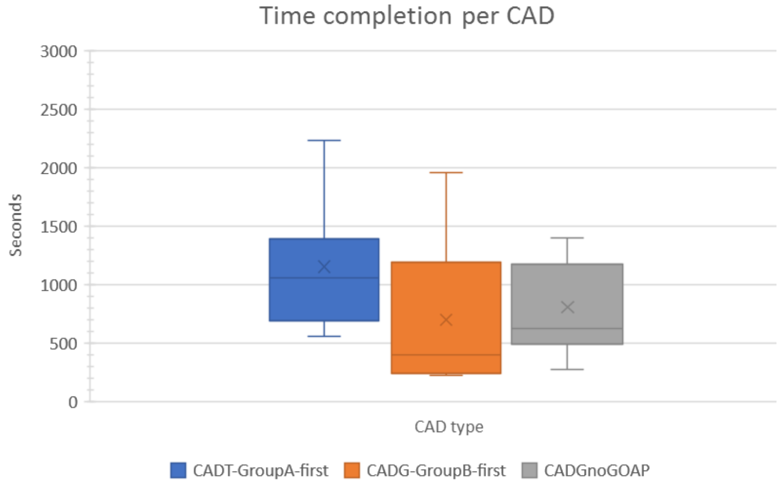


Figure 50 Efficiency or time completion per CAD type

Limiting the effect of GOAP and emphasising the rest of the game mechanics had no direct impact on engineers' efficiency but as seen in the effectiveness results (and GOMs in the following sections) it did affect the problem-solving approach used.

c. Satisfaction

Satisfaction describes a positive emotional response related to fulfilment. Users rated their ***Satisfaction*** of their interactions with the CAD environments in a scale 1-10. Similar to the previous metrics of effectiveness and efficiency testing structures, two stages of TTESTs were carried out: Test 1 for Group A, CADT data. Test 2 for Group B, CADG data.

In this case the following TTEST definitions apply:

- Dependent variable: ***Satisfaction***
- Independent variable: **CAD Environment** (CADT, CADG and CADGnoGOAP)

Test 1: Unpaired TTEST within participants from Group A

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' satisfaction when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' satisfaction when using different CAD environments"*

Test 2: Unpaired TTEST within participants from Group B

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' satisfaction when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' satisfaction when using different CAD environments"*

Table 28 shows the TTESTs for ***Satisfaction***.

Table 28 TTESTs output for difference in satisfaction ratings per CAD type

	Paired Differences			
	Means	Std. Dev.	t	p < 0.05
Test 1 (CADT-CADGnoGOAP): Satisfaction CADT first vs CADGnoGOAP (Group A)	CADT: 6.71 CADGnG: 8.36	CADT: 2.29 CADGnG: 1.43	1.68	0.12
Test 2 (CADG-CADGnoGOAP): Satisfaction CADG first vs CADGnoGOAP (Group B)	CADG: 6.67 CADGnG: 8.36	CADG: 2.18 CADGnG: 1.43	1.98	0.06

Both test results failed to reject each relevant null hypothesis (***H0***); therefore, the alternative hypotheses (***H1***) are both rejected with each TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers' satisfaction (Test 1 $t(9) = 1.68$, $p < 0.12$ and Test 2 $t(14) = 1.98$, $p < 0.06$). In Figure 51 satisfaction ratings showed to be similar between the CAD environments, however the means are considerably different indicating sample variance. It needs to be noted that, by increasing the number of participants within the groups would provide a more distributed representation of data.

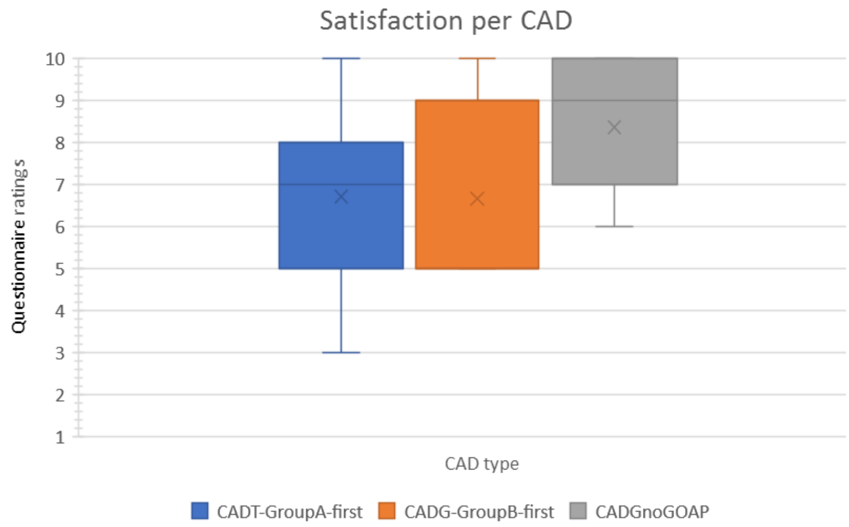


Figure 51 Satisfaction ratings per CAD type

GOAP influenced the solution strategy taken as evidenced by the efficiency and effectiveness results. Satisfaction did not indicate statistically significant results. However, the mean values indicate that the more gamified interface of CADGnoGOAP was rated higher by engineers when compared to CADG and CADT.

d. Cognitive load

As presented previously ***Cognitive load*** describes the level of mental demand, temporal demand, performance, effort and frustration of users within a context of an interaction. Users rated their ***Cognitive load*** for their interactions with the CAD environments in a scale 1-20. The calculations of the cognitive load are done though the NASA TLX framework and its questionnaire. The questionnaire can be seen in the Appendix E. Similar to effectiveness and efficiency testing structures, two stages of TTESTs were carried out: Test 1 for Group A, CADT data. Test 2 for Group B, CADG data.

In this case the following TTEST definitions apply:

- Dependent variable: ***Cognitive load***
- Independent variable: **CAD Environment** (CADT, CADG and CADGnoGOAP)

Test 1: Unpaired TTEST within participants from Group A

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' cognitive load when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' cognitive load when using different CAD environments"*

Test 2: Unpaired TTEST within participants from Group B

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' cognitive load when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' cognitive load when using different CAD environments"*

Table 29 show the TTESTs for ***Cognitive load***.

Table 29 TTESTs output for difference in cognitive ratings per CAD type

	Paired Differences			
	Mean	Std. Dev.	t	p < 0.05
Test 1 (CADT-CADGnoGOAP): Cognitive load CADT first vs CADGnoGOAP (Group A)	CADT: 36.38 CADGnG: 62.24	CADT: 18.67 CADGnG: 9.09	3.39	0.009
Test 2 (CADG-CADGnoGOAP): Cognitive load CADG first vs CADGnoGOAP (Group B)	CADG: 40.44 CADGnG: 62.24	CADG: 15.01 CADGnG: 9.09	3.77	0.002

Both test results reject each relevant null hypothesis (***H0***); therefore, the alternative hypotheses (***H1***) are both accepted with each TTEST showing significant statistical difference regarding the influence of the CAD environment on the engineers' cognitive load (Test 1 $t(8) = 3.39$, $p < 0.009$ and Test 2 $t(13) = 3.77$, $p < 0.002$). Based on the observations, the participants calculated the best possible solutions on paper first before moving onto the game-based CAD. Switching between working on paper and entering parameters in the CAD interface causes an increase in the users' cognitive loads (Figure 52).

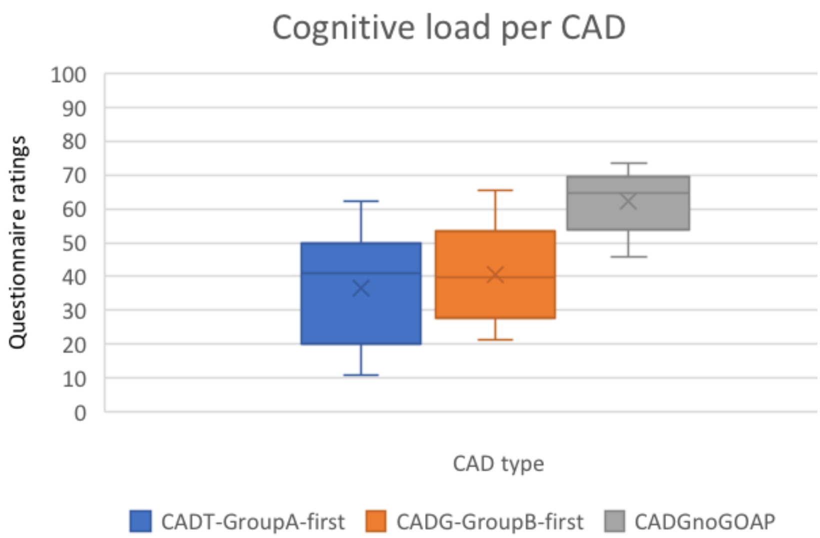


Figure 52 Cognitive load ratings per CAD type

It was observed that engineers switching between paper and screen (digital) had a direct impact on increased cognitive load ratings [151]. Thus, it was difficult to differentiate the exact source of high cognitive load but to assume that the overall effect of an engineers' design strategy was based on their perception of the task's goal within the game-environment, i.e. the need to do calculations.

Cognitive load had statistically significant differences between the CAD interfaces, however, the game mechanics cannot be clearly assumed to have an effect in this instance. Cognitive load is affected by the information provided within a system and how users interpret the feedback provided and decide on the next actions to carry out. Such demands, particularly within the context of a game with graphical richness, can increase the cognitive load. Alongside the increased performance and the optimised design strategy (see next paragraph, GOMs) can hint effective learning and playability [91], [150].

e. GOMs

The task goal was to effectively configure the bracket such that it will not fail under the applied load. Within that task's goal the main methods or functional descriptions to achieve that goal, otherwise called functional level operators (FLOs) are:

- Check resources
- Entering cross–sections / weld type–size
- Test

Participants' design strategies or task flows for configuring the bracket differed from the early experiments (Chapter 5). The use of formulas and calculations were part of the design strategy to fulfil the requirements/goals of the task for the CADGnoGOAP.

- Calculating-first approach: Participants checked the resources, material stock list, and formulas, locate the parameters to configure, calculated cross–sections, weld type-size and then tested them within the CAD interface to see if they obtain successful feedback.

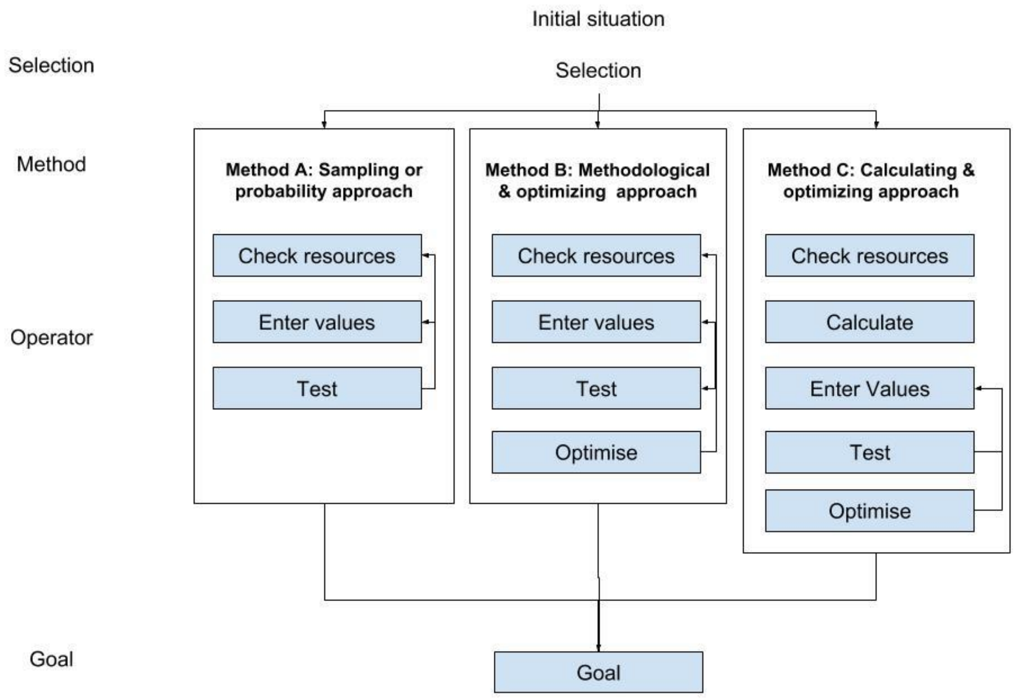


Figure 53 Participants' strategies for CADG & CADT (Method A and Method B) and CADGnoGOAP (Method C)

All participants working on CADGnoGOAP calculated the optimal design solution using the Calculating-first approach (Figure 53, Method C). During the task, it was observed that the majority planned their approach and proceeded after responding to the information feedback from the CADGnoGOAP interface. Moreover, the participants were eager to achieve higher scores with the majority calculating possible alternative outcomes on paper before testing them within the CAD interface and choosing the most efficient and cost-effective solution (FLOs order: Check resources, Calculate, Enter values, Test). Limiting the effect of GOAP and revising the game mechanics presentation / aesthetics had an impact on the participant' design strategy for the parameterization of the bracket:

- Participants had a more structured approach in solving the engineering design problem by recognising schemas, reconstructing the design problem and setting up a strategy for meeting the end goal.
- Participants' used an "expert approach" strategy by calculating the outcomes and choosing the one that fulfilled best the requirements of the task.

6.3.1 Engineer's performance results summary

As seen from the presented metrics in the previous sections, limiting the effect of GOAP while emphasising the game mechanics of Performance-Feedback and Rewards-Achievements had an impact on engineers' performance. Participants approached the task by breaking it down into problem areas aligned with the given formulas and interacting with the system to obtain information, framing the problem. Their optimised strategy positively affected the Effectiveness (number of iterations) and Efficiency (time completion) on the task for the gamified system. The cognitive load was significantly different between the interfaces, however participants' switching between paper and screen (digital) could be a contributing factor to the increased ratings rather that the impact of the game mechanics and the reduction of the GOAP effect within the CADG.

Emotional responses

The emotional responses were captured using a 1-10 scale questionnaire and analysed as seen in 6.3 Engineers' performance:

- Participants in Group A used CADT first, so their CADT data are compared with participants using the new version of CADG, CADGnoGOAP.
- Participants in Group B used CADG first, so their CADG data are compared with participants using the new version of CADG, CADGnoGOAP to review the impact of the new gamified version, against the older one

The emotion of satisfaction, being part of the usability metrics within the engineer's performance will be referenced here but its analysis can be found in 6.3 Engineers' performance.

a. **Emotions questionnaire**

Participants' rated their ***Engagement, Frustration, Challenge*** of their interactions with the CAD environments in a scale 1-10. Similar to the previous metrics of effectiveness and efficiency testing structures, two stages of TTESTs were carried out: Test 1 for Group A, CADT data. Test 2 for Group B, CADG data.

In this case the following TTEST definitions apply:

- Dependent variable: ***Engagement, Frustration, Challenge***
- Independent variable: **CAD Environment** (CADT, CADG and CADGnoGOAP)

Test 1: Unpaired TTEST within participants from Group A

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Engagement, Frustration, Challenge when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Engagement, Frustration, Challenge when using different CAD environments"*

Test 2: Unpaired TTEST within participants from Group B

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Engagement, Frustration, Challenge when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Engagement, Frustration, Challenge when using different CAD environments"*

Table 30 shows the TTESTs for ***Engagement, Frustration,*** *and* ***Challenge***.

Table 30 TTESTs output for difference in engagement, challenge, frustration, and satisfaction (for reference) ratings per CAD type

	Paired Differences			
	Mean	Std. Dev.	t	p < 0.05
Test 1 (CADT-CADGnoGOAP): Engagement CADT first vs CADGnoGOAP (Group A)	CADT: 6.57 CADGnG: 8.36	CADT: 2.51 CADGnG:1.36	1.73	0.12
Test 2 (CADG-CADGnoGOAP): Engagement CADG first vs CADGnoGOAP (Group B)	CADG: 5.33 CADGnG: 8.36	CADG: 2.69 CADGnG: 1.36	3.07	0.01
Test 1 (CADT-CADGnoGOAP): Challenge CADT first vs CADGnoGOAP (Group A)	CADT: 5.71 CADGnG:7.00	CADT: 3.09 CADGnG:2.49	0.92	0.37
Test 2 (CADG-CADGnoGOAP): Challenge CADG first vs CADGnoGOAP (Group B)	CADG: 4.11 CADGnG: 7.00	CADG: 2.37 CADGnG: 2.49	2.65	0.01
Test 1 (CADT-CADGnoGOAP): Frustration CADT first vs CADGnoGOAP (Group A)	CADT: 5.00 CADGnG: 5.45	CADT: 3.92 CADGnG: 2.84	0.26	0.79
Test 2 (CADG-CADGnoGOAP): Frustration CADG first vs CADGnoGOAP (Group B)	CADG: 3.44 CADGnG: 5.45	CADG: 2.40 CADGnG: 2.84	1.71	0.10

For the emotional response of Engagement for Test 1 the results failed to reject the null hypothesis (***H0***); therefore, the alternative hypothesis (***H1***) is rejected, with TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers' engagement (Test 1 t(8) = 1.73 p < 0.12). However, for Test 2 the results rejected the null hypothesis (***H0***); therefore, the alternative hypothesis (***H1***) is accepted (Test 2, t(11) = 3.07, p < 0.01).

For the emotional response of Challenge for Test 1 the results failed to reject the null hypothesis (***H0***); therefore, the alternative hypothesis (***H1***) is rejected, with TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers' challenge (Test 1 t(11) = 0.92 p < 0.37). However, for Test 2 the results rejected the null hypothesis (***H0***); therefore, the alternative hypothesis (***H1***) is accepted (Test 2, t(18) = 2.65, p < 0.01).

For the emotional response of Frustration both tests the results failed to reject each relevant null hypothesis (***H0***); therefore, the alternative hypotheses (***H1***) are both rejected with each TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers' frustration (Test 1 t(10) = 0.26 p < 0.79 and Test 2 t(18) = 1.71 p < 0.10).

Overall the ratings of the questionnaire shown that the participants in CADGnoGOAP were more engaged and challenged with the problem-solving process while working on their own defined strategy (Table 30, Figure 54, Figure 55). Again, variance artefacts can be resolved with an increased sample.

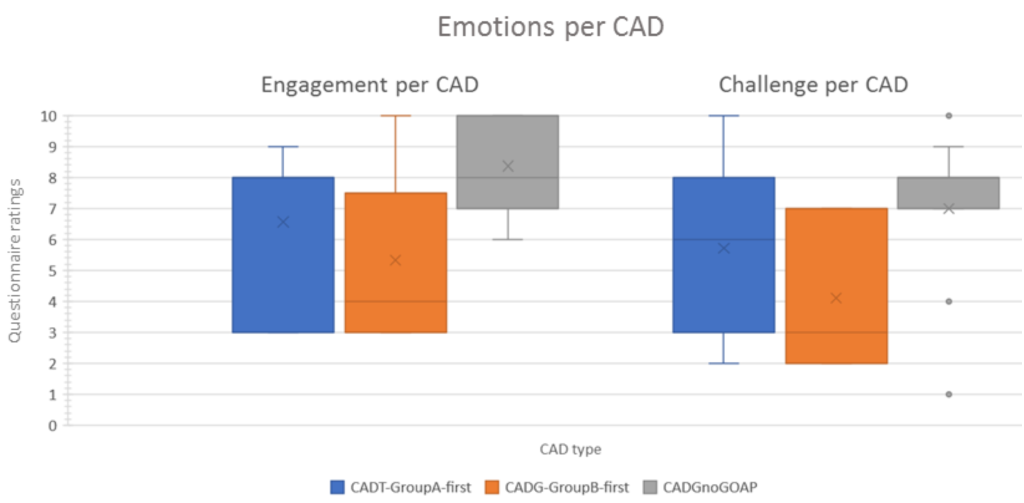


Figure 54 Engagement and challenge per CAD type

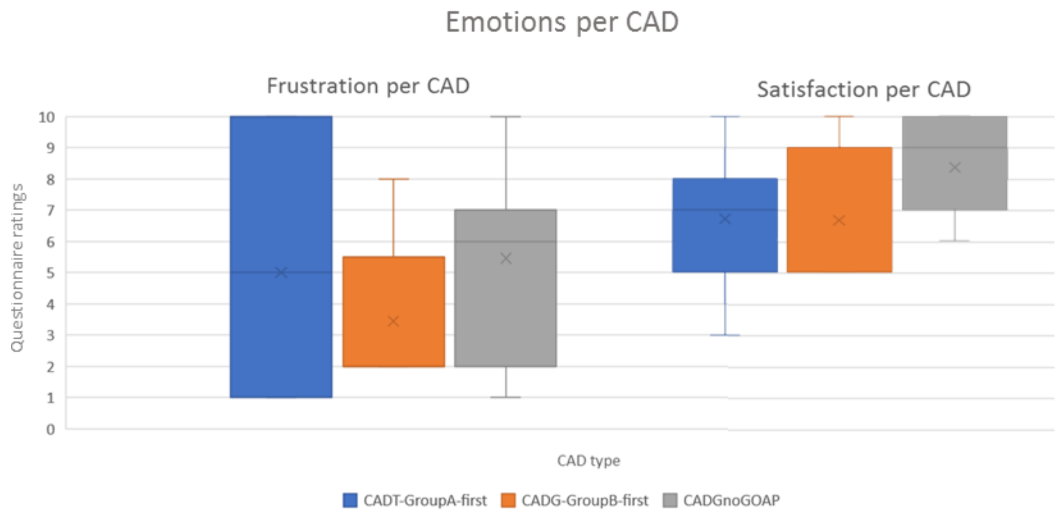


Figure 55 Frustration and satisfaction (for reference) per CAD type

Participants with prior knowledge of engineering approached the task in more conventional and empirical way of problem solving limiting the influence of GOAP. Feeling challenged with the task, were engaged in the process using the CAD to review performance and achieve higher scores.

6.3.2 Emotional response results summary

The results on emotion's responses indicate a positive view on the aspects of the game mechanics, in particular a significant impact on the engagement and challenge of the engineers.

6.4 Discussions and lessons learned

The (limited) goal-oriented effect (GOAP) influenced engineers' approach on how the task was solved. Engineers were focused and engaged (emotional responses) to reach their final optimised solution. This is evidence by their cognitive load as seen in Figure 52. However, the emotional questionnaires of the engagement-challenge pair with the influence of (limited) GOAP for the current gamified approach was a good motivational driver for the completion of the task.

Lessons learned:

1. The design strategy is influenced by the cognitive load as indicated through cognitive load and GOMs results. Engineers employed calculating methods for optimising the bracket also resolving to different means of visualizing their problem space (i.e. making calculations on a physical paper). This also positively influenced their overall effectiveness.
2. Aesthetics and graphical richness are an influential factor on engineers' experience within the gamified environment as seen from the compassions CADG vs CADGnoGOAP. CADGnoGOAP GUI provided a clear focus of the main goal of the task without presenting its problem-structure, enabling engineers to figure out for themselves (break it down) as they were making the connections between geometry and design performance.
3. Provide alternative or/and additional techniques to conduct emotion evaluation as it provides significant information on how engineers perceive the engineering task within the context of a gamified interface and how well they respond to the game mechanics.
4. Include bigger number of participants for a more diverse sample.

6.5 Goal-oriented cognition

The GOMs results on cognitive load and task strategy of the engineers were significantly different compared to the previous experiment. Hypothesising that a cognitive flow, under a set of design criteria, is different between game-based and traditional CAD, means that game mechanics have an impact on how engineers think. Within this context, this study explores the hypothesis, suggesting EEG can be used as evaluation metrics in understanding engineering design thinking process.

To further understand the cognitive aspects relating to design thinking, a neurometric approach consisting of EEG data for brain activations and user task flow models were derived. EEG spectral features can discriminate cognitive loads of different task-based activities. Hence, provide a correspondence validation against questionnaires, which are subjective by nature.

Understanding a designer's thinking and cognitive process during design activities plays a significant role in the problem solving of a task (in this case the bracket configuration). By using EEG, the user's cognitive processes can be quantified and lead to structuring an effective design methodology. The first known study in design using brain signal data focused on the effect of designer's experience on approach to a design solution [152]. Alexiou et al [153], used magnetic resonance imaging (fMRI) to show brain activations areas of users doing a design task and a problem-solving task. The authors concluded that the active brain areas were distinctly different between design task and problem-solving task. Current research has expanded in the area of correlating and presenting EEG with a user's cognitive processes and task engagement [154] [155].

6.5.1 eConnectome and Task Flow

eConnectome [156], a MATLAB EEG toolbox, was used to analyse the users' cognitive operations during the design task with a view to measuring any statistical differences of brain activation in relation to the impact of game mechanics. eConnectome can visualize the brain activations per task segment (Figure 56).

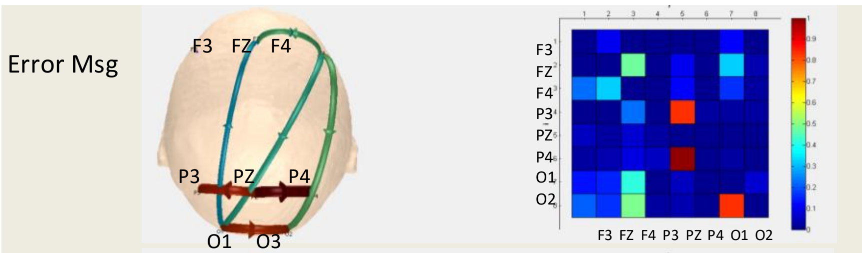


Figure 56 Brain activation on user receiving error

To analyse cognitive operations during the design task alpha wave was chosen. An increase of Alpha amplitude is known to be connected with cognitive performance and memory demands [157], [158], [159] [160].

The frontal, parietal and occipital regions of the brain are the sites with the highest Alpha activity [161], [162] and generally represent different brain function as seen in Figure 57 and Table 31.

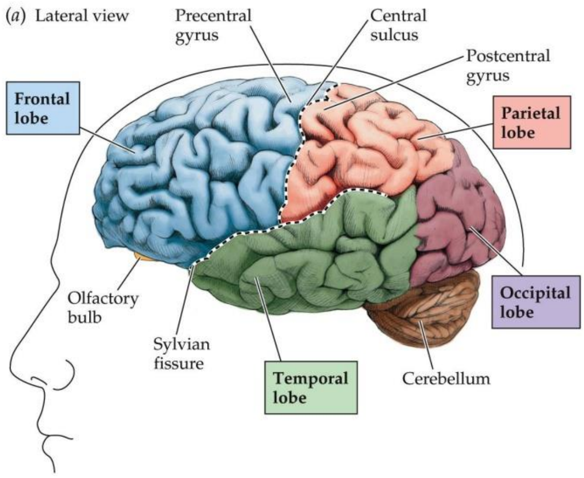


Figure 57 Frontal, parietal and occipital regions of the brain

Table 31 Brain regions and their functions [155]

Brain region	Functions
Frontal lobe	Planning, judgement, making decision, concentration
Parietal lobe	Verbal understanding, texture and shape interpretation
Occipital lobe	Visual processing, visual experiences, eye focusing

To identify the EEG data corresponding to each of the FLOs of the user, the mouse clicks on the users' screen were used together with the EEG. Based on the GOMs model for the parametric task, the design activities were categorised for the following operations: Check Resources, Calculate, Enter Values, Test, and Optimise. Using the defined FLOs synchronised with the user data, time-stamped task segments (see Figure 58) were made. The time-stamped task segments in turn were matched against sections of synchronised raw EEG data. Each EEG segment is then processed based on the model of the human processor [163] which involves three process stages: perceptual, cognitive and motor:

- The perceptual processor (Tp) places a visual auditory image into the corresponding code in the working memory

- The cognitive processor (Tc) checks for matches between items in the working memory, retrieves information from memory, makes decisions and selects a response
- The motor processor (Tm), executes the physical act, decided upon.

Each processor has a cycle time and a set of ranges that correspond to the values within the brackets (e.g. 50~200 ms). The human model processor describes the reaction time for the user to hit a button when recognised; Tp + Tc + Tm [163].

For:

Tp = [50~200] milliseconds, Tc = [25~170] milliseconds, Tm = [70~360] milliseconds

In the bracket design task, the average reaction time was based on the number of characters displayed in GUI; when defining the breadth, thickness, diameter, task, formulas and material for both CADT and CADG. The perceptual 3Tp, cognitive 2Tc and motor 1Tm, are [270~1200] milliseconds up to a maximum value of 1.2 seconds. The feedback loop for perception to action is between 300~500 milliseconds. Adding the minimum time for the feedback loop occurring at 0.3 seconds, the reaction time equals a total 1.5 seconds: analysing the Alpha wave, based on the FLOs, the time segment comes to 1.2 seconds prior to the operation / FLOs (users' mouse click) and 0.3 post the operation /FLOs.

For example, in Figure 58, a user checked the FLOs of resources on the 29.928 second, which means that the Alpha wave time slot analysed for that operation will be between 29.928-1.2=28.728 and 29.928+0.3 = 30.228.

User Task Activities

Segment	Description Activity	Time Stamp	Label	Prior 1.2	Post 0.3
1	Click Level1	9.872		8.672	10.172
2	Check Stock	17.493	Recourses	16.293	17.793
3	Change Breadth	23.993	Enter Values	22.793	24.293
...	...	...	...	...	...

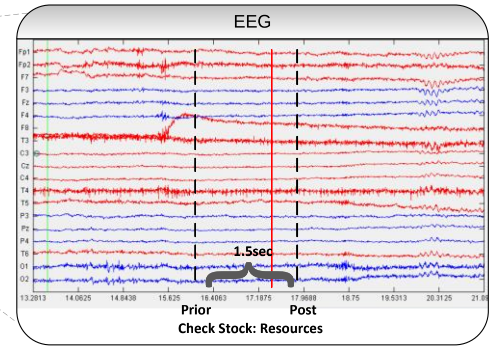


Figure 58 Logging EEG segments

Finally, when the time-based segments are made, the raw EEG data are assigned to the header file of eConnectome toolbox (header file includes: number of channels = 19 for the brain regions, points = equals to the user's data number of points, sample rate = 256, and channel labels = lopes names for the brain regions). The EEG records are then filtered for the selected brain regions of frontal (F3, FZ, F4), parietal (P3, PZ, P4) and occipital regions (O1, O2). Brain connectivity is visualised by filtering the EEG for Alpha wave (8-12 Hz) and entering the time-based operation / FLOs segments. As seen in Figure 59, the complete engineering design process can be mapped against the mouse actions and time-based segments in relation to EEG strength. The arrows indicate the activation flow whereas the matrix captures all the activated areas and their strength.

Participant's ID 16

	Mouse Action	Time Stamp (s)	Value	prior 1.:	post 0.3
1	level1	4.395		3.195	4.695
2	Error Message	8.012		6.812	8.312
3	Breadth	21.043	25	19.84	21.343
4	Test	28.328		27.13	28.628
5	Error Message	30.02		28.82	30.32
6	Enter Values: Breadth	32.156	25	30.96	32.456
7	Enter Values: Thickness	33.003	25	31.8	33.303
8	Test	36.019		34.82	36.319
9	Pass Message	37.715		36.52	38.015
10	Ok_btn	39.491		38.29	39.791

Brain Activation per Mouse Action

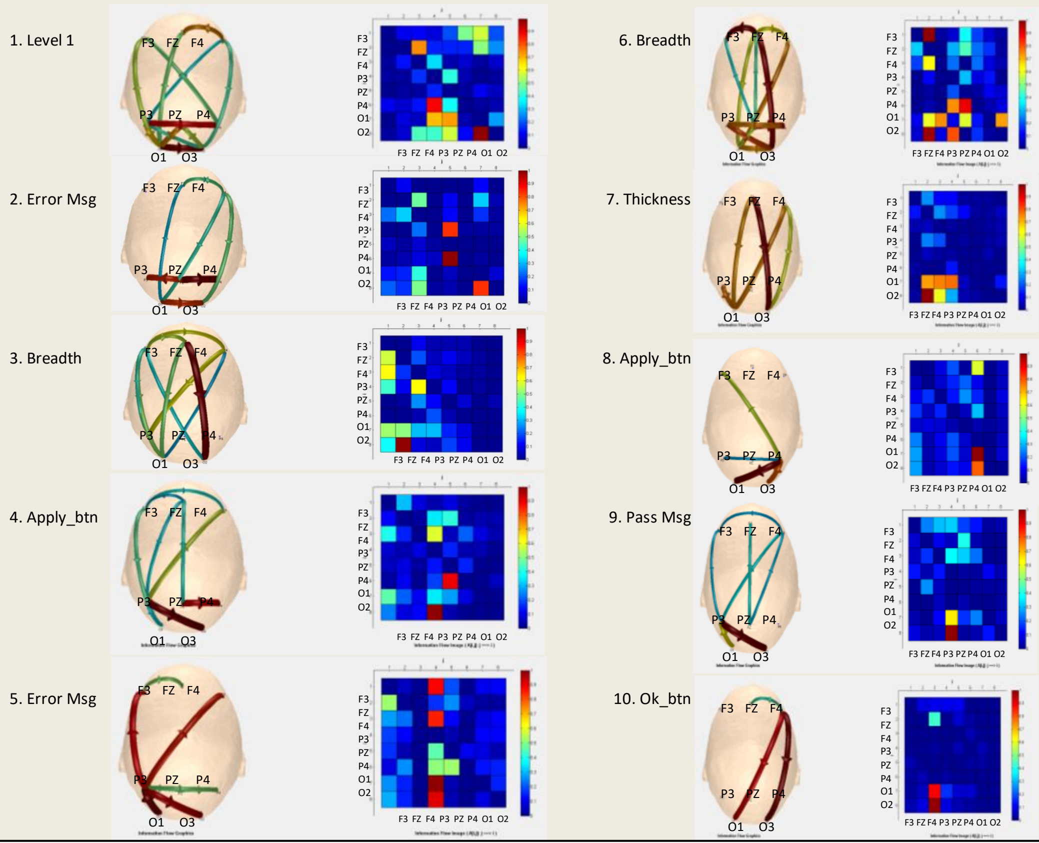


Figure 59 Engineering design process mapped to brain activations

6.5.2 Comparing CADT, CADG and CADGnoGOAP

Brain activity during the bracket design task was analysed between CADT on group A, CADG on Group B and CADGnoGOAP. Of nineteen (19) only thirteen (13) were complete for analysis due to corrupted/bad EEG signals (possible due the electro gel drying) during the recording of the experiments:

- Participants in Group A used CADT first, so their CADT data are compared with participants using the new version of CADG, CADGnoGOAP.
- Participants in Group B used CADG first, so their CADG data are compared with participants using the new version of CADG, CADGnoGOAP to review the impact of the new gamified version, against the older one

A two-way ANOVA univariate analysis was used to evaluate the way in which the alpha strength clusters around the within-subject factors:

- FLOs (Resources, Enter values and Test)
- CAD (CADT, CADG and CADGnoGOAP)
- Hemisphere activation (left vs. Right vs. Cross vs. Center)
- Brain area (Frontal-Center (FC), Frontal-Parietal(FP), Frontal-Occipital(FO), Center-Frontal (CF), Center-Parietal (CP), Center-Occipital (CO), Parietal-Central (PC), Parietal-Occipital (PO), Parietal-Frontal(PF), Parietal-Center-Frontal(POF), Occipital-Parietal (OP), Occipital-Central(OC), Occipital-Frontal (OF), Occipital Occipital (OO), Frontal-Frontal (FF), Parietal-Parietal(PP).

The probability of a Type II error (testing the significance of the within subject factors, one at the time while controlling for the level of the other factors, assuming no interaction between factors) is maintained at $p < 0.05$.

In this case the following ANOVA definitions apply:

- Dependent variable: ***Resources, Enter values and Test (FLOs), Hemisphere, Brian Area***
- Independent variable: **CAD Environment** (CADT, CADG and CADGnoGOAP)

Test 1: ANOVA

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no a difference in the participants' function-level operators (FLOs), within the Hemisphere and Brain area when using different CAD environments"

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' function-level operators (FLOs), within the Hemisphere and Brain area when using different CAD environments"*

The ANOVA for ***Resources, Enter values and Test (FLOs)*** are found in Table 32 and the SPSS analysis outputs can be seen in Appendix B.

Table 32 ANOVA output for strength difference in hemisphere and brain activation, for FLOs, per CAD type

Subject factors	Two-way ANOVA univariate analysis							
	Mean Sq.		F		t		p < 0.05	
	Hemisphere (left, right, cross, centre)	Brain area (groups)	Hemisphere (left, right, cross, centre)	Brain area (groups)	Hemisphere (left, right, cross, centre)	Brain area (groups)	Hemisphere (left, right, cross, centre)	Brain area (groups)
Resources CADT-GroupA-first, CADG – GroupB-first and CADGnoGOAP	0.049	0.055	1.025	1.150	4	38	0.393	0.243
Enter values CADT GroupA-first, CADG – GroupB-first and CADGnoGOAP	0.060	0.053	1.264	1.125	4	38	0.282	0.276
Test CADT GroupA-first, CADG – GroupB-first and CADGnoGOAP	0.035	0.046	0.658	0.879	4	31	0.622	0.654

The results failed to reject the null hypothesis (**H0**); therefore, the alternative hypothesis (**H1**) is rejected with each ANOVA showing no significant statistical difference regarding the Resources with hemisphere t(4) = 1.025, p< 0.393 and brain area t(38) = 1.150, p< 0.243, for the Enter values with hemisphere t(4) = 1.264, p<0.282 and brain area t(38) = 1.125, p < 0.276 and finally for the Test with hemisphere t(4) = 0.658, p< 0.622and brain area t(31) = 0.879, p< 0.654.

There are no statistical differences in the brain activations or hemispheres between CADT and CADG and CADGnoGOAP (Table 32). However, participants in the game-based CADs had more activated brain areas compared to CADT indicating higher cognitive processes. Additionally, CADG and CADGnoGOAP show higher brain activation over the front regions, indicating that participants processed more information compared to those working on the conventional CAD (Figure 60).

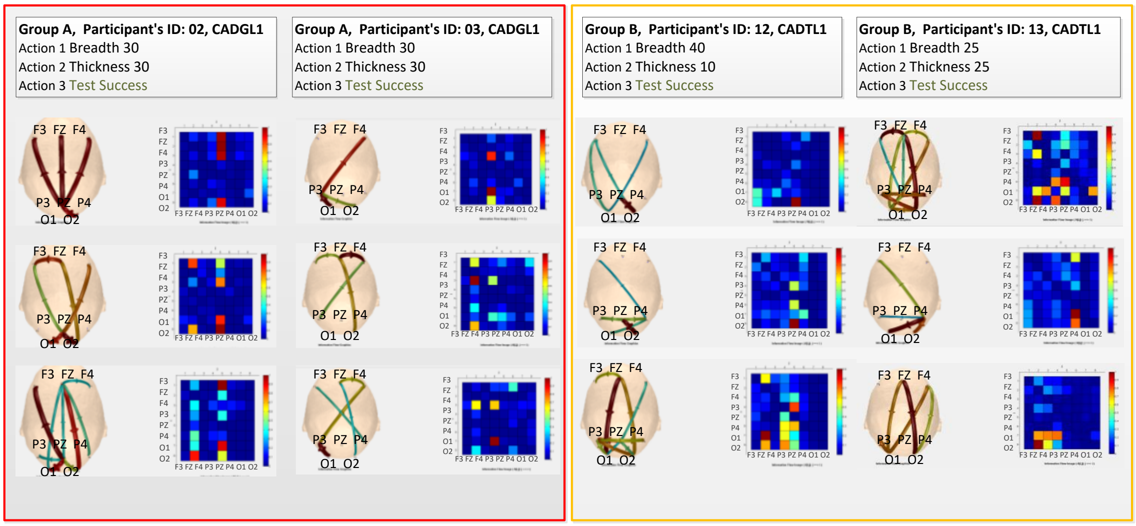


Figure 60 Participants' frontal, parietal and occipital brain region activations for the simple task of changing the parametric values in the bracket design. Here, participants on the left have significant higher inflow in the frontal regions of the brain. Whereas participants on the right focus on the parietal-occipital areas (in FLOs: Enter Values).

The occipital area during CADGnoGOAP was more active, possibly indicating an inter-area connectivity due to visual information processing (bracket colour change based on success/fail status; red when fail and green when successful). In contrast, CADT had a distinctive pattern of the occipital-parental area being more active; indicating increased working memory performance and perceived resolution of events through non-verbal reasoning (see Figure 61).

Overall, the CADGnoGOAP had a wider-septum of brain activation highlighting the impact of participants' different strategies compared to CADG and CADT (see Figure 61). The visual-spatial relations and general process of information were higher in both game-based CADs. In contrast CADT exhibited increased working memory performance signifying a possible level of users' readiness to perceive relevant information [164].

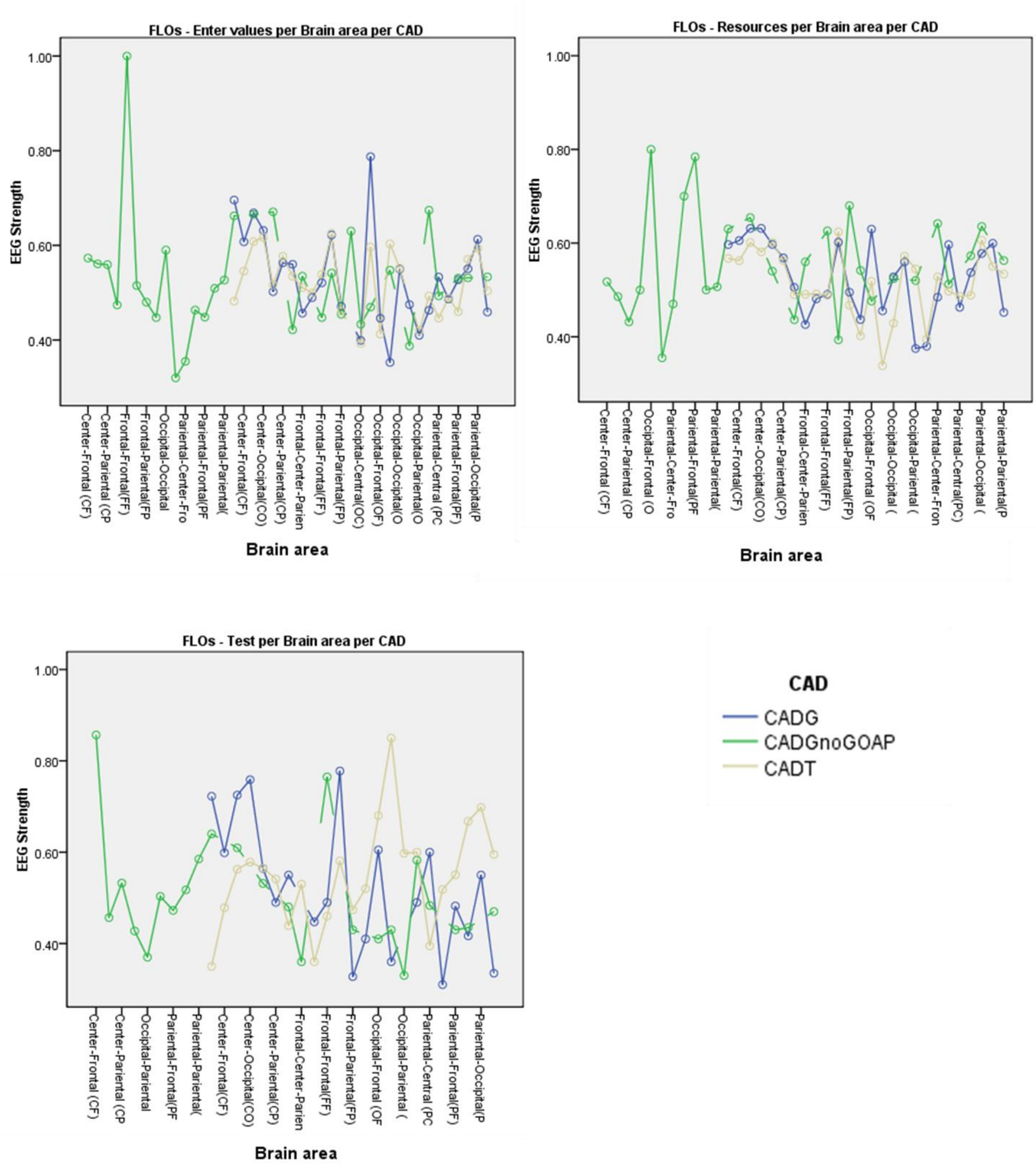


Figure 61 Brain signals per FLOs; Enter Values (top left), Check resources (top right), Test (bottom left)

6.6 Summary

Investigating the goal-oriented effect or GOAP in CADG for the bracket design task highlighted its influence on engineers' design strategy. Balancing the game mechanics of goals against the rest of the game mechanics and particularly focusing on the game mechanics of Performance-Feedback and Rewards-Achievements showed a positive impact both on engineers' performance and emotional response. The engineers' optimised strategy driven by their knowledge and experience of engineering design and CAD influenced their interaction with CADG: Engineers calculated the possible tasks' solutions on paper, which were then tested in the game-based environment. The game mechanics of Performance-Feedback and Rewards-Achievements acted as drivers in that interaction. Engineers' cognitive load was affected both by the strategy followed, and by the two-different interaction means: paper and CAD.

The emotional responses of engagement and challenge also presented a positive picture of engineers interacting with the CADGnoGOAP and having a positive overall experience. The fuzzy logic outputs were not included in this analysis as resulted in erroneous data.

The neurometric approach allowed a different review perspective of the cognitive aspects on the design strategy employed. The findings suggest the graphical richness of the gamified CAD had an impact on engineers' information processing and their perceived resolution of events through visual-spatial relations.

Overall, the findings indicate a positive impact of the game mechanics however, further experimentation is recommended with a larger number of engineers.

Chapter 7 : Improving and extending the DeReFrame framework

Chapters 5 and 6 provided some empirical evidence of the effect of game mechanics in engineering design and the use of psycho-physiological data as indicators of emotional response. They also highlighted gaps on diversity of participants (engineering knowledge) and effect of task's goal detailed description. Based on the previous experimental studies, some of the game mechanics have not decidedly defined of their impact. Chapter 7 details an improved protocol to expand the investigative design approach and determine the effect of game mechanics within a more diverse group of engineers.

7.1 Experimental design optimisations

Experiments in chapter 5 and 6 indicated that the game mechanics impact design strategy and emotional response. In particular, the game mechanics of Directed Goals and the game mechanics of Performance-Feedback, Rewards-Achievements were highlighted as the most influential. The first had an overpowering effect on the participants' interaction of formulating a problem-solving strategy and the latter affected their overall performance and motivation to optimise the task's solution. Questionnaires as well as the spectral electroencephalogram and psychometric analysis' in chapter 6, indicated that aesthetic perception or graphics richness played an important role on how they perceived their interaction with the task.

Results from those experiments were not conclusive (Table 33), thus in this chapter, the improved protocol creates the opportunity to provide a clearer, more determining picture of the game mechanics phenomena by gaining deeper insight of their impact within a more collated open CAD system.

Table 33 Overview of game mechanics and aesthetics in previous experimentation

Chapters	**Description**
4-5	Game mechanics of performance-feedback and rewards-achievements influence engineers' performance and design strategy. This created some transferable interactions and behaviours in a non-game context. The emotional responses associated to game mechanics and game aesthetics did not impact the given design task as anticipated.
6	Minimising the effect of GOAP (game mechanic of directed goals) by having participants with higher level of engineering knowledge and design expertise and revising the game aesthetics to focus on performance-feedback and rewards-achievements, did influenced the performance and emotional responses of the engineers. Engineers' problem-solving strategy was significantly different, given a more expert approach on completing the parametric task while at the same time having a more engaging interactive experience with the gamified system.

Previous findings suggested that the goal-oriented nature of the parametric task within a game mechanics and game aesthetics embedded environment could create an engaging experience for the engineers. To decidedly define this experience and the elements that greatly impact it, *for the engineers*, the experimental framework, DeReFrame is optimised with the additional state of ideation to gain immediate feedback on the experimental process and aesthetics (GUI) of the CAD system (see bullet-points below) from an actual engineer (user) point of view.

Through investigative design sessions [165] with professional engineers (10 participants) activities, would allow the collection of engineers' feedback/input for GUI and interaction improvements before the final state of the experimentation (Figure 62)

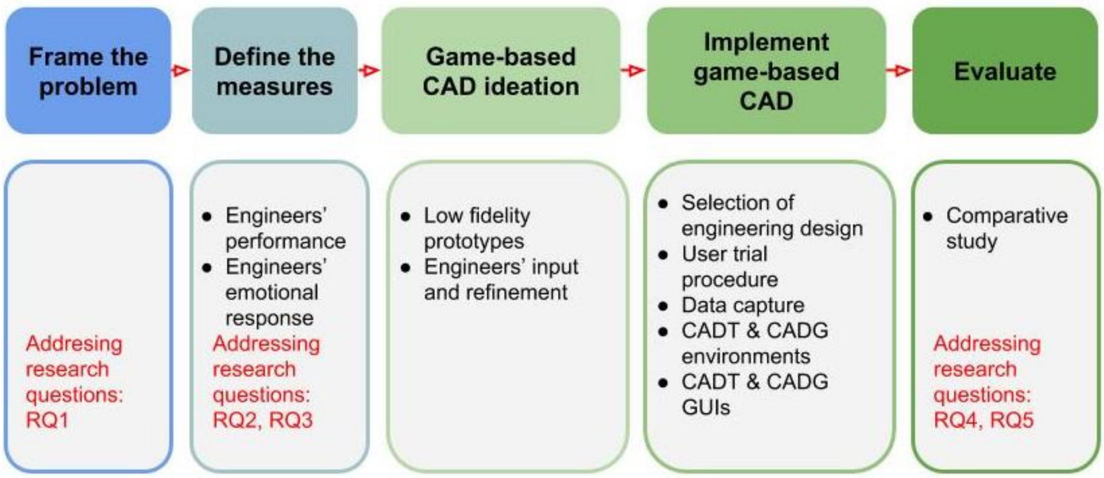


Figure 62 DeReFrame framework improvements

In detail, the specific actions for this optimization to be achieved through an ideation phase are:

- ✓ Review the balance and set-up between the game mechanics of directed goals, performance-feedback, progression, and rewards-achievements against CAD **level of expertise (e.g. novice, intermediate, expert),**
- ✓ Review emotional responses data capture (EEG cap) with a more comfortable / convenient for the participants' method,
- ✓ Review and iterate the design of the GUI (aesthetics, graphics richness) based on user feedback.

7.2 Game mechanics evaluation metrics

The game mechanics evaluation metrics for *engineers' performance* remain the same as in chapter 4, 5, and 6. However, the metrics for emotional response were modified to address the larger number of participants in different locations. Instead of using the EEG device, a more direct approach was utilised using online psychometric questionnaire.

Flow Short Scale (FSS) questionnaire [166] (Table 34) with its psychometric properties have been found to be an acceptable measure of flow in the context of video gaming ([97], [166]) game-based applications [167], gamification ([96], [168], [169]) as well as activities on the web [132].

Table 34 Flow Short Scale questionnaire

F 1: Fluency
7.3 My thoughts/activities ran fluidly and smoothly. I had no difficulty concentrating. My mind was completely clear. The right thoughts/movements occurred of their own accord. I knew what I had to do each step of the way. I felt that I had everything under control.
F 2: Absorption
I felt just the right amount of challenge. I didn't notice time passing. I was totally absorbed in what I was doing. I was completely lost in thought.

7.3 Implementation

As with Chapters 5 and 6, a comparative study was conducted between a gamified CAD (CADG) and a traditional CAD (CADT) for the same engineering design task of a bracket. The difference is that this set-up is to be online through a custom CAD application called Interactive Computer Aided Design (ICAD). ICAD is designed around the defined experiment task with the embedment of game mechanics. Participants worked in their own time on the task and from their own environment. The items that are modified for this new experiment are described in the following sections:

- Data capture (7.2.1)
- ICAD (CADG & CADT) environments (7.2.2)

7.3.1 Data Capture

The metrics for evaluating the game mechanics are as in section 7.1.1:

- Engineers' performance with: Usability metrics, design strategy (GOMs) and cognitive load
- Emotional responses with: Flow Short Scale (FSS) and emotional rating questionnaires

a. **Engineer's performance**

Mouse /Keyboard events

Mouse / keystroke logger records the users' interactions with the system (for the effectiveness and efficiency metrics) with timestamps in a sequential manner to enable for the analysis on users' design strategy (for the design strategy-GOMs metrics).

b. **Psycho-physiological Status**

The Flow Short Scale (FSS) scale measures flow via two factors, the fluency of the examined activity and the absorption (5-point Likert scales [129] ranging from 1 (strongly disagree) to 5 (strongly agree) while conducting the activity [166]. See Table 34.

For both ICAD (CADG & CADT) the FSS questionnaire as well as the emotional rating questionnaire (satisfaction, frustration, engagement, and challenge) provides the emotional response comparison between the experiments.

For the CADG, additional questions from the Flow State Scale (FSS-2) [170] are asked describing four dimensions (each dimension has 2 questions-items, with the same 5-point Likert scales): Clear goals, unambiguous feedback, autotelic experience (rewarding experience) and playability or action awareness [171].

The questions (Table 35) assess the degree of flow dimensions that characterises the complete experience. Because of the need of a holistic interactive experience, one should consider, game mechanics and aesthetics as a single unit in the game environment:

- The goals dimension can be represented with the game mechanics of directed goals and progression in terms of moving the user towards a solution flow, with a clarity of purpose and task cues (progression)
- The unambiguous feedback dimension can be represented with the game mechanic of performance-feedback in terms of the user perceiving and reflecting on the consequence of his/her actions within the game-environment
- The autotelic experience dimension can be represented with the game mechanic of rewards-achievements in terms of viewing the involvement of the user in further activity; user completes/reaches the task’s end goal, but voluntarily continue his/her effort to move to a more optimal outcome
- Finally, playability can describe game design and aesthetics in terms of providing the user a fluent and effortless interaction with the game (game usability). The focus is on information processing (problem solving) rather than putting effort on using / learning / controlling the game interface [171].

Table 35 Flow characteristics scales

Directed Goals (game mechanic: directed goals and progression-levels)
I had a strong sense of what I wanted to accomplish. My goals were clearly defined.
Unambiguous Feedback (game mechanic: performance feedback-status)
It was really clear to me how my performance was going. I had a good idea while I was performing about how well I was doing.
Autotelic Experience (rewarding experience) (game mechanic: rewards-achievements)
I really enjoyed the experience. I found the interaction experience extremely rewarding.
Playability
The user interface was easy to use. The controlling of the user interface was intuitive.

Table 36 lists the production reaction cards [172] used in as part of a questionnaire, to gauge the participants' descriptors and emotional responses for the visual design of the application for further comparison between the two ICAD (CADG & CADT).

Table 36 Production reaction cards example for both ICAD (CADG & CADT)

The complete set of 118 Product Reaction Cards				
Accessible	Creative	Fast	Meaningful	Slow
Advanced	Customizable	Flexible	Motivating	Sophisticated
Annoying	Cutting edge	Fragile	Not Secure	Stable
Appealing	Dated	Fresh	Not Valuable	Sterile
Approachable	Desirable	Friendly	Novel	Stimulating
Attractive	Difficult	Frustrating	Old	Straight Forward
Boring	Disconnected	Fun	Optimistic	Stressful
Business-like	Disruptive	Gets in the way	Ordinary	Time-consuming
Busy	Distracting	Hard to Use	Organized	Time-Saving
Calm	Dull	Helpful	Overbearing	Too Technical
Clean	Easy to use	High quality	Overwhelming	Trustworthy
Clear	Effective	Impersonal	Patronizing	Unapproachable
Collaborative	Efficient	Impressive	Personal	Unattractive
Comfortable	Effortless	Incomprehensible	Poor quality	Uncontrollable
Compatible	Empowering	Inconsistent	Powerful	Unconventional
Compelling	Energetic	Ineffective	Predictable	Understandable
Complex	Engaging	Innovative	Professional	Undesirable
Comprehensive	Entertaining	Inspiring	Relevant	Unpredictable
Confident	Enthusiastic	Integrated	Reliable	Unrefined

c. Data Capture and Synchronisation

As the experiment was online, an embedded data capture mechanism was implemented. The application records the ICAD activity as a history file (.csv) for mouse/keyboard and their timestamps and system/task status (an example of the .csv file can be seen in the Appendix D).

Figure 63 shows an overview of the setup used.

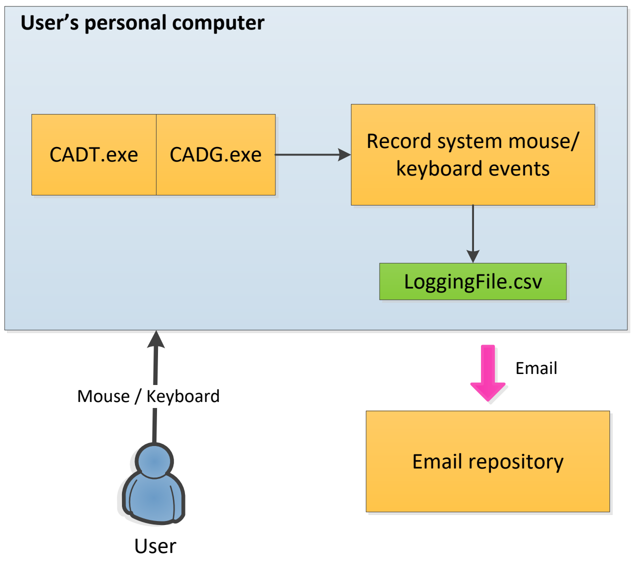


Figure 63 Overview of experimental setup

d. Data Analysis

Similar with previous experiments, two distinct groups of participants will work on either ICAD CADG or ICAD CADT. Their performance and emotional responses will be captured and analysed with independent (unpaired) TTEST [123] and ANOVA [144] analysed for any statistical significance in interaction within the two environments.

7.3.2 ICAD (CAG & CADT) environments

ICAD was developed using QT's [173]extensive open source libraries (Figure 64). Developing ICAD from the bottom up allows for detailed logging of the required participants' actions.

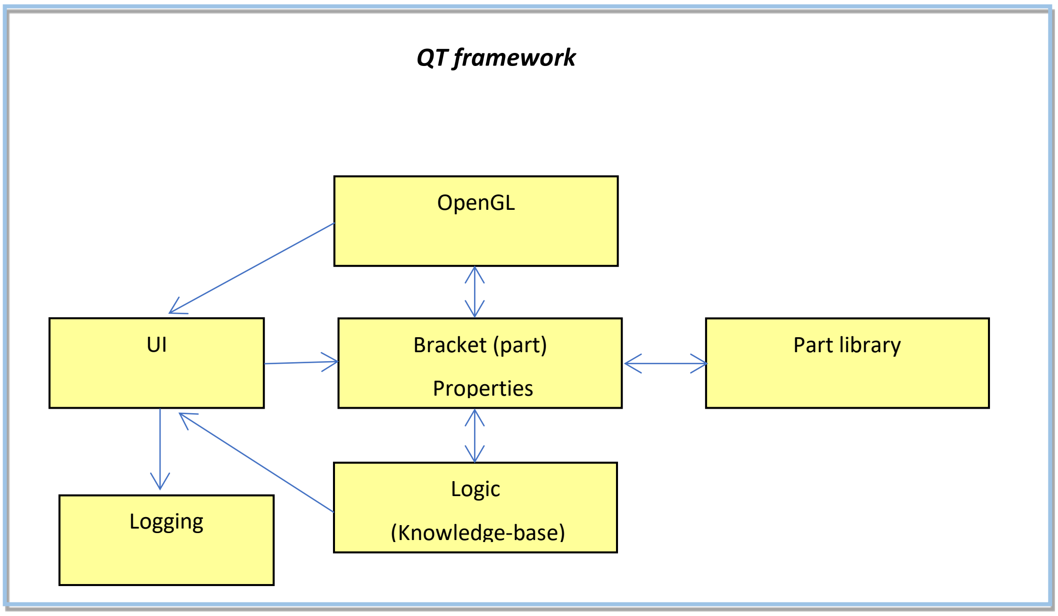


Figure 64 ICAD architecture

For this set of experiments the focused was on reviewing the GUI aesthetics by creating a seamless experience, and balancing the game mechanics:

- Goals - limiting the effect of GOAP
- Rewards-Achievements – increase the impact of scoring (points)

Revising and improving the DeReFrame framework with the addition of the 'Game-based ideation' phase (Figure 62) involved low fidelity (paper-based) prototypes. By gathering participating engineers' feedback during the investigative design approach enables a more complete ICAD CADG to be developed.

a. ICAD CADG environment prototyping

10 participants were selected to design and evaluate the ICAD CADG versions. Participants had a mixed level of expertise in CAD and engineering (4 novices, 4 intermediates and 2 experts).

Table 37 lists participants' feedback on the game mechanics and aesthetics during the first investigative design exercise.

Table 37 ICAD CADG version 1 user feedback

Iteration	Users' feedback
#1 **(Figure** 65**)**	• The information-tab did not provide enough information about the problem they were tasked to do. Also, the scoring and points were not clearly connected to the bracket design **Recommendation:** Provide more detail on task and applications' available actions as well as users can score points • Icons and labelling of resources and action buttons did not meet participants' expectations for engineering design **Recommendation:** Revise wording/content • The action history did not provide any useful interaction. **Recommendation:** Remove history feature • Reviewing available stock to enter parameters of the bracket felt as an unnecessary step. **Recommendation:** Provide alternative method of select and entry, such as drop downs.

Figure 65 illustrates the prototype they provided feedback upon on the first investigative design exercise.

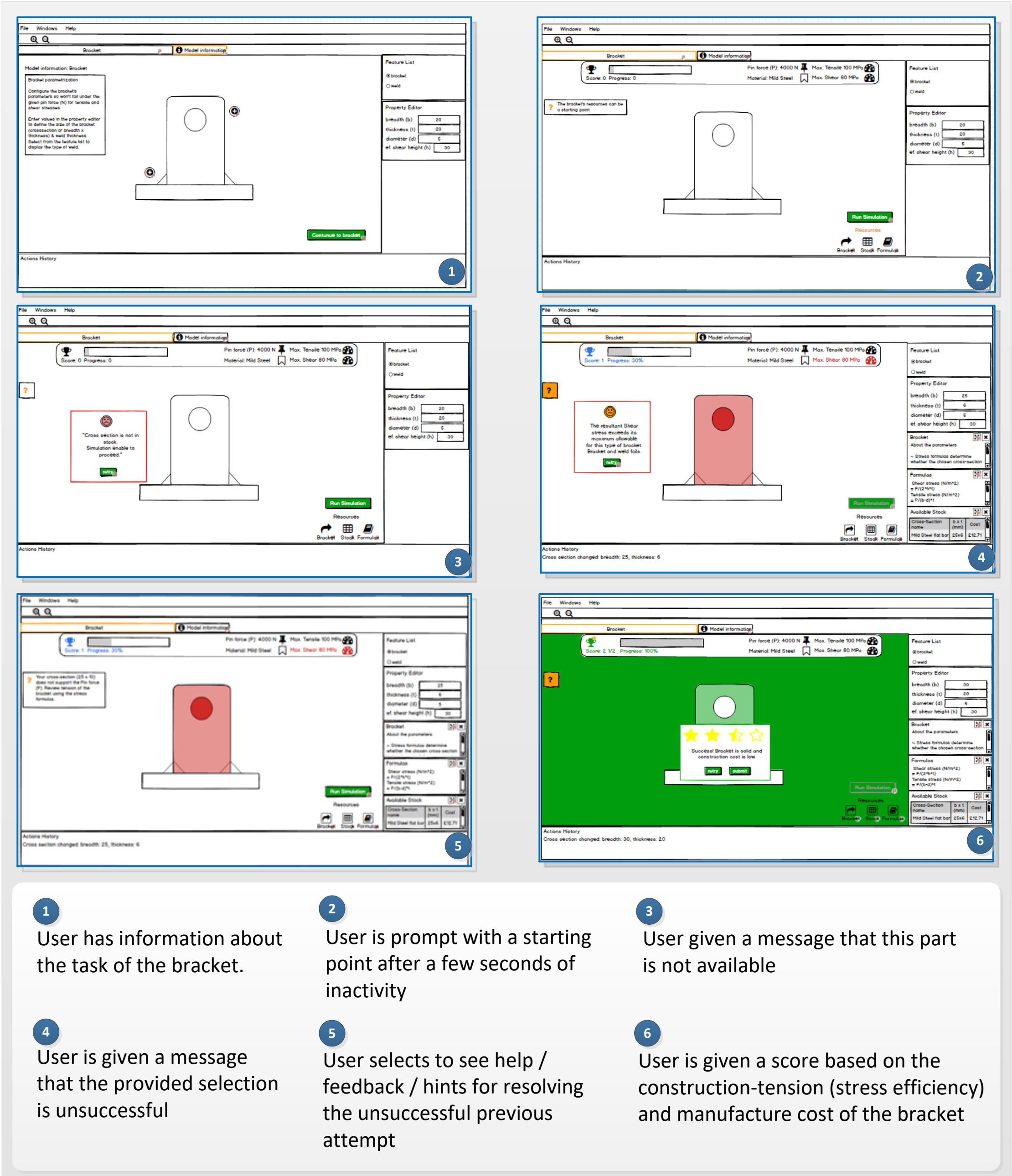


Figure 65 ICAD CADG version 1

Table 38 lists participants' feedback on the game mechanics and aesthetics during the second investigative design exercise.

Table 38 ICAD CADG version 2 user feedback

Iteration	Users' feedback
#2 **(Figure 66)**	• Clearer explanation about score calculations and how a better score can be achieved **Recommendation**: Provide more information on scoring-calculations • "Test" action button and resources location problematic **Recommendation**: Review position of those set of buttons • A clear presentation of the design steps in the process might be necessary, particularly for novices **Recommendation**: Review the addition of a 'stages feature' • A visual display of which part of the bracket fails can be helpful for thinking of what needs to be done next **Recommendation:** Review the addition of a 'stages feature' • A combined tool of formulas and calculation could be more helpful during the problem-solving process of the task **Recommendation:** Review the addition of a calculator with formulas

Figure 66 illustrates the prototype the provided feedback upon for second investigative design exercise.

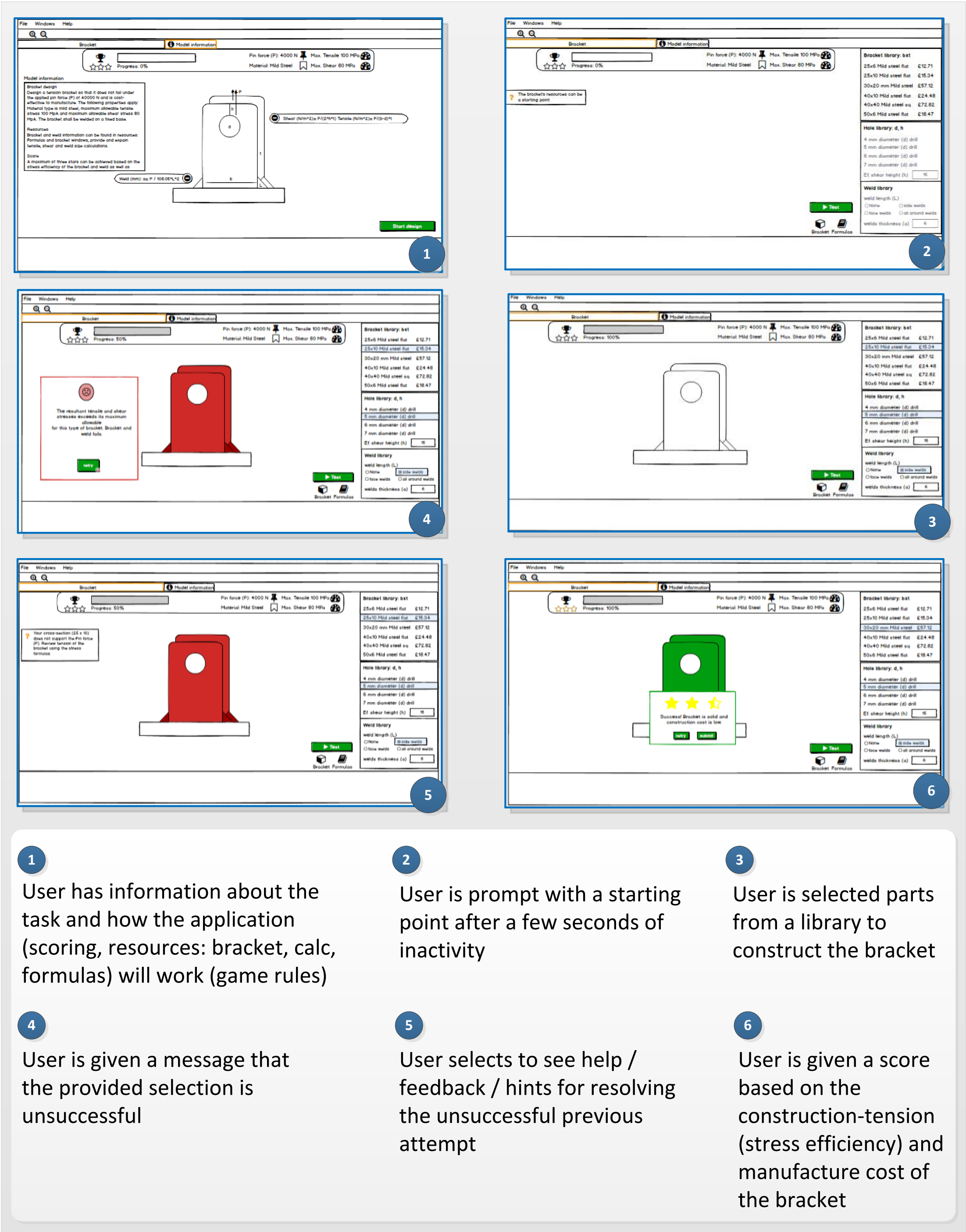
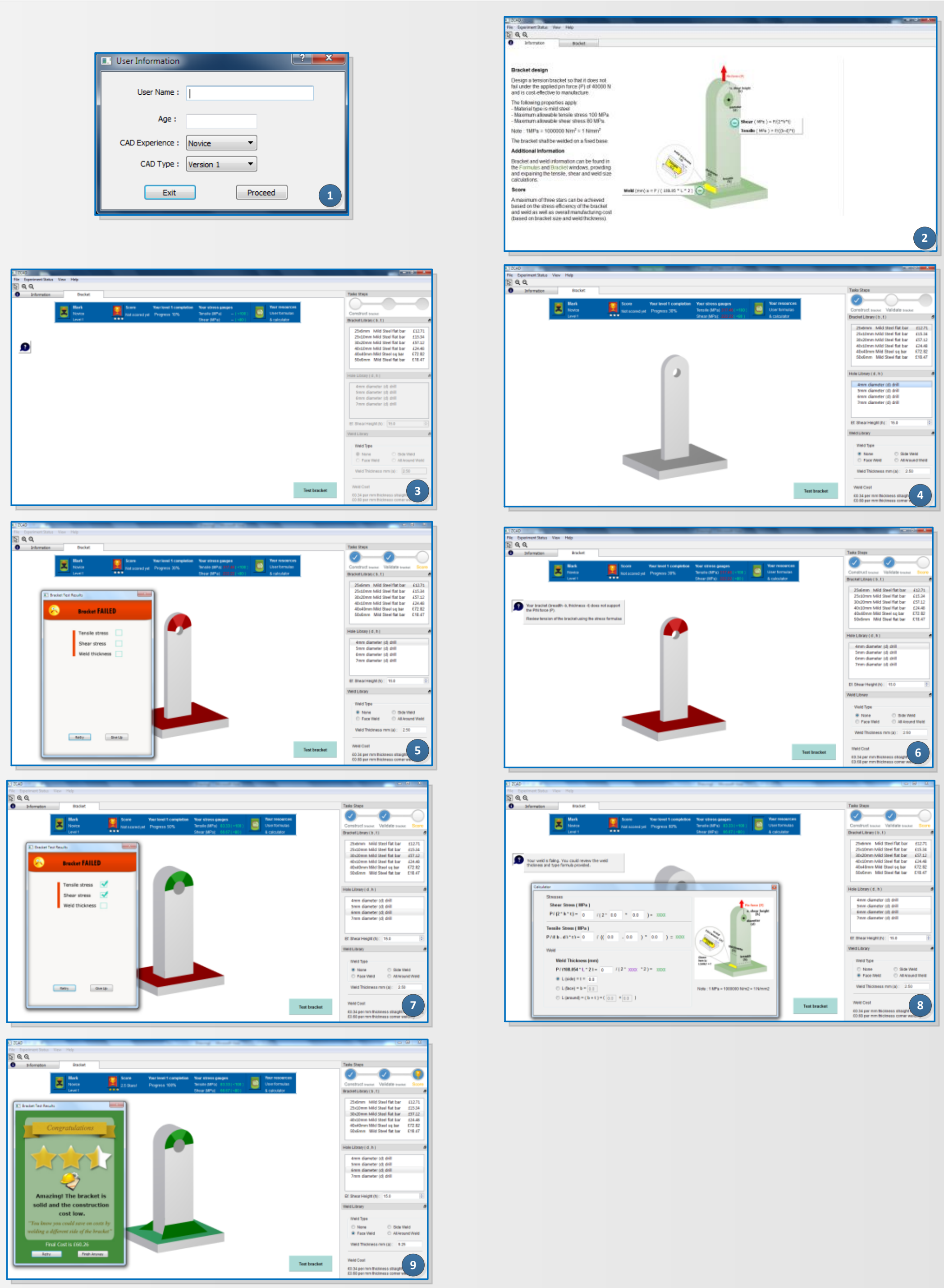


Figure 66 ICAD CAG version 2

The final ICAD CADG incorporates all participant feedback now includes:

- A window is included in the top-level interface to profile the participant; name, age, level of expertise (novice, intermediate, expert) and initiate the logging process (feature also incorporated in CADT)
- Two windows-tabs: one for information relating to the task (directed goals) and how to use the application to score (information-tab) and one for constructing the bracket (bracket-tab)
- Feedback is provided in two forms: messages incorporated within the main panel and colour changes (green for success and red for unsuccessful) of the bracket parts.
- Progressive-text bars on top of the main panel indicate the completion of the task and the steps taken on the design process. This together with the visceral outputs make up the performance-feedback mechanics
- Rewards in form of scoring-stars and bracket overall costs are displayed upon completion of the task to indicate how well the participant had done and provide option to re-start / retry the task
- A combined formula and calculator tool is provided to aid the optimisation process (Figure 67).



1. Users' profile window

2. User has information about the task and how the application (scoring, resources: bracket, calc, formulas) will work (game rules)

3. User is prompt with a starting point after a few seconds of inactivity

4. User selects the parts of the bracket from the given geometry to build it while checking his design progress

5 6 7 8 User can test the bracket to evaluate its construction-tension. The system provides a task list of what has been achieved and further on provide help/hints and tools for user to use

9. User is given a score based on the construction-tension (stress efficiency) and manufacture cost of the bracket with the option to retry the construction for better result

Figure 67 User interfaces of the ICAD CADG final version with additional profile window, including information and bracket tabs

***b.* ICAD CADT environment**

The CADT environment follows the same layout as the CADG except all the game mechanics and aesthetics are removed. This is to replicate a similar environment without the game approaches for the comparison experimentations (Figure 68).

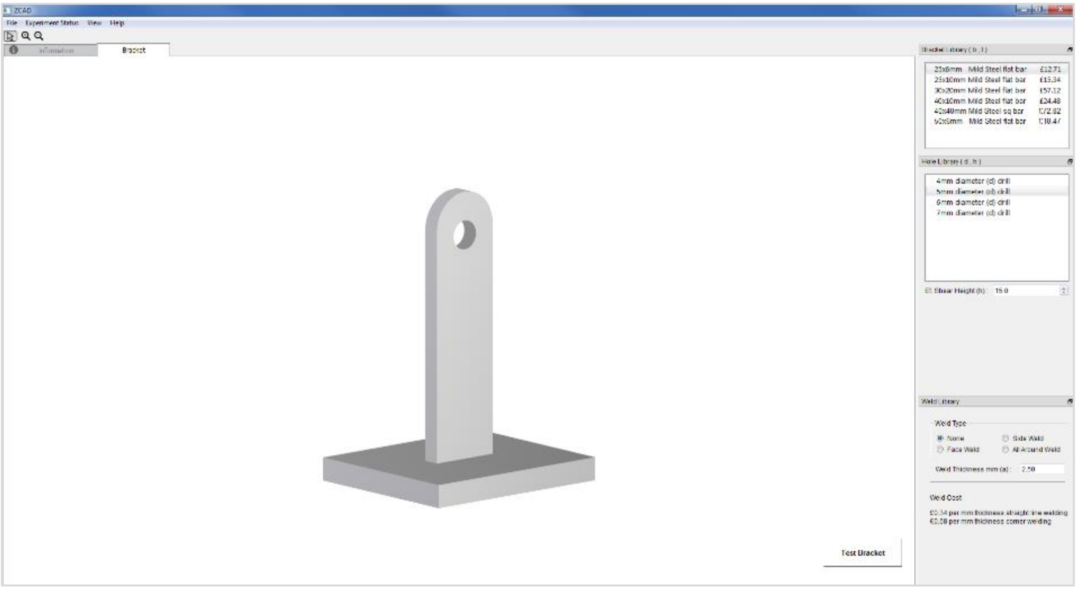


Figure 68 User interface of the conventional-based ICAD (CADT).

7.4 ICAD experimentation and results

Thirty-eight (38) engineers with different level of CAD expertise (16 novices, 16 intermediate and 6 experts) were tasked to design a bracket by configuring it to withstand an applied pin force. The participants where split in two equal-number groups (8 novices, 8 intermediate and 3 experts for each group) and asked to work with either the ICAD CADG or ICAD CADT. They worked online, on their own time and on their own devices.

7.4.1 ICAD experimental procedure

Figure 69 illustrates the experiment stages. Participants have no time restrictions on the bracket design task, with either the of ICAD versions (CADG or CADT). Questionnaires and a 'README' file with a set of steps of opening and filling the questionnaires were provided.

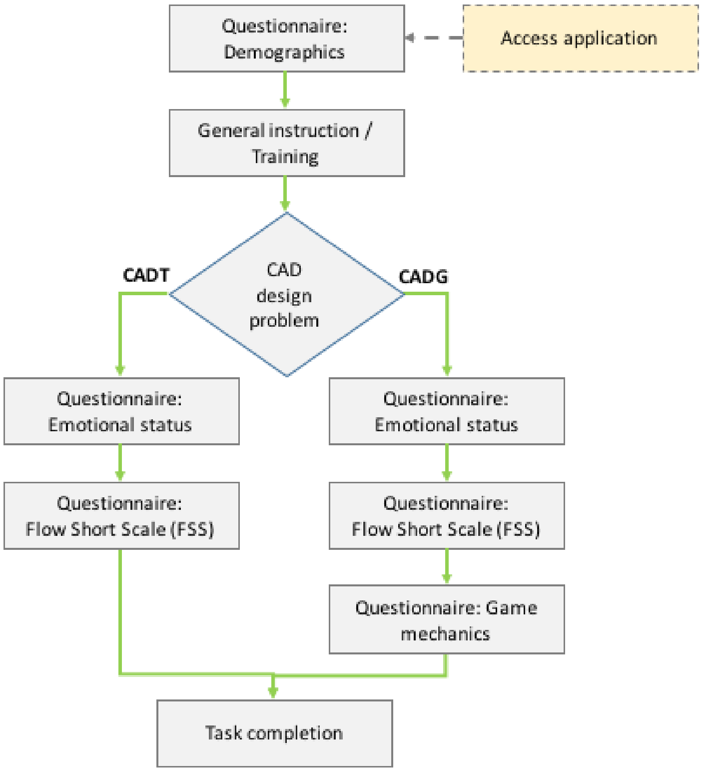


Figure 69 User trials procedure

Participants follow the README file instructions:

1. Unzip the experiment files
2. Familiarise with stress analysis formulas provided
3. Open ICAD application and select either CADG or CADT
4. Fill the online questionnaire when design task is completed (See Appendix E for questionnaire)
5. ICAD log files (.csv file) and completed questionnaires returned by email.

7.4.2 ICAD experimental results

The following sections report the findings. All datasets and statistical outputs are in Appendix C.

The analysis was conducted per ICAD environment and per participants' level of expertise: novice, intermediate and expert.

Engineers' performance

a. **Effectiveness**

As defined previously, the ***Effectiveness*** constitutes the number of times users try and modify the bracket while designing it within the CAD environment (i.e. the number of design iterations). Since participants were divided into groups based on the level of expertise using one of the environments, two stages of TTESTs were carried out to compare this variable against each specific CAD interface (CADT and CADG) and level of expertise.

In this case the following TTEST definitions apply:

- Dependent variable: ***Effectiveness*** (number of iterations).
- Independent variable: **CAD Environment** (CADT and CADG), **Level of expertise**

Test 1: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Effectiveness (number of iterations) when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Effectiveness (number of iterations) when using different CAD environments"*

Test 2: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

“There is no difference in participants’ Effectiveness (number of iterations) when considering their level of expertise: novice, intermediate, expert”

The general **alternative hypothesis (H1)** is: *“There is a difference in participants’ Effectiveness (number of iterations) when considering their level of expertise: novice, intermediate, expert.”*

Table 39 shows the TTESTs for ***Effectiveness***.

Table 39 TTESTs output for difference in effectiveness or num. iterations per ICAD type and level of expertise

	Paired Differences			
	Mean	Std. Dev.	t	p < 0.05
Test 1: Effectiveness CADT vs CADG	CADT: 15.95 CADG: 14.95	CADT: 12.18 CADG: 15.61	0.22	0.83
Test 2 (CADT-CADG): Effectiveness Beginner	CADT: 11.125 CADG: 11.5	CADT: 3.98 CADG: 5.78	0.15	0.88
Test 2 (CADG-CADT): Effectiveness Intermediate	CADT: 23.125 CADG: 15.125	CADT: 16.22 CADG: 22.66	0.81	0.43
Test 2 (CADG-CADT): Effectiveness Expert	CADT: 9.66 CADG: 23.66	CADT: 0.57 CADG: 10.78	2.24	0.15

Both results failed to reject each relevant null hypothesis (***H0***); therefore, the alternative hypotheses (***H1***) are both rejected with each TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers’ effectiveness (Test 1 $t(34) = 0.22$, $p < 0.83$, Test 2 (CADG-CADT) Novice $t(12) = 0.15$, $p < 0.88$, Intermediate $t(13) = 0.81$, $p < 0.43$ and Expert $t(2) = 2.24$ $p < 0.15$.

In Figure 70, the trend looks similar.

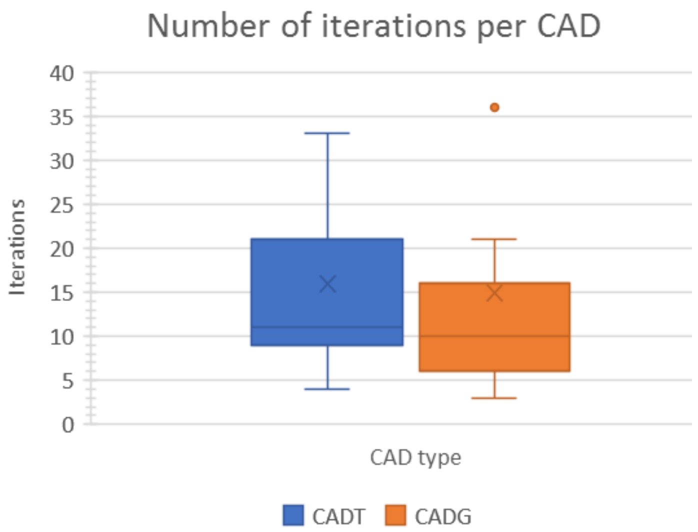


Figure 70 Effectiveness or num. iterations per ICAD type

In Figure 71, CADG showed no significant impact on the effectiveness of the bracket design task. However, looking at the means of the ICAD CADG vs CADT for the intermediate and experts, it suggests there was a difference in effectiveness. Wider sample would need to be considered making this conclusive.

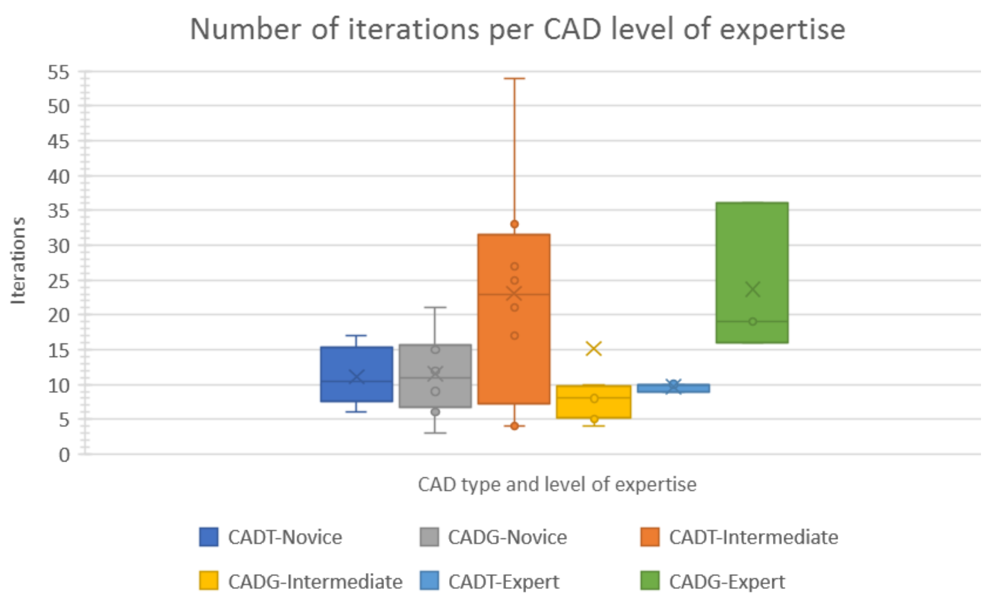


Figure 71 Effectiveness or num. iterations per ICAD type and per level of expertise

b. **Efficiency**

As defined previously, ***Efficiency*** constitutes the Task Completion Time (TCT) or Time completion, for users, to reach a solution for the design task of the bracket within the CAD environment. As seen in the effectiveness analysis, participants were divided into groups based on the level of expertise using one of the environments. In this case two stages of TTESTs were carried out to compare this variable against each specific CAD interface (CADT and CADG) and level of expertise.

In this case the following TTEST definitions apply:

- Dependent variable: ***Efficiency*** (time completion).
- Independent variable: **CAD Environment** (CADT and CADG), **Level of expertise**

Test 1: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Efficiency (time completion) when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Efficiency (time completion) when using different CAD environments"*

Test 2: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Efficiency (time completion) when considering their level of expertise: novice, intermediate, expert"

The general **alternative hypothesis (H1)** is: *"There is a difference in participants' Efficiency (time completion) when considering their level of expertise: novice, intermediate, expert."*

Table 40 shows the TTESTs for ***Efficiency***.

Table 40 TTESTs output for difference in efficiency or time completion (sec) per CAD type

	Paired Differences			
	Mean	Std. Dev.	t	p < 0.05
Test 1: Efficiency CADT vs CADG	T: 1514.93 G: 1422.02	T: 614.06 G: 501.10	0.51	0.61
Test 2 (CADT-CADG): Efficiency Beginner	T: 1633.368 G: 1537.006	T: 481.154 G: 619.609	0.34	0.73
Test 2 (CADG-CADT): Efficiency Intermediate	T: 1500.374 G: 1409.073	T: 828.246 G: 434.675	0.27	0.79
Test 2 (CADG-CADT): Efficiency Expert	T: 1237.878 G: 1149.918	T: 101.136 G: 300.492	0.48	0.67

Both results failed to reject each relevant null hypothesis (***H0***); therefore, the alternative hypotheses (***H1***) are both rejected with each TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers' efficiency (Test 1 $t(35) = 0.51$, $p < .61$, Test 2 Novice $t(13) = 0.34$, $p < 0.73$, Intermediate $t(11) = 0.27$, $p < 0.79$ and Expert $t(2) = 0.48$, $p < 0.67$). The independent TTEST results show no significant difference on the efficiency of the engineers, between the CAD environments as shown in Figure 72.

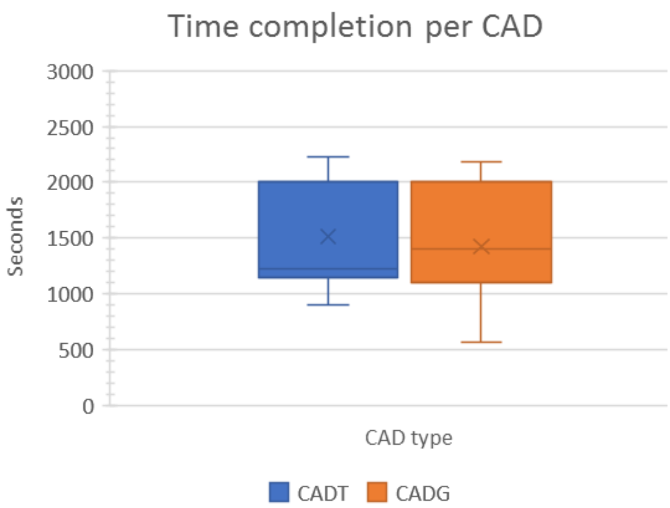


Figure 72 Efficiency or time completion per ICAD type

Also, no differences per CAD level of expertise as shown in Figure 73.

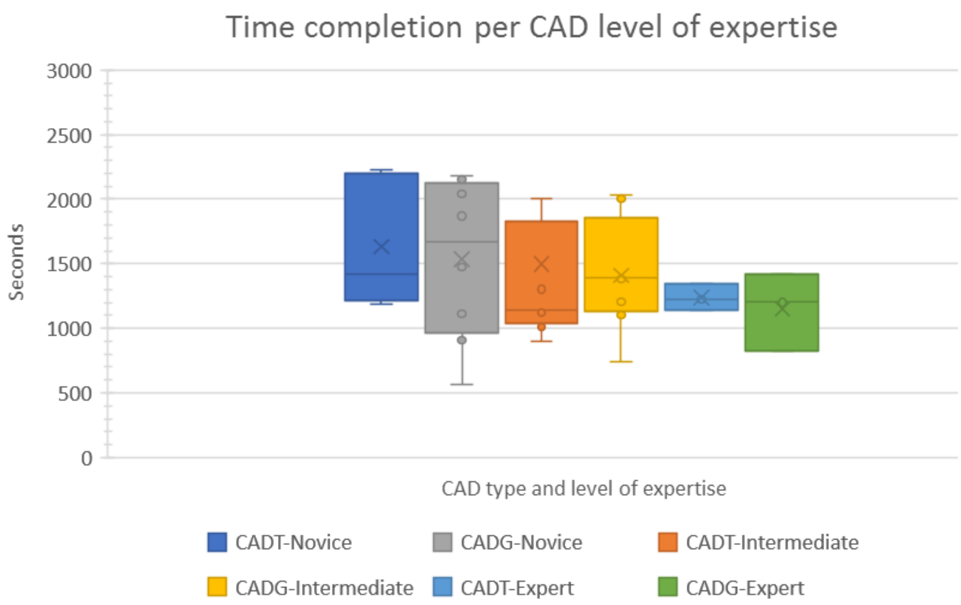


Figure 73 Efficiency or time completion per ICAD type and per level of expertise

Similar with the metric of Effectiveness there was no direct impact of CADG on the Efficiency of the engineers. It may be that the game aesthetics (see 7.2.3) created a more familiar engineering look and feel, which affected the interaction of the engineers during the experimentation.

c. Satisfaction

The same satisfaction questionnaire was employed as in Chapters 5 and 6.

Satisfaction describes a positive emotional response related to fulfilment. Users rated their ***Satisfaction*** of their interactions with the CAD environments in a scale 1-10. Similar to the previous metrics of effectiveness and efficiency testing strictures, participants were divided into groups based on the level of expertise using one of the environments. Two stages of TTESTs were carried out to compare this variable against each specific CAD interface (CADT and CADG) and level of expertise.

In this case the following TTEST definitions apply:

- Dependent variable: ***Satisfaction***
- Independent variable: **CAD Environment** (CADT and CADG), **Level of expertise**

Test 1: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Satisfaction when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Satisfaction when using different CAD environments"*

Test 2: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Satisfaction when considering their level of expertise: novice, intermediate, expert"

The general **alternative hypothesis (H1)** is: *"There is a difference in participants' Satisfaction when considering their level of expertise: novice, intermediate, expert."*

Table 41 shows the TTESTs for ***Satisfaction***.

Table 41 TTESTs output for difference in satisfaction ratings per CAD type

	Paired Differences			
	Mean	Std. Dev.	t	p < 0.05
Test 1: Satisfaction CADT vs CADG	1.31	1.35	0.29	0.10
Test 2 (CADT-CADG): Satisfaction Beginner	CADT: 5 CADG: 5.5	CADT: 1.690 CADG: 1.195	0.68	0.51
Test 2 (CADG-CADT): Satisfaction Intermediate	CADT: 7.25 CADG: 8.5	CADT: 0.886 CADG: 0.925	2.75	0.02
Test 2 (CADG-CADT): Satisfaction Expert	CADT: 4 CADG: 5.6	CADT: 1 CADG: 1.527	1.58	0.20

For Test 1 the results failed to reject the null hypothesis (***H0***); therefore, the alternative hypothesis (***H1***) is rejected, with TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers; satisfaction (Test 1 t(36) = 1.68, $p < 0.10$). However, for Test 2 the results rejected the null hypothesis (***H0***); therefore, the alternative hypothesis (***H1***) is accepted (Test 2 Novice t(14) = 0.68, $p < 0.51$, Intermediate t(14) = 2.75, $p > 0.02$ and Expert t(3) = 1.58, $p < 0.20$). As shown in Figure 74, the participants rated their satisfaction similarly for both two CADs.

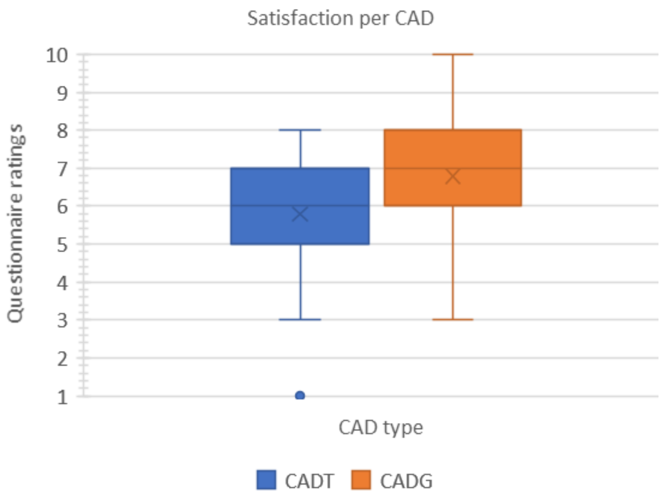


Figure 74 Satisfaction ratings per ICAD type

The independent TTEST results indicated a significant difference on the satisfaction of the intermediate level engineers. Presume that the knowledge and length of experience with traditional engineering approaches impact the way the game-based engineering environments is experienced and perceived (Figure 75).

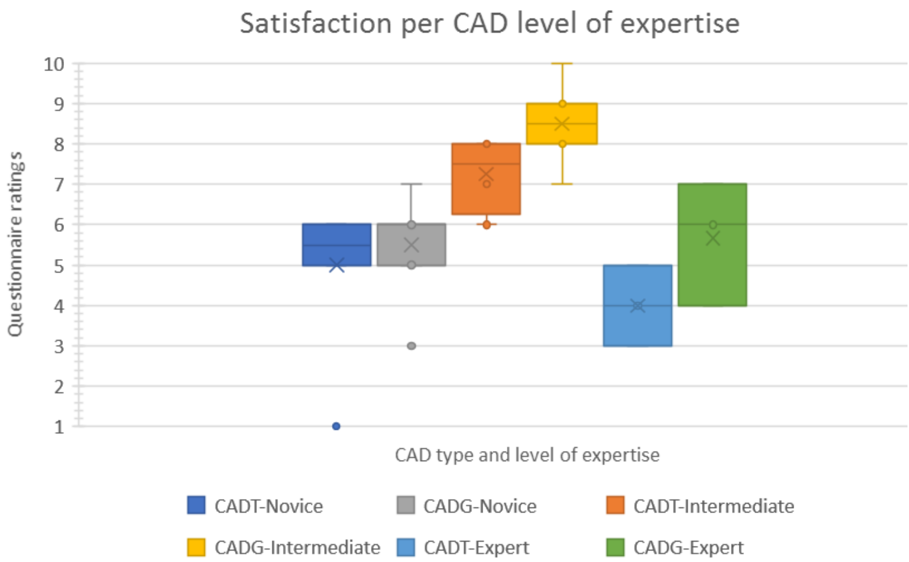


Figure 75 Satisfaction ratings per ICAD type and per level of expertise

CADG had an impact of the satisfaction levels of the engineers. Intermediate engineers, comfortable with their engineering knowledge were more satisfied under game mechanics enabled interacting for the defined task. Whereas novices found their lack of experience increased their effort in trying to complete the task. Thus, in contrast they focused on the end goal, interacting less with the game mechanics of Performance-Feedback and Progression. For experts, their experience, training, and familiarity with problem-solving methods meant they either ignored the performance game mechanics or found them distracting.

d. Cognitive load

Cognitive load describes the level of mental demand, temporal demand, performance, effort and frustration of users within a context of an interaction. Users rated their ***Cognitive load*** for their interactions with the CAD environments in a scale 1-20. The calculations of the cognitive load are done though the NASA TLX framework and its questionnaire. The questionnaire can be found in Appendix E.

Similar to the previous metrics of effectiveness and efficiency testing strictures, participants were divided into groups based on the level of expertise using one of the environments. Two stages of TTESTs were carried out to compare this variable against each specific CAD interface (CADT and CADG) and level of expertise.

In this case the following TTEST definitions apply:

- Dependent variable: ***Cognitive load***
- Independent variable: **CAD Environment** (CADT and CADG), **Level of expertise**

Test 1: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Cognitive load when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Cognitive load when using different CAD environments"*

Test 2: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Cognitive load when considering their level of expertise: novice, intermediate, expert"

The general **alternative hypothesis (H1)** is: *"There is a difference in participants' Cognitive load when considering their level of expertise: novice, intermediate, expert."*

Table 42 shows the TTESTs for ***Cognitive load***.

Table 42 TTESTs output for difference in cognitive ratings per CAD type

	Paired Differences			
	Mean	Std. Dev.	t	p < 0.05
Test 1: Cognitive load CADT vs CADG	CADT: 53.157 CADG: 50.158	CADT: 8.62 CADG:8.26	0.64	0.28
Test 2 (CADT-CADG): Cognitive load Beginner	CADT: 47.791 CADG: 55.333	CADT: 8.05 CADG: 9.36	3.21	0.01
Test 2 (CADG-CADT): Cognitive load Intermediate	CADT: 60.416 CADG: 47.875	CADT: 3.67 CADG: 0.50	2.87	0.01
Test 2 (CADG-CADT): Cognitive load Expert	CADT: 48.11 CADG: 42.443	CADT: 4.26 CADG: 5.07	2.64	0.11

For Test 1 the results failed to reject the null hypothesis (***H0***); therefore, the alternative hypothesis (***H1***) is rejected, with TTEST showing no significant statistical difference regarding the influence of the CAD environment on the engineers; cognitive load (Test 1 $t(36) = 1.09$, $p < 0.28$) (Figure 76).

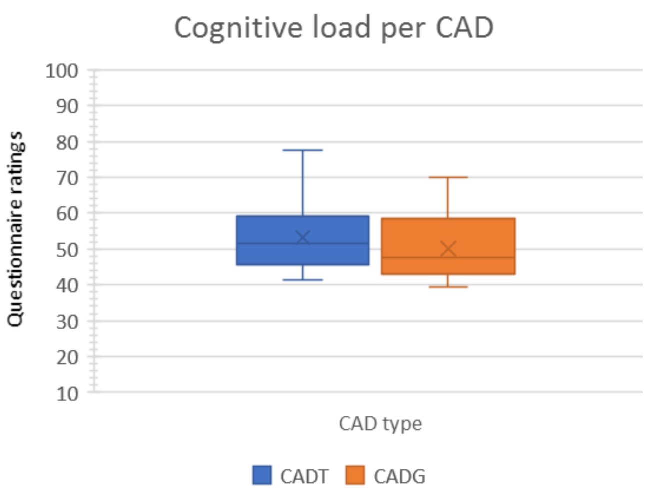


Figure 76 Cognitive load ratings per ICAD type

However, for Test 2 the results rejected the null hypothesis (***H0***); therefore, the alternative hypothesis (***H1***) is accepted (Test 2 Novice $t(14) = 3.21$, $p = 0.01$, Intermediate $t(14) = 2.87$, $p = 0.01$ and Expert $t(2) = 2.64$, $p < 0.11$.)

The independent TTEST results showed a significant difference on the cognitive load of the novice and intermediate engineers between the CAD environments (Figure 79). Engineers with intermediate expertise were engaged with the game-based environment and their interaction with the game mechanics. Expert engineers from the other hand, did not respond in the same manner as with engineers with intermediate expertise; Experts ascertain of their engineering knowledge for the task, proceeded with problem solving process without the need to invest much of their cognitive recourses to complete the task.

Novices on the other hand with their limited engineering experience found the task more difficult. Additionally, they had to adjust to a new way of interaction in CADG, which differed from the conventional engineering problem-solving approach in CADT. This resulted in increased levels of cognitive load.

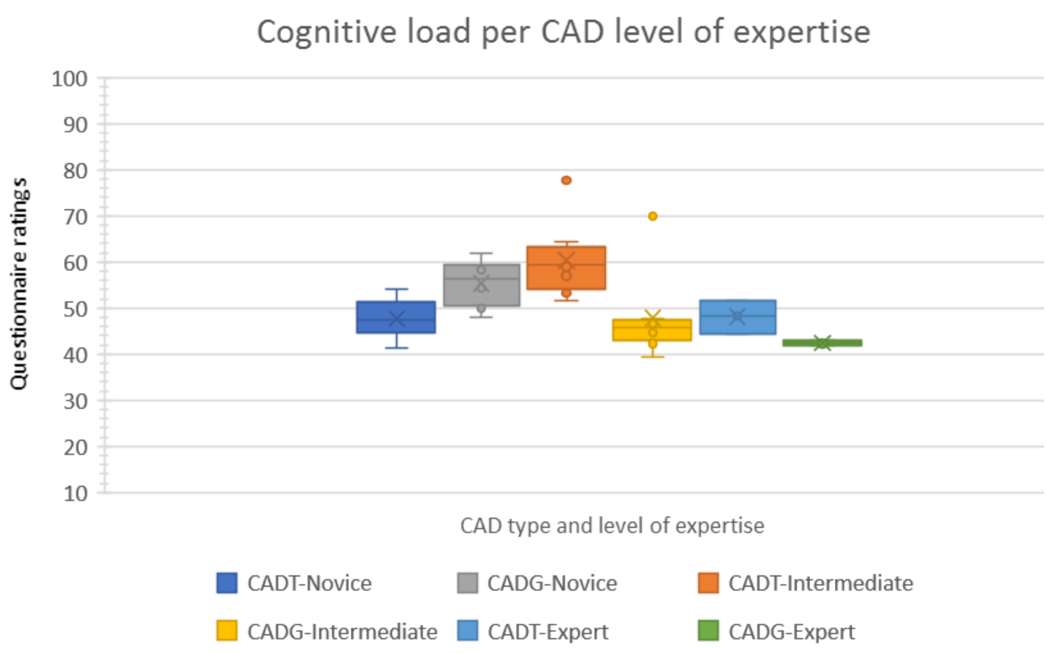


Figure 77 Cognitive load ratings per ICAD type and per level of expertise

The level of expertise on engineering design paired with game elements can influence the cognitive load of engineers. CADG showed cognitive levels of intermediate engineers benefited from the game mechanics to 'aid' their problem-solving process, resulting in lower cognition load. Whereas novices' due to their lack of experience and knowledge, coming into a less conventional environment showed increased levels of cognitive load driven by their effort to cope with the task in an unconventional environment. Looking into the cognitive load results from chapter 5 and 6, the goal-oriented nature of the task influences cognitive load as well as the design approach followed (calculate for optimisation). The game mechanics and aesthetics can reduce or increase the cognitive load in relation to the design strategy followed and engineers' level of expertise.

e. **GOMs**

The same GOMs analysis (with FLOs - engineers' executable actions) was employed in Chapters 5 and 6.

Functional level operators (FLOs):

- Check resources
- Entering cross–sections / weld type–size
- Test

The event loggings indicated that the task flows for configuring the bracket followed a mixed design strategy of sampling but also calculating and optimising approach:

- Participants in CADG used the calculator feature during the middle or at the end of their design process to review the available options chosen and optimise their bracket.
- Participants in CADT primarily used sampling approach. They indicated through the questionnaires that the application would benefit from an integrated tool of calculating the various simulation scenarios.

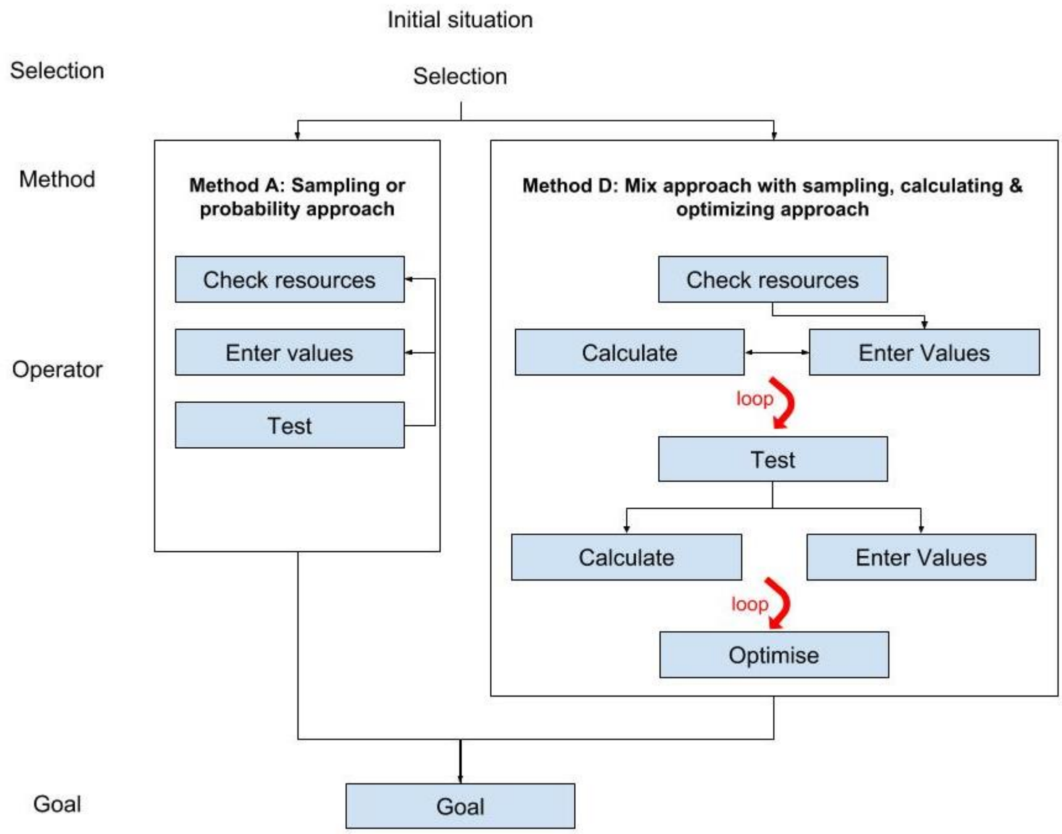


Figure 78 Design strategies (GOMS) for CADG and CADT

GOMs indicate that CADG impacted the engineers' design strategy. Similar to the results from the previous experiment's iteration (6.4 Engineers' performance results -GOMs), participants used the CADG as a means of testing their solutions; getting feedback and iterating until the best possible score was achieved (Figure 78).

7.4.3 Engineer's performance results summary

Depending on an engineer's level of expertise game mechanics and game aesthetics impact on performance. Efficiency and effectiveness showed no direct influence, and this could be attributed to the simplicity of the task. However, the gamified system influenced satisfaction and cognitive levels regardless of their level of expertise.

Prior knowledge and problem-solving approaches do affect the interaction experience. The game mechanics of directed goals and progression resulted with different interaction experiences:

- Novices were focused on understanding the problem and completing the task (high effort levels); their interaction experience was influenced by that effort making it difficult to connect with the given game mechanics.
- Intermediate engineers having a better understanding on the engineering problem-solving process and approaches, were engaged with the gamified CAD and the completion of the task. They exhibited a continuous and engaging interaction with the gamified CAD.
- Experts were primarily focused on completing the task and their interaction was identified as indifferent.

Emotional responses

The emotional responses were captured and analysed for each CAD environment and at the level of engineering design expertise. The emotion of satisfaction, being part of the usability metrics within the engineer's performance will be referenced here but its analysis can be found in 7.4 Engineer's performance. Flow and game flow dimensions rating questions were defined as seen in section 7.2.2 Data capture.

a. **Emotions questionnaire**

Participants' rated their ***Engagement, Frustration, Challenge*** of their interactions with the CAD environments in a scale 1-10. Similar to the previous metrics testing structures, participants were divided into groups based on the level of expertise using one of the environments. Two stages of TTESTs were carried out to compare this variable against each specific CAD interface (CADT and CADG) and level of expertise.

In this case the following TTEST definitions apply:

- Dependent variable: ***Engagement, Frustration, Challenge***
- Independent variable: **CAD Environment** (CADT, CADG), **Level of expertise**

Test 1: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Engagement, Frustration, Challenge when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Engagement, Frustration, Challenge when using different CAD environments"*

Test 2: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Engagement, Frustration, Challenge when considering their level of expertise: novice, intermediate, expert"

The general **alternative hypothesis (H1)** is: *"There is a difference in participants' Engagement, Frustration, Challenge when considering their level of expertise: novice, intermediate, expert."*

Table 43 shows the TTESTs for ***Engagement, Frustration,*** *and* ***Challenge***.

Table 43 TTESTs output for difference in engagement, challenge, frustration and satisfaction

	Paired Differences			
	Mean	Std. Dev.	t	p < 0.05
Test 1: Engagement CADT vs CADG	CADT: 5.95 CADG: 7.21	CADT: 1.13 CADG: 1.18	3.36	0.00
Test 2 (CADT-CADG): Engagement Beginner	CADT: 6 CADG: 7	CADT: 1.414 CADG: 1.309	1.47	0.16
Test 2 (CADG-CADT): Engagement Intermediate	CADT: 6 CADG: 7.5	CADT: 1.069 CADG: 1.195	2.64	0.02
Test 2 (CADG-CADT): Engagement Expert	CADT: 5.7 CADG: 7	CADT: 0.577 CADG: 1	2	0.13
Test 1: Challenge CADT vs CADG	CADT: 6.84 CADG: 5.11	CADT: 1.57 CADG: 1.37	3.86	0.00
Test 2 (CADT-CADG): Challenge Beginner	CADT: 8 CADG: 5	CADT: 0.925 CADG: 1.69	4.40	0.00
Test 2 (CADG-CADT): Challenge Intermediate	CADT: 6.25 CADG: 5.25	CADT: 1.581 CADG: 1.281	1.39	0.19
Test 2 (CADG-CADT): Challenge Expert	CADT: 5.33 CADG: 5	CADT: 0.577 CADG: 1	0.5	0.65
Test 1: Frustration CADT vs CADG	CADT: 5 CADG: 3.79	CADT: 2.16 CADG: 1.47	2.01	0.05
Test 2 (CADT-CADG): Frustration Beginner	CADT: 5.38 CADG: 4	CADT: 2.326 CADG: 1.772	1.33	0.21
Test 2 (CADG-CADT): Frustration Intermediate	CADT: 5.38 CADG: 4.13	CADT: 2.133 CADG: 1.125	1.47	0.17
Test 2 (CADG-CADT): Frustration Expert	CADT: 3 CADG: 2.34	CADT: 0 CADG: 0.577	2	0.18

Both results reject each relevant null hypothesis (***H0***); therefore, the alternative hypotheses (***H1***) are both accepted with each TTEST showing significant statistical difference regarding the influence of the CAD environment on the engineers' emotional responses of engagement and challenge:

- Test 1, Engagement t(36) = 3.36, p = 0.00, Challenge t(34) = 3.86, p = 0.00 and Frustration t(32) = 2.01, p= 0.05
- Test 2 Engagement for Novice t(14) = 1,47, p < 0.16 Intermediate t(14) = 2.64, p = 0.02 and Expert t(3) = 2, p < 0.13
- Test 2 Challenge for Novice t(11) = 4.40, p = 0.00 Intermediate t(13) =1.39, p < 0.19 and Expert t(3) = 0.5, p < 0.65
- Test 2 Frustration for Novice t(13) = 1.33, p < 0.21 Intermediate t(11) = 1.47, p < 0.17 and Expert t(2) = 2, p < 0.18

As seen in Figure 79 and Figure 80, CADG participants were more engaged and less challenged compared to CADT participants.

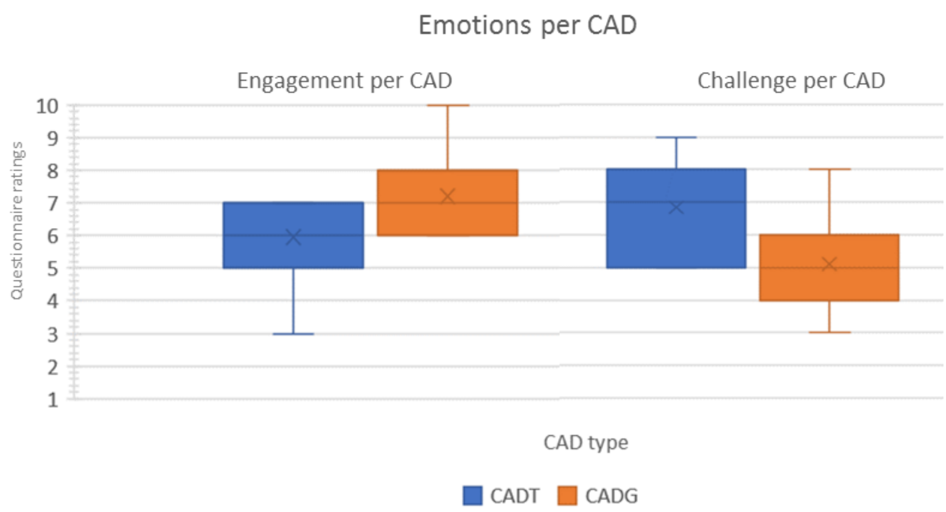


Figure 79 Engagement and challenge per ICAD type

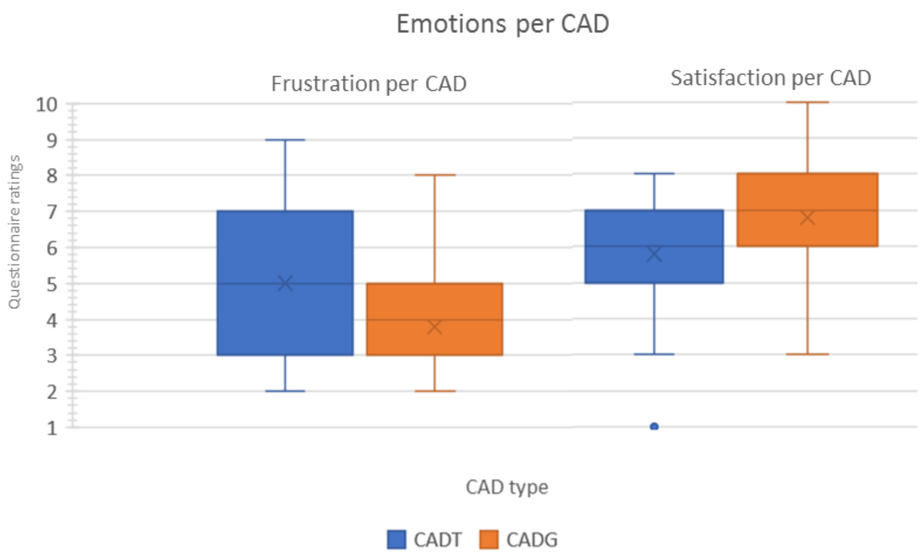


Figure 80 Frustration and satisfaction (for reference) per ICAD type

Intermediate level engineers engaged more in the process compared to novices or experts (Figure 81) but did not appear to be challenged. For the emotional response of challenge, unsurprisingly novices rated it highly (statistical significant result) confirming the fact that lack of engineering knowledge on the task can increase the level of challenge for that level of expertise (Figure 82).

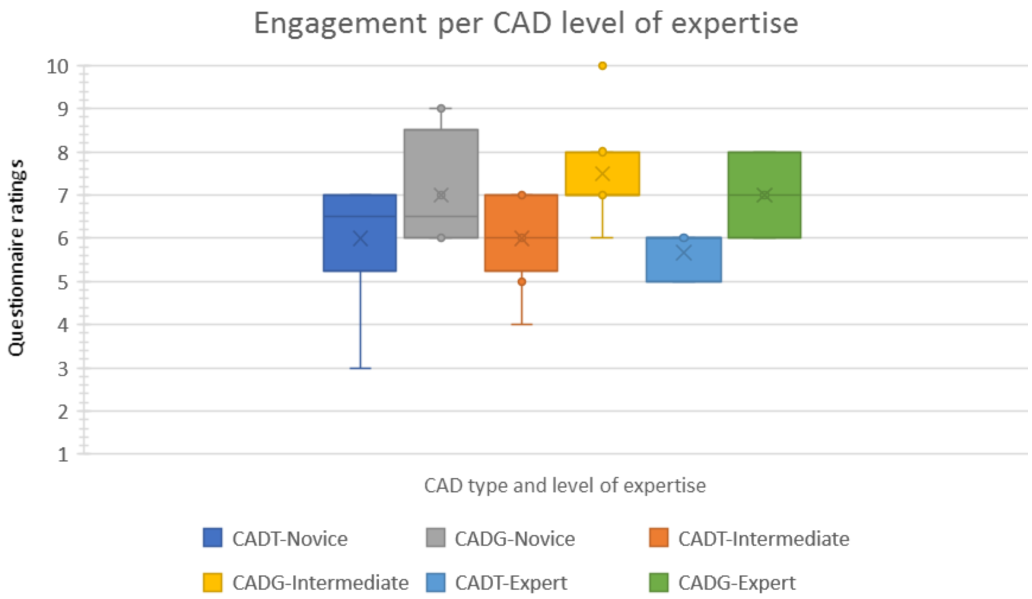


Figure 81 Engagement per CAD level of expertise

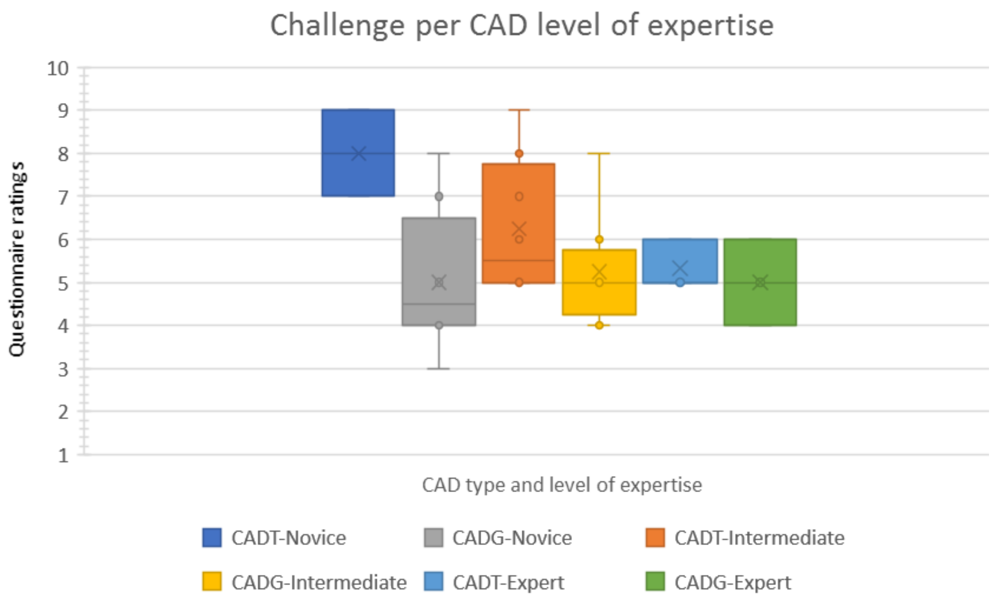


Figure 82 Challenge per CAD level of expertise

With regards to frustration ratings, there were no statistically significant differences between the level of expertise and CADs (Figure 83).

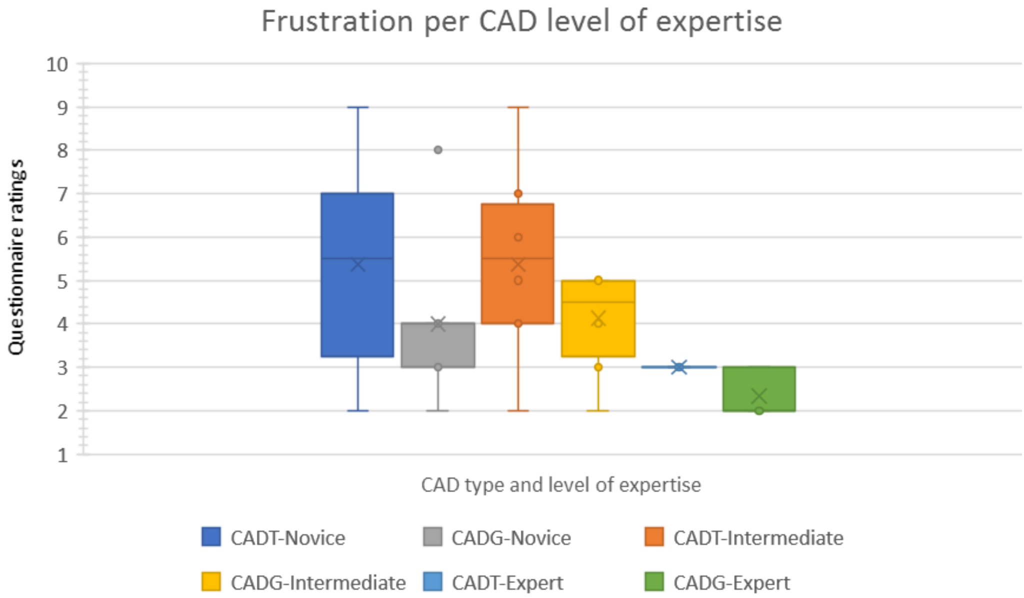


Figure 83 Frustration per CAD level of expertise

CADG had an impact on the emotional responses of the engineers. For all engineers, the level of challenge influence the level of frustration they experienced (Figure 82, Figure 83) - Engineers being challenged is dependent on their knowledge and level of expertise. For the parametric task, game approaches reduced the emotional responses of challenge and frustration and increased the response of engagement. This clearly indicates game approaches can influence positively the state of the engineers at task and at system level based on their knowledge and expertise. The task of the parameterisation the bracket was not significantly challenging for the experts regardless of the CAD environment. Novices on the other hand found the game-based system less challenging. The game mechanics drove the engagement loop [174] with the intermediate engineers, who interacting with the gamified system were encouraged (positive reinforcement) to continue (engagement) to reach an optimised result.

As seen before in the engineer’s performance summary 7.4.1, the level of expertise influences the interaction with the gamified system as well as engineer’s emotional responses.

b. **Flow questionnaire**

Participants completed the Flow Short Scale (FSS) questionnaire on 'fluency of performance' and 'absorption' using the 5-point scale ranging from 1 (strongly disagree) to 5 (strongly agree). Similar to the previous metrics testing structures, participants were divided into groups based on the level of expertise using one of the environments. Two stages of TTESTs were carried out to compare this variable against each specific CAD interface (CADT and CADG) and level of expertise.

In this case the following TTEST definitions apply:

- Dependent variable: ***Flow***
- Independent variable: **CAD Environment** (CADT, CADG), **Level of expertise**

Test 1: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Flow when using different CAD environments."

The general **alternative hypothesis (H1)** is: *"There is a difference in the participants' Flow when using different CAD environments"*

Test 2: Paired TTEST within all participants

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Flow when considering their level of expertise: novice, intermediate, expert"

The general **alternative hypothesis (H1)** is: *"There is a difference in participants' Flow when considering their level of expertise: novice, intermediate, expert."*

Table 44 shows the TTESTs for *Flow*.

Table 44 TTESTs output for difference in flow ratings per CAD type

	Paired Differences			
	Mean	Std. Dev.	t	p < 0.05
Test 1: Flow CADT vs CADG	CADT: 2.60 CADG: 3.31	CADT: 0.45 CADG: 0.65	3.89	0.00
Test 2 (CADT-CADG): Flow Beginner	CADT: 2.525 CADG: 3.188	CADT: 0.47 CADG: 0.95	1.77	0.11
Test 2 (CADG-CADT): Flow Intermediate	CADT: 2.77 CADG: 3.375	CADT: 0.50 CADG: 0.24	3.12	0.01
Test 2 (CADG-CADT): Flow Expert	CADT: 2.37 CADG: 3.43	CADT: 0.15 CADG: 0.50	3.51	0.06

Both results reject each relevant null hypothesis (***H0***); therefore, the alternative hypotheses (***H1***) are both accepted with each TTEST showing significant statistical difference regarding the influence of the CAD environment on the engineers' flow (Test 1, $t(32) = 3.89$ $p > 0.00$, Test 2 Novice $t(10) = 1.77$, $p < 0.16$ Intermediate $t(10) = 3.12$, $p > 0.01$ and Expert $t(2) = 3.51$, $p < 0.06$). The independent TTEST results show a significant difference on the level of flow of the engineers between the CAD environments.

In Figure 84, game-based CAD participants rated highly their experience with the system in terms of fluency of performance. The absorption by activity indicated a high level of commitment completing the task. Taking into consideration the emotional ratings, the flow results further support the impact of game-based approaches on the experience of the engineers.

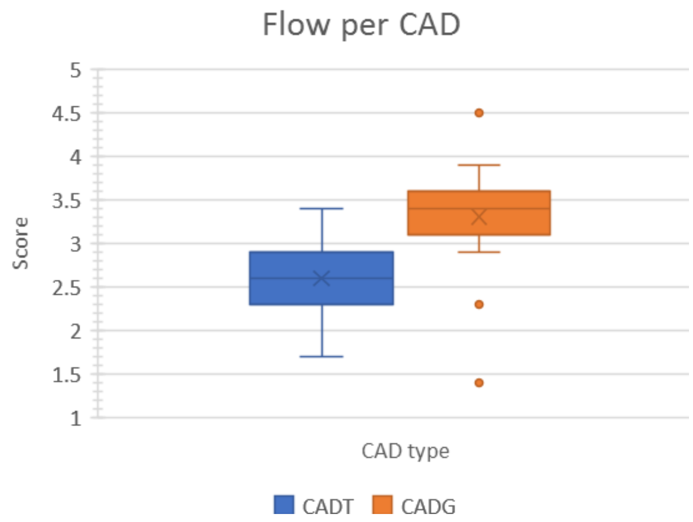


Figure 84 Flow per CAD type

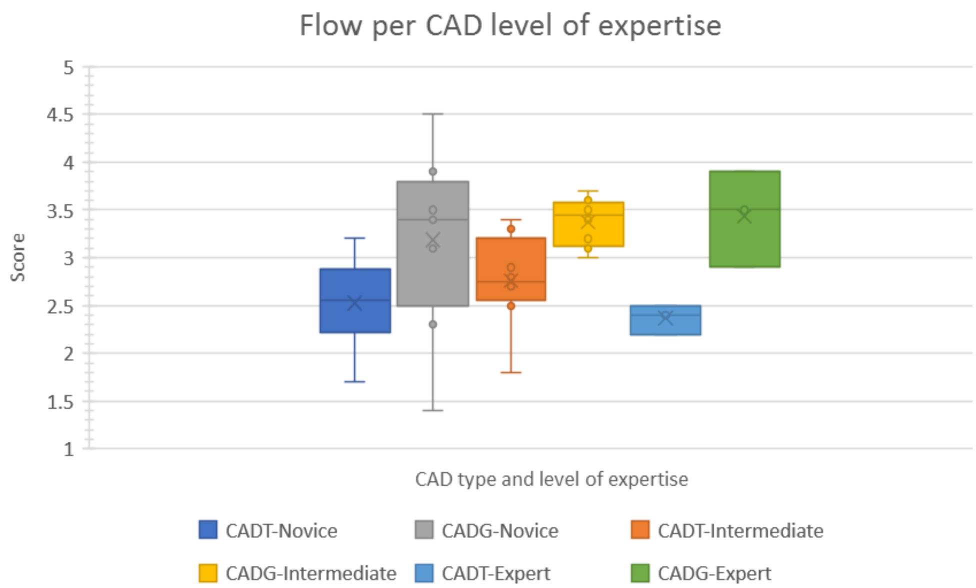


Figure 85 Flow per CAD level of expertise

Seeing in Figure 85 the flow theory, a model of balance between challenge and skills [95], fits with the current findings in terms of emotional responses;

- Novices have not enough skill (engineering knowledge) and were challenged by the task, thus had not senesce of control which led to being disengaged, less satisfied and exhibiting a low state of flow

- Experts have high level of skill (engineering knowledge) but were not challenged enough, thus not engaged or satisfied, showing a mid-intensity state of flow
- Intermediate engineers have adequate skill (engineering knowledge), were challenged, engaged and satisfied resulting in a high state of flow.

Taking into consideration engineers' emotional responses per level of CAD expertise, we can safely assume there are implications between flow and emotional responses. For all engineers and within their skills level, the emotional responses indicated that when they are significantly challenged, frustration increased, engagement is low, and flow is low. With the CADG the game mechanics create a more positive interaction with the frustration and challenge being low whereas engagement and flow being high.

In this case, the game mechanics of Rewards-Achievements influence positively the motivation and commitment of the engineers to complete the task. This was also observed in the game elements questionnaire on the autotelic experience in the next section.

***c.* Game flow dimensions' / Game elements' questionnaire**

To rate individually the impact of flow dimensions and their representations with the game mechanics, an additional questionnaire was requested from the participants in CADG. The rating questionnaire has four type dimensions (with 2 questions-items, 5-point Likert scales) that are represented in the game, through the game mechanics and game aesthetics: directed goals (game mechanics of goals and progression), unambiguous feedback (game mechanics of performance-feedback), autotelic experience (rewards-achievements game mechanics), and playability or action awareness (game aesthetics). ANOVA was carried out to compare this set of variables against participants'' level of expertise.

In this case the following ANOVA definitions apply:

- Dependent variable: **Directed goals, Unambiguous feedback, Autotelic experience, Playability**
- Independent variable: **Level of expertise**

Test 1: ANOVA

The general **NULL hypothesis (H0)** for this test was defined as follows:

"There is no difference in participants' Directed goals, Unambiguous feedback, Autotelic experience, Playability *when considering their level of expertise: novice, intermediate, expert"*

The general **alternative hypothesis (H1)** is: *"There is a difference in participants'* Directed goals, Unambiguous feedback, Autotelic experience, Playability *when considering their level of expertise: novice, intermediate, expert."*

The ANOVA for game flow dimensions and game elements shown in Table 45.

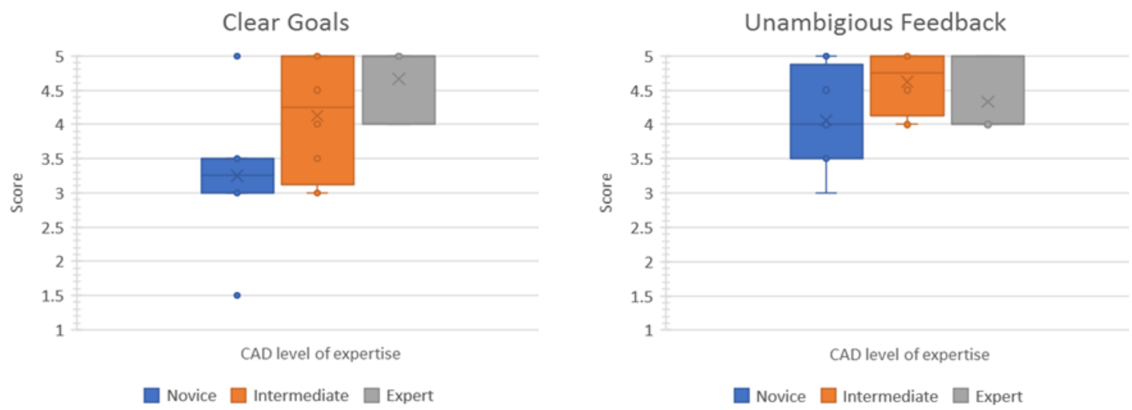
Table 45 ANOVA output for difference in game flow dimension/ game elements per CAD level of expertise

	One-way ANOVA univariate analysis		
	Mean Sq.	F	p < 0.05
Directed goals	2.74	3.50	0.05
Unambiguous feedback	1.83	2.21	0.14
Autotelic experience (rewards)	0.63	1.75	0.20
Playability	0.72	1.13	0.35

The results failed to reject the null hypothesis (***H0***); therefore, the alternative hypothesis (***H1***) is rejected, with the ANOVA showing no significant statistical difference regarding the influence of the engineers' level of expertise on Directed goals $F(2,16) = 3.50$, $p = 0.05$, Unambiguous feedback $F(2,16) = 2.21$, $p < 0.14$, Autotelic experience $F(2,16) = 1.75$, $p < 0.20$, and Playability $F(2,16) = 1.13$, $p < 0.45$.

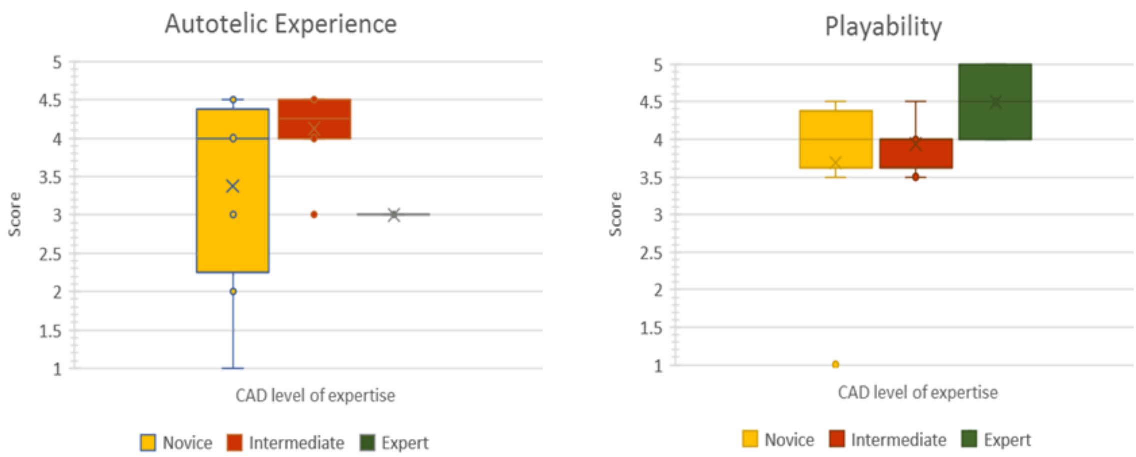
Overall, participant ratings indicate no difference in variance between the game flow dimensions or game elements and the level of expertise. As see in Figure 76 and Figure 77, ratings were similar across the Novices, Intermediates and Experts with each group having a slight difference on the game flow dimensions / game elements:

- Novices found the directed goals not impactful enough
- Intermediates found the autotelic experience or game mechanics of rewards-achievements particularly influential
- Experts found the autotelic experience or game mechanics of rewards-achievements not impactful enough



(a) (b)

Figure 86 Flow dimension or game mechanics of directed goals (a) and unambitious feedback (b) per level of expertise



(a) (b)

Figure 87 Flow dimension or game elements of autotelic experience (a) and playability (b) per level of expertise

d. **Visual design review**

Further to validating the CADG and CADT application experience the visual representation of the GUI was reviewed with production reaction cards.

Participants used the production cards to describe their experience, allowing for a visual comparison as well as the emotional response between the CAD versions. For CADG (Figure 88) the top four adjectives participants selected with the highest frequency: “appealing”, “engaging”, “usable” and “satisfying”.

Figure 88 Top four words describing participants’ experience in CADG

The CADG interface had an overall positive reaction from the participants indicating that the game-based GUI had the desired emotional effect. For the CADT the top five adjectives with the highest frequency in Figure 89 were: “accessible”, “confusing”, “controllable”, “easy” and “frustrating”.

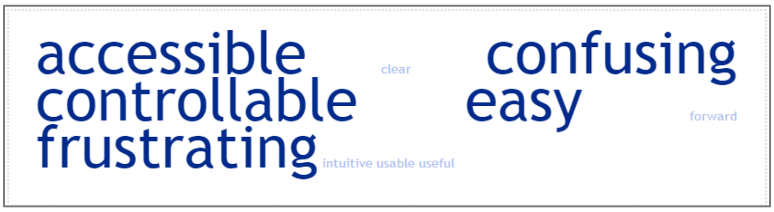


Figure 89 Top five words describing participants’' experience in CADT

The CADT interface had an overall good reaction from the participants; however, the adjectives of “frustrating” and “confusing” indicating that an alternative design approach is preferred.

7.4.4 Emotional response results summary

Game mechanics have a positive impact on the overall emotional response of the engineers who characterised CADG experience as “appealing”, “satisfying” and “engaging”.

Engineers’ engagement with the gamified environment for the bracket design task was influenced by their expertise. Intermediate engineers driven by the game mechanics were placed within an engagement loop, encouraged to reach an optimised result while having a positive experience (Figure 90). They understood the task and the feedback, felt autonomous and engaged in that process and in consequence had an optimal performance.

Novices from the other hand rated their experience as challenging with the tasks’ goals not being clear or impactful enough thus having a less engaging experience which further influenced their overall design process.

Finally, experts perceived the task as not challenging enough to have an impact on their interaction experience between the two CAD versions. They did not find the task significant and consequently were not highly engaged with the process.

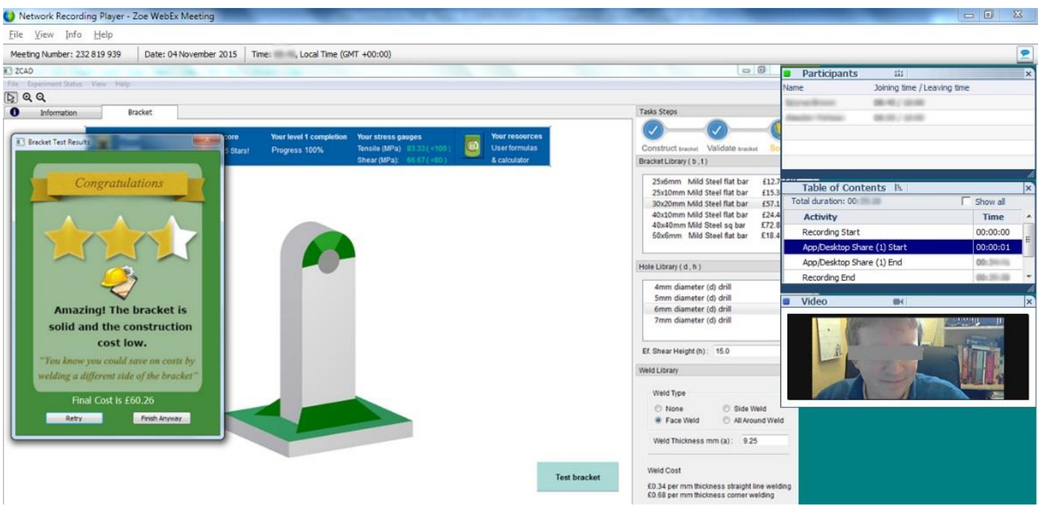


Figure 90 Participant smiling on achieving one of the top scores for the task

7.5 Summary

The DeReFrame approach included an investigative design exercise with engineers early on the ICAD design, to improve its functionality. Furthermore, the framework included a newly derived experimental protocol and system development. The inclusion of the Flow Short Scale (FSS), Flow State Scale (FSS-2) and production reaction cards provided good measure of the emotional responses of the engineers with the given game mechanics.

The results indicated that game mechanics and game aesthetics have an impact the engineers' performance and emotional response based on the engineer's level of expertise. Engineers' prior engineering knowledge and design skills with CAD influenced their problem-solving approach and emotional responses for the task, which further affected their interaction experience with the gamified system:

- Novices with their lack of experience and knowledge, focused on understanding the problem and completing the task. Thus, putting lots of effort on meeting the end goal, interacting less with the interface. They showed increased levels of cognitive load driven by their effort to cope with the task in an unconventional environment.
- Intermediate engineers comfortable with their engineering knowledge were more satisfied interacting with the gamified CAD to reach an optimal result for the given task. Their emotional responses of satisfaction and flow were statistically significant for the CADG. The game mechanics of rewards or their autotelic experience was rated highly / influential.
- Experts primarily focused on completing the task and found to be indifferent throughout the process. The emotional responses were indifferent between the two different ICADs expect of the engagement level and flow.

Overall, the game mechanics and aesthetics triggered high level of satisfaction among the engineers. The production reaction cards exercise indicated that engineers choose to describe the ICAD CADG process as "appealing", "satisfying" and "engaging". The ICAD CADT found to be difficult to interact with and had lower rates on the engagement and flow whereas higher on frustration and challenge. The interaction was more linear (followed a specific sequence of actions) for the engineers, who were unaware of their progression thus described their experience as “confusing” and “frustrating”. The ICAD CADT system does not provide design progress to the engineer (through a set of steps / stages) and does not provide no real-time feedback which resulted in a disengage experience.

In summary, having a CADG system have showed to be beneficial throughout an engineering design experience; continuously engaging the engineers into the design process, providing a motivational and emotional driver to reach an optimal solution.

Chapter 8: Discussion & Conclusions

The research aim was to identify whether the appealing characteristics of game systems and gameplay could improve engineers' performance and engagement in engineering design with CAD. A framework, called DeReFrame, was employed to construct an experimental game-based CAD environment to explore this proposition by compare it to a traditional CAD. The findings indicate that there is a positive influence of game mechanics and game aesthetics on the performance and emotional response of the engineers.

8.1 Game systems for CAD

One of the key characteristics that distinguish game systems from CAD systems is gameplay, which can be seen as the result of a large number of game elements. Games are systems that expose players to components, interactions and emergence without overwhelming the players. They can abstract a 'real problem' so players can have targeted experiences. Seeing this within the engineering space, the question posed was: could we explore this kind of gameplay from an engineering design perspective?

As evidenced by findings on designing interactive engineering applications, CAD and engineering design has long been considered a less engaging system due to its limited interaction with the engineers. As seen in Table 2 in literature review, efficiency limits in CAD, limited creativity and interaction with suboptimal use were some of the drawbacks.

Studies identified in the literature such as the GamiCAD [78], Think3D CAD system [79] with "The Monkey Wrench Conspiracy" (MWC) and Tideman [81] with the VR gaming simulation for a lane change support system, provided a good indication of the positive effect of the game mechanistic in CAD and engineering design. However, they were all instructional with a wizard-based features that provided a very structured interaction. Thus, the user experience provided was very system-oriented, without encouraging engineers to apply exploratory thinking and experimentation to achieve a successful state. The adoption of game systems and game mechanics in engineering reveals several appealing aspects, beyond task progression and faster time completion as the literature studies presented. Abstraction of complexity, guided discovery of behaviours, explorative processes and appeal are some of those aspects further studied to push the boundaries of game mechanistic to CAD and engineering design. However, these aspects necessitated the development of a framework to evaluate further the potential for leveraging game systems design and user experience (UX) techniques into a CAD system.

8.2 Framework for CAD comparisons: DeReFrame

Within the two domains of games and engineering design with CAD, the integration of game mechanics and aesthetics in CAD needs further understanding. For this study, the research interpreted the problem space with the solution designed simultaneously. Games are not designed for CAD and vice versa. However, within their different domains they both have rule-based relationships and mechanisms. To test the integration of those two different architectures a DeReFrame framework was created. This enabled insights to understand the design process and functional spaces in games and CAD. In its initial set up, the DeReFrame framework's findings (with ICAD CADG and CADT) indicated that the game mechanics of Directed Goals, Performance-Feedback, Progression, Rewards-Achievements and the game element of aesthetics were the most common game components across the game domain which could be studied in a straightforward manner (see Chapter 2, Table 6).

The thesis provides a contribution to knowledge in the form of a framework that can be used to study game-based approaches in engineering design and CAD leading to better design experience in digital engineering systems. Novel data capture methods and metrics for implementing game-based CAD environments has been presented for both commercial (APIs) and open source systems. A guideline for implementing and reporting game-based CAD design processes has been presented in this work.

The meaning of investigative design sessions is emphasised in its last version. This allows for the fast-turnaround of the implementation of game features and provides opportunities for engineers (end-users) to be incorporated in the CADG design process.

8.3 The role and impact of game mechanics on engineering design

Engineering design with CAD is a knowledge and skill driven process, whereas in games it is a designed experience geared around player's level of play. In gamified CAD, players have demonstrated transferable behaviours from conventional (traditional) CAD as evidenced by findings on Chapters 4 and 5 (following in the next set of bullet points) because of game interaction. Additionally, strategy was evidently different in the game-based CAD, as seen in Chapter 6 and 7 triggered by limiting the goal-orientedness effect (GOAP). Consequently, it became apparent to consider the functional/interaction game mechanisms that could affect engineers' performance and emotional responses (engagement).

The choice of game mechanics investigated for engineering design, though limited was due to many possible engineering design approaches for solving a problem and the complexity of engineering systems. In this study, the goal was to investigate the effects of specific game elements, a selection that is not exhaustive but one that represents some of the game elements highlighted from the literature. Directed goals, Performance-Feedback, Progression, Rewards-Achievements and the game elements of Aesthetics were found to be suitable to explore for their engaging / motivational aspects, in the context of a simple engineering task. From pre-and post ICAD, their effects as independent, dependent and combinatorial entities are summarised in the following bullet points:

- **Game mechanics of Directed Goals and Performance-Feedback impact on engineers' performance:**
  Users adopted a more optimised design strategy when working on the game-based interface. GOMS indicated the majority of participants employed a 'sampling' approach to reach the optimal/best solution. Directed goals act as facilitators, enabling knowledge construction by focusing users' attention on the relevant information. This, in conjunction with a well-defined scenario supported by Performance-Feedback mechanics, meant that participants were able to quickly optimise the solution to the problem. Performance is a function of resources invested and strategy used. Thus, a success or failure state as feedback

could create a pseudo-structured interaction, leading to an optimal result. That said, the game mechanics of Directed Goals and Performance-Feedback provided a CAD functionality in the form of parametric routines to support engineers in fulfilling the task goals at an appropriate pace. This aligns to design and configuration of a GOAP approach. This link between parametric design and GOAP is the connection of geometry and design performance allowing for the deeper understanding of the engineering design problem space. It can simultaneously create opportunities for a chosen problem-solving process to be further enriched (with game mechanics) and lead to an optimal design outcome (Chapter 6, Figure 53). This provided a significant insight on parametric design and its connection to GOAP and in extend, engineering design with CAD have a similar process to game mechanics. This is also consistent with theory of Directed Goals and Performance-Feedback game mechanics. Specifically, the Directed Goals are related to the contextualised activities in CADG to bring the user closer to the end goal. The early BAMZOOKi study, and later with ICAD, highlighted that Performance-Feedback worked better in conjunction with Directed Goals to reach a more optimal result. The role of these two game mechanics (Performance-Feedback and Directed Goals) worked as a means of gathering information to solve the defined problem and to further reflect on the task variables and their relationships. This facilitated an interaction with the system to reach an optimal engineering design solution (Chapter 6, Figure 53 and Chapter 7, Figure 78).

The results on the brain activation outputs during design strategizing (Chapter 6) can also be interpreted as a direct impact of the given game mechanics. The goal-directed behaviours, guided by the goal-oriented nature of the task (GOAP), were reinforced by the Directed Goals, Performance-Feedback and Rewards-Achievement mechanics. The gamified design activities indicated a sustained attention to the task evident both from the frontal activation of the brain as well as its volume but also, from the calculating and optimising approach or methodological and optimising approach taken. (Chapter 6, Figure 60 and Figure 38)

The literature postulated that brain activity during a design task is related to process involving information-gathering, visual scanning and sustained attention. However, this kind of evidence had not been linked to engineering design. This work is believed to be the first to show that brain activation links engagement patterns and flow during design thinking and problem solving.

- **Game mechanics of Performance-Feedback and Rewards-Achievements impact on engineers' engagement:**

  The statistical analysis on the ICAD for the game environment indicated that engineers had increased satisfaction and engagement for the task. The Performance-Feedback game mechanics with their different graphical and content representation (game aesthetics), along with the game mechanics of Rewards-Achievements created a continuous interaction leading to an engaging state. Engineers continued to iterate their design solutions to reach an optimised result, encouraged by the feedback mechanics (Chapter 6, Figure 54, Figure 55 and Chapter 7, Figure 74, Figure 75, Figure 79, Figure 81).What was encouraging was the focus of the engineers' experience via the system's aesthetics and interactivity. In this instance, the game mechanics and graphics provided the visual context for the engineer to interpret the interface and connect the dots on the design 'know-how', 'who for' and design consequences, making the design's outcome traceable. Alternatively, it can be described as engineers connecting the geometry or parameters to the design performance and in consequence get a deeper understanding on a process to reach an optimal design state for the given task.

  The findings indicate that participants (total 69), worked to the problem's solution by reviewing decision points rather than investing 'tool-time' and devoting cognitive load to understand the system.

  The game elements of Performance-Feedback, Rewards-Achievements and element of Aesthetics together rendered a prescribed progression path within the gameplay. As seen previously, Performance-Feedback combined with the Rewards-Achievements mechanics, they serve to numerically represent a user's progress. Furthermore, the mechanics in combination with game aesthetics visually confirm users' achievements, creating a compelling feeling of play (as see for the ICAD CADG experimentation results and within the engagement levels in graphs of Figure 79, Figure 81). Throughout the empirical studies, the results on GOMs for the game-based CAD indicate design strategies incorporating continuous interaction with the environment. Specifically, engineers have, on average, an additional 2-3 iterations after completing the task's goal indicating that the Rewards-Achievements game mechanic providing the incentive of 'better scoring', is a motivator factor to actively engage with the environment to find a better solution.

In addition, the game mechanics with the goal-orientedness of the parametric task provided a focus on engineers' cognitive process to establish a clear goal, break it down into high-level building blocks and create a sequence of actions to reach its solution, similar to GOAP.

Such compelling evidence suggests these game mechanics positively influence the engineers' flow for the duration of the interaction. Engineers were immersed with the process of progress (keep iterated until reach optimal solution, see GOMS in Chapter 6, Figure 53 and Chapter 7, Figure 78), which was facilitated through meaningful and relatable task interactions.

Overall, the game mechanics of Directed Goals and Performance-Feedback were found to be the most impactful on engineers' performance. On the other hand, the visual performative mechanics and graphical elements impacted an emotional response the most, as seen in the next set of bullet points. Delving deeper the game mechanics for CAD and its impact on users review the following insights:

- **CAD level of expertise and game aesthetics impact engagement experience**
  RQ5 was about game mechanics and game aesthetics, having an effect on the emotional response of the engineers. To this end, a cross-case analysis between the BAMZOOKi study and ICAD studies provided some insights into the phenomena associated to interaction design, aesthetics and user experience.

Within the BAMZOOKi vs. SolidEdge experimentation the user interface affected user's ability to complete the task (Chapter 3, Figure 14). BAMZOOKi's game interface provided engineers with a simple but more engaging interaction. Results indicated that engineers had an enjoyable time and would have liked to spend more time on it. Compared to the Solid edge, engineers not only were unable to finish the task but also their interaction with the interface was stressful and disrupting of their design process. This was even more pronounced from the ICAD experiments, where the engineers' effort and their interest of interacting or experiencing the game design features (an extension of the game mechanics) was indicated by the additional iterations in optimizing the task's solution (bracket).

The findings indicate the perceived appeal of a simple but effective, game –based interface is linked to sustainability of interest and motivation, which impacts engineers' interaction and engagement. Engineers felt encouraged to 'discover' interactions when the exploration space was simpler and game-like. Theoretically, this conflicts with the preconceived concept of simple interfaces and their "limited" interaction capability for engineering design. As seen from the literature review, modern CAD has increased its functionality and mechanisms to create a more integrated system to support the design processes across all its stages (Chapter 2, Figure 2).

- **Flow impacted by game mechanics of Directed Goals, Performance-Feedback, Rewards-Achievement**

  Engineers' knowledge and expertise were challenged by the game-based CAD to change their design thinking process in a more interactive way. It provided the way of reflectively exploring the problem space and testing hypothesis. The *system*, rather than presenting errors on the embedded design task, has proactively calibrated the next step (in a form of Performance-Feedback), enabling them to move towards the end-goal.

  The game mechanics created constructs of engagement and flow experienced by engineers, engaging them in a set of repeated interactions. Engineers have a clear understanding of the task's end goal and are engaged with the problem-solving activity (Chapter 6 Figure 54, Figure 55, Table 32 and Chapter 7, Figure 79, Figure 80) The playability of the game-based interface supported their interaction, which was further driven by the game mechanics of Performance-Feedback for gathering information. Rewards-Achievement mechanics provided a motivational factor for reaching the optimal engineering design solution.

- **Game mechanics of Performance-Feedback and Rewards-Achievement influence game aesthetics and CAD GUI**

  This effect was most significant with the intermediate engineers, positively affecting their ability to perceive and understand task information. The game mechanics of Performance-Feedback and Rewards-Achievements and their representation within the CAD, were the engineers' main focus during the design investigation phase (Chapter 7, Table 37 and Table 38). They were consequently the most influencing factors on the design of CAD GUI.

  The game mechanics and aesthetics are essentially clarifying cause and effect; they represent the relationship between the task variables and provide hints on the engineers' performing actions, thus supporting their cognitive processes.

  The notion of game mechanics' interaction through the UI and game aesthetics provided another dimension; the one of play-like behaviour. As seen by the findings, engineers continue interacting with the interface, looking for the visual performance cues (e.g. points, stars). The aesthetic element of scores or points, when updated to be more prominent (Chapter 6,
  Figure 45,
  Figure 47 and Chapter 7, Figure 67), created a clearer connection with effort, performance and outcome thus affecting engineers' motivation. The results on the brain activation outputs (Chapter 6) also showed a higher level of activation across the brain spectrum suggesting improved game aesthetics as a consequence of visually perceiving information (feedback).

As seen from above, the outcomes of the research activities performed, including observational (concept testing, A|B testing) and interview methods identified connections and pathways of game mechanisms' applicability to engineering design with CAD. DeReFrame has allowed the exploration of game mechanics and aesthetics in a generic framework. However, it is clear that this work is only the beginning of such research. With respect to that, future directions are necessary and can be seen in the section 8.4 below.

8.4 Contributions to science

The literature revealed limited information on the integration and analysis of game elements in engineering design and CAD. The game-based solutions found addressed concepts on learnability and emergence but did not directly derive the game mechanics and aesthetics that could be used in a serious and productive engineering design activity.

A key novelty of this study is that no other research provided a design framework to investigate and compare game-based approaches for CAD. The work reported herein presents a framework, DeReFrame, able to evaluate gamified productive systems and, as demonstrated, highlights the shortfalls of engineering design with CAD.

DeReFrame has further enabled the design and development of the ICAD applications. This provided the means to consider game elements systematically from the engineers' perspective and revealed ways to optimise and balance the game mechanics and game aesthetics in an engineering context. The positive results were highly encouraging, particularly the positive correlations between game mechanics and aesthetics in the design strategy and persistence of reaching optimal results of the engineering task (see GOMs sections in Chapter 6, 7).

The potential to inform on the design of game-based CADs including insights to redesign or enriching existing CADs could not have possible without this reusable and scalable design framework.

8.5 Addressing research limitations through future work

This work reported in this thesis is an alternative to more conventional approaches to research into engineering design. As a proof of concept, the DeReFrame has shown encouraging results. However, extensions are needed to include more complex game mechanics and engineering design activities. The parametric task used in the experimentation could likely have influenced a 'sampling' approach, thus a more experimental, explorative and creative task needs to be explored.

At the moment, the findings are consistent with the overall impression of game mechanics' positive impact in non-game contexts. However, these results should not be generalised to suit the complete engineering design process cycle. This is due to the nature of the task (configuration, parametric) tested (Chapter 4, Figure 16) which usually represents activity in the embodiment design phase.

The ICAD versions need further exploration and integration within the engineering design cycle. While the ICAD CADT was designed to alongside the CADG, it was not meant to be a holistic system but is an instance to validate a framework. While it provided a good starting point for the purpose of establishing and comparing the impact of games in CAD, its key shortfall was its development based on the game-based CAD, minus the game mechanics and aesthetics. Another point to make is that the game aesthetics were implemented based on the author's experience of designing prototypes and composing the appropriate code. In order to achieve better understanding on the appeal of the game design patterns for CAD, it needs to be studied with the input from game designers.

Significant time was needed to establish the metrics to ascertain emotional responses of the engineers and this required a new approach. Although the Fuzzy logic and neurometric approaches were eventually deemed an unsuitable method for the type of audience as they provided the first insights into game-based CAD. Such methods, perhaps with the connection of eye tracking (e.g. Tobii) for direct connection of eye gaze to emotional response, have real potential and should be further investigated into a more pragmatic deployment. The flow questionnaires provided a satisfactory, useful tool for assessing the flow experience for a game-based engineering task and in a conjunction with cognitive load questionnaire, they create a good, potentially integrated, evaluation framework for any context related to engineering and CAD.

In the long run the DeReFrame framework enables the 'game-based CAD design knowledge' to be constructed due to the cyclic nature of design processes. Thus, design knowledge can be re-used productively not only in the current study but also in other projects and contexts promoting time efficiency. DeReFrame offers a means to investigate future underlying gamification of productive systems.

8.6 Closing statement

This research shows that gameplay progression structures can introduce an element of instructional experience unlike any other, allowing for a systematic approach to reach a solution similar to GOAP:

1. Rationalise the problem (game mechanics of Directed Goals)
2. Clarify conditions and constraints (game mechanics of Performance-Feedback)
3. Explore variations of the solution (activities of trial-error and calculations)
4. Evaluate based on goals and constraints (game mechanics of Directed Goals, Performance-Feedback)
5. Decide solution

The game mechanics of Directed Goals and Performance -Feedback influence engineers' behaviour within the problem-solving process, by encouraging them to take certain actions and learn the consequences. This allows them to develop a new frame for the problem. Their behaviour and systematic design approach were observed to be transferrable especially when working on the traditional CAD after using a gamified CAD. There is strong evidence that ICAD CADG induced a set of new interaction expectations as experienced in the game-based environment.

With regards to engineers' emotional response, the performance feedback and rewards-achievements had a direct impact on creating an engaging-challenging interaction as a result of prior CAD expertise.

The chosen game mechanics played an important role in the context of engineering design and engineers' interaction with a task. They supported and encouraged a feedback loop leading to an optimal engineering design solution. In conjunction with the literature (Chapter 2), the findings indicate that using the game mechanics for feedback/guidance and motivational factors has an impact on engineers' emergence in a problem-solving activity with direct consequences for performance and emotional engagement. Expanding on the literature, the findings also demonstrate that game mechanics and game aesthetics can positively impact a real engineering problem-solving activity, following a systematic approach for finding a solution.

In conclusion, game elements embedded in CAD and engineering design depend on the future evolution of additional research combining the two domains; engineering design and games. The DeReFrame framework for engineering design with CAD will continue to evolve as it is continually refined based on engineers' feedback and further integration of game mechanics and game aesthetics.

References

[1] T. M. Connolly, E. A. Boyle, E. MacArthur, T. Hainey, and J. M. Boyle, 'A systematic literature review of empirical evidence on computer games and serious games', *Comput. Educ.*, vol. 59, no. 2, pp. 661–686, Sep. 2012.

[2] J. P. Gee, *What Video Games Have to Teach Us about Learning and Literacy*. Palgrave Macmillan, 2004.

[3] L. Sardi, A. Idri, and J. L. Fernández-Alemán, 'A systematic review of gamification in e-Health', *J. Biomed. Inform.*, vol. 71, pp. 31–48, Jul. 2017.

[4] L. Gallo, 'A Glove-Based Interface for 3D Medical Image Visualization', in *Intelligent Interactive Multimedia Systems and Services*, G. A. Tsihrintzis, E. Damiani, M. Virvou, R. J. Howlett, and L. C. Jain, Eds. Springer Berlin Heidelberg, 2010, pp. 221–230.

[5] M. Zyda, 'From visual simulation to virtual reality to games', *Computer*, vol. 38, no. 9, pp. 25–32, Sep. 2005.

[6] T. Marsh, 'Serious games continuum: Between games for purpose and experiential environments for purpose', *Entertain. Comput.*, vol. 2, no. 2, pp. 61–68, Jan. 2011.

[7] F. Xu, D. Buhalis, and J. Weber, 'Serious games and the gamification of tourism', *Tour. Manag.*, vol. 60, pp. 244–256, Jun. 2017.

[8] A. Mitchell, C. Savill-Smith, Great Britain, and Learning and Skills Development Agency, *The use of computer and video games for learning: a review of the literature*. London: Learning and Skills Development Agency, 2004.

[9] J. Kirriemuir, A. Krotoski, H. Ellis, A. McFarlane, and S. Heppell, *Unlimited learning: computer and video games in the learning landscape*. 2006.

[10] L. P. Rieber, 'Seriously considering play: Designing interactive learning environments based on the blending of microworlds, simulations, and games', *Educ. Technol. Res. Dev.*, vol. 44, no. 2, pp. 43–58, Jun. 1996.

[11] A. Radford, 'Games and learning about form in architecture', *Autom. Constr.*, vol. 9, pp. 379–385, Jul. 2000.

[12] G. Huang, 'Introducing virtual engineering technology into interactive design process with high-fidelity models', in *Simulation Conference, 2005 Proceedings of the Winter*, 2005, p. 10 pp.-pp.

[13] A. K. Goel, S. Vattam, B. Wiltgen, and M. Helms, 'Cognitive, collaborative, conceptual and creative — Four characteristics of the next generation of knowledge-based CAD systems: A study in biologically inspired design', *Comput.-Aided Des.*, vol. 44, no. 10, pp. 879–900, Oct. 2012.

[14] C. H. Séquin, 'CAD Tools for Aesthetic Engineering', *Comput Aided Des*, vol. 37, no. 7, pp. 737–750, Jun. 2005.

[15] Z. Kosmadoudi, R. Sung, Y. Liu, T. Lim, and J. Ritchie, 'Evaluating user interfaces for engineering tasks with biometric logging', in *Eighth International Symposium on Tools and Methods of Competitive Engineering*, Ancona, Italy, 2010, pp. 267–276.

[16] 'Cloud CAD is really difficult - and Evan Yares thinks "cloud CAD won"t replace desktop CAD for a very long time, if ever.?' [Online]. Available: http://www.linkedin.com/groups/Cloud-CAD-is-really-difficult-4445738.S.137296180. [Accessed: 19-Jun-2014].

[17] 'CAD Architecture'. [Online]. Available: http://www.cadcambasics.com/cad-systems-architecture.

[18] D. Harrison, A. Newton R., R. L. Spicklemier, and T. J. Barnes, 'CAD Frameworks', in *IEEE*, 1990, vol. 78, pp. 552–557.
[19] D. C. Liebisch and A. Jain, 'JESSI common framework design management-the means to configuration and execution of the design process', in *Design Automation Conference, 1992., EURO-VHDL '92, EURO-DAC '92. European*, 1992, pp. 552–557.
[20] W.-K. Chen, *Computer Aided Design and Design Automation*. CRC Press, 2009.
[21] S. Myung and S. Han, 'Knowledge-based parametric design of mechanical products based on configuration design method', *Expert Syst. Appl.*, vol. 21, no. 2, pp. 99–107, Aug. 2001.
[22] L. Ming Wong and G. Gary Wang, 'Development of an automatic design and optimization system for industrial silencers', *J. Manuf. Syst.*, vol. 22, no. 4, pp. 327–339, 2003.
[23] K.-H. Chang and S.-H. Joo, 'Design parameterization and tool integration for CAD-based mechanism optimization', *Adv. Eng. Softw.*, vol. 37, no. 12, pp. 779–796, Dec. 2006.
[24] C.-H. Chu, M.-C. Song, and V. C. S. Luo, 'Computer aided parametric design for 3D tire mold production', *Comput. Ind.*, vol. 57, no. 1, pp. 11–25, Jan. 2006.
[25] 'The Problems With CAD Tools: Vendors Address User Pain Points'. [Online]. Available: http://www.techbriefs.com/component/content/article/23-ntb/features/feature-articles/920.
[26] K.-G. Waern, 'Cognitive Aspects of Computer Aided Design', in *Handbook of Human Computer Interaction*, Amsterdam: Elsevier Science Publishers, 1988.
[27] K.-G. Waern, *Design engineers' strategies in three-dimensional CAD work*. 1989.
[28] L. G. Parletun, P. Hansson, and G. Karlsson, *From CAM till CIM*. 1990.
[29] H. Luczak, 'Frictions and Frustrations in Creative-Informatory Work with Computer Aided Design -- CAD-Systems -- Congress I: Work with Terminals: HEALTH ASPECTS: WORKLOAD, STRESS AND STRAIN AND IRREGULAR WORKING HOURS; Causes and Measures of Stress', *Proceedings of the Fourth International Conference on Human-Computer Interaction 1991 v.1 pp. 175-179*, 1991. [Online]. Available: http://cumincad.scix.net/cgi-bin/works/BrowseAZ&name=authors/Show?eee5. [Accessed: 19-Jun-2014].
[30] S. K. Bhavnani, 'CAD usage in an architectural office: from observations to active assistance', *Autom. Constr. 5 3 1996 Pp 243-255*.
[31] M. K. Stacey and C. M. Eckert, 'CAD system bias in engineering design', in *Proceedings of the 12th International Conference in Engineering Design (ICED'99); Vol. 3*, Munich, Germany, 1999, vol. 26, pp. 1413–1418.
[32] M. Petre, 'Representations for Idea Capture in Early Software and Hardware Development'.
[33] R. C. W. Sung, J. M. Ritchie, T. Lim, and Z. Kosmadoudi, 'Automated generation of engineering rationale, knowledge and intent representations during the product life cycle', *Virtual Real.*, vol. 16, no. 1, pp. 69–85, Mar. 2012.
[34] G. Lee, C. M. Eastman, T. Taunk, and C.-H. Ho, 'Usability principles and best practices for the user interface design of complex 3D architectural design and engineering tools', *Int. J. Hum.-Comput. Stud.*, vol. 68, no. 1–2, pp. 90–104, Jan. 2010.
[35] B. F. Robertson and D. F. Radcliffe, 'Impact of CAD tools on creative problem solving in engineering design', *Comput.-Aided Des.*, vol. 41, no. 3, pp. 136–146, Mar. 2009.

[36] B. F. Robertson, J. Walther, and D. F. Radcliffe, ‘Creativity and the Use of CAD Tools: Lessons for Engineering Design Education From Industry’, *J. Mech. Des.*, vol. 129, no. 7, p. 753, 2007.
[37] C. Charlesworth, ‘Student Use of Virtual and Physical Modelling in Design Development - An Experiment in 3D Design Education’, *Des. J.*, vol. 10, no. 1, pp. 35–45, 2007.
[38] M. J. Nelson and M. Mateas, ‘Towards Automated Game Design’, in *Proceedings of the 10th Congress of the Italian Association for Artificial Intelligence on AI*IA 2007: Artificial Intelligence and Human-Oriented Computing*, Berlin, Heidelberg, 2007, pp. 626–637.
[39] C. A. Lindley, ‘Game Taxonomies : A High Level Framework for Game Analysis and Design’, *Gamasutra*, Oct. 2003.
[40] R. Koster, *A theory of fun for game design*. Scottsdale AZ: Paraglyph Press, 2005.
[41] R. J. Pagulayan, K. Keeker, D. Wixon, R. L. Romero, and T. Fuller, ‘The Human-computer Interaction Handbook’, J. A. Jacko and A. Sears, Eds. Hillsdale, NJ, USA: L. Erlbaum Associates Inc., 2003, pp. 883–906.
[42] T. Fullerton, C. Swain, and S. Hoffman, *Game Design Workshop: A Playcentric Approach to Creating Innovative Games*. Morgan Kaufmann, 2008.
[43] F. Press, ‘Story and Simulations for Serious Games: Tales from the Trenches (Paperback)’. [Online]. Available: http://www.focalpress.com/books/details/9780240807881/. [Accessed: 19-Jun-2014].
[44] J. Takatalo, J. Häkkinen, J. Kaistinen, and G. Nyman, ‘Presence, Involvement, and Flow in Digital Games’, in *Evaluating User Experience in Games*, R. Bernhaupt, Ed. Springer London, 2010, pp. 23–46.
[45] Nicole Lazzaro, ‘Why We Play: Affect and the Fun of Games’, in *Human-Computer Interaction*, 0 vols, CRC Press, 2009, pp. 155–176.
[46] N. Ducheneaut, N. Yee, E. Nickell, and R. J. Moore, ‘“Alone Together?”: Exploring the Social Dynamics of Massively Multiplayer Online Games’, in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, New York, NY, USA, 2006, pp. 407–416.
[47] C. Jennett *et al.*, ‘Measuring and Defining the Experience of Immersion in Games’, *Int J Hum-Comput Stud*, vol. 66, no. 9, pp. 641–661, Sep. 2008.
[48] D. A. Norman, *Emotional Design: Why We Love (or Hate) Everyday Things*. Basic Books, 2005.
[49] A. Mcmahan, ‘Immersion, Engagement, and Presence: A Method for Analyzing 3D Videogames’, in *The Video Game Theory Reader*, M. Wolf and B. Perron, Eds. Routledge, 2003, pp. 67–86.
[50] E. Brown and P. Cairns, ‘A Grounded Investigation of Game Immersion’, in *CHI ’04 Extended Abstracts on Human Factors in Computing Systems*, New York, NY, USA, 2004, pp. 1297–1300.
[51] M. Csikszentmihalyi, ‘The flow experience and its significance for human psychology’, in *Optimal experience*, Cambridge University Press, 1988.
[52] M. Slater and S. Wilbur, ‘A Framework for Immersive Virtual Environments (FIVE) - Speculations on the Role of Presence in Virtual Environments’, *Presence Teleoperators Virtual Environ.*, vol. 6, no. 6, pp. 603–616, Dec. 1997.
[53] ‘Siemens NX’. [Online]. Available: http://www.plm.automation.siemens.com/en_gb/products/nx/.

[54] E. Vick, *Emotion Notions: Modeling Personality in Game Character AI*. Cengage Learning, 2009.
[55] J. Juul, *Half-real: video games between real rules and fictional worlds*. MIT Press, 2005.
[56] K. Salen and E. Zimmerman, *Rules of Play: Game Design Fundamentals*. MIT Press, 2004.
[57] Pietro Polsinelli, 'Game mechanics for thinking users', 10:38:53 UTC.
[58] M. Sicart, 'Game Studies - Defining Game Mechanics', *Gamestudies*, vol. 8, no. 2.
[59] L. Pulsipher, 'Game descriptions, rules, and mechanics: what are the differences and similarities?'.
[60] J. Schell, *The art of game design a book of lenses*. Amsterdam; Boston: Elsevier/Morgan Kaufmann, 2008.
[61] C. Fabricatore, in *Gameplay and game mechanics design: a key to quality in videogames*, Dantiago de Chile, Chile, 2007.
[62] K. Charmie, 'Designing around a core mechanic'. [Online]. Available: http://www.gamasutra.com/blogs/CharmieKim/20120612/172238/Designing_around_a_core_mechanic.php.
[63] A. Rollings and E. Adams, *Andrew Rollings and Ernest Adams on Game Design*, 1 edition. Indianapolis, Ind: New Riders, 2003.
[64] M. McGuire and O. C. Jenkins, *Creating Games: Mechanics, Content, and Technology*. Wellesley, Mass: A K Peters/CRC Press, 2008.
[65] 'Mechanic/Aesthetic Videogame Genres: Adventure and Adventure'. [Online]. Available: http://www.academia.edu/1009537/Mechanic_Aesthetic_Videogame_Genres_Adventure_and_Adventure. [Accessed: 25-Nov-2014].
[66] J. Juul, *The Game, the Player, the World: Looking for a Heart of Gameness*. 2003.
[67] E. Adams and J. Dormans, *Game Mechanics: Advanced Game Design*, 1 edition. Berkeley, CA: New Riders, 2012.
[68] E. Schonfeld, 'SCVNGR's Secret Game Mechanics Playdeck'. [Online]. Available: http://techcrunch.com/2010/08/25/scvngr-game-mechanics/.
[69] C. Remo, 'Top 5 Gameplay Mechanics'. [Online]. Available: http://www.gamasutra.com/view/news/112330/Gamasutras_Best_Of_2008_Top_5_Gameplay_Mechanics.php.
[70] Y. Yudkowsky, 'Creating Friendly AI-The Analysis and Design of Benevolent Goal Architectures'. [Online]. Available: https://intelligence.org/files/CFAI.pdf.
[71] J. V. Dempsey, L. L. Haynes, B. A. Lucassen, and M. S. Casey, 'Forty Simple Computer Games and What They Could Mean to Educators', *Simul Gaming*, vol. 33, no. 2, pp. 157–168, Jun. 2002.
[72] V. Dumblekar, 'Interpersonal competitiveness : a study of simulation game participants' behaviour', 2010. .
[73] P.-Y. Oudeyer and F. Kaplan, *What is intrinsic motivation? A typology of computational approaches*. 2007.
[74] S. Bjork and J. Holopainen, *Patterns in Game Design*, Pap/Cdr edition. Hingham, Mass: Charles River Media, 2004.
[75] L. Georg, 'The Pleasure of the Playable Text: Towards an Aesthetic Theory of Computer Games', 2002.

[76] C. Fabricatore, M. Nussbaum, and R. Rosas, ‘Playability in Action Videogames: A Qualitative Design Model’, *Human–Computer Interact.*, vol. 17, no. 4, pp. 311–368, Dec. 2002.
[77] E. Brown and P. Cairns, ‘A Grounded Investigation of Game Immersion’, in *CHI ’04 Extended Abstracts on Human Factors in Computing Systems*, New York, NY, USA, 2004, pp. 1297–1300.
[78] W. Li, T. Grossman, and G. Fitzmaurice, ‘GamiCAD: A Gamified Tutorial System for First Time Autocad Users’, in *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology*, New York, NY, USA, 2012, pp. 103–112.
[79] ‘The Monkey Wrench Conspiracy’. [Online]. Available: http://www.games2train.com/site/default.html.
[80] M. Prensky, ‘Information and Background on The Monkey Wrench Conspiracy’. .
[81] M. Tideman, M. C. Voort, and F. J. A. M. Houten, ‘A new product design method based on virtual reality, gaming and scenarios’, *Int. J. Interact. Des. Manuf. IJIDeM*, vol. 2, no. 4, pp. 195–205, Oct. 2008.
[82] Z. Kosmadoudi *et al.*, ‘Harmonizing interoperability - Emergent serious gaming in playful stochastic CAD environments’, presented at the First International Conference on Games and Learning Alliance (GALA), Paris, France, 2013, vol. 1.
[83] *Game Studies 0101: Eskelinen: The Gaming Situation*.
[84] P. Tabuada, G. J. Pappas, and P. Lima, ‘Composing Abstractions of Hybrid Systems’, in *Hybrid Systems: Computation and Control*, C. J. Tomlin and M. R. Greenstreet, Eds. Springer Berlin Heidelberg, 2002, pp. 436–450.
[85] M. F. Shiratuddin and W. Thabet, ‘Virtual Office Walkthrough Using a 3D Game Engine’, *Int. J. Des. Comput.*, vol. 4, p. 4, 2002.
[86] O. C. Magnus, B. Staffan, and D. Steve, ‘The Conceptual Relationship Model: Understanding Patterns and Mechanics in Game Design’, 2014.
[87] K. L. Norman, ‘GEQ (Game Engagement/Experience Questionnaire): A Review of Two Papers’, *Interact. Comput.*, p. iwt009, Mar. 2013.
[88] J. Forlizzi and S. Ford, ‘The Building Blocks of Experience: An Early Framework for Interaction Designers’, in *Proceedings of the 3rd Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques*, New York, NY, USA, 2000, pp. 419–423.
[89] K. Battarbee, ‘Co-experience: The Social User Experience’, in *CHI ’03 Extended Abstracts on Human Factors in Computing Systems*, New York, NY, USA, 2003, pp. 730–731.
[90] J. McCarthy, *Technology as Experience*. MIT Press, 2004.
[91] J. L. G. Sánchez, N. P. Zea, and F. L. Gutiérrez, ‘From Usability to Playability: Introduction to Player-Centred Video Game Development Process’, in *Human Centered Design*, M. Kurosu, Ed. Springer Berlin Heidelberg, 2009, pp. 65–74.
[92] H. Desurvire, M. Caplan, and J. A. Toth, ‘Using Heuristics to Evaluate the Playability of Games’, in *CHI ’04 Extended Abstracts on Human Factors in Computing Systems*, New York, NY, USA, 2004, pp. 1509–1512.
[93] H. Desurvire and C. Wiberg, ‘Game Usability Heuristics (PLAY) for Evaluating and Designing Better Games: The Next Iteration’, in *Proceedings of the 3D International Conference on Online Communities and Social Computing: Held As Part of HCI International 2009*, Berlin, Heidelberg, 2009, pp. 557–566.
[94] C. Koeffel, W. Hochleitner, J. Leitner, M. Haller, A. Geven, and M. Tscheligi, ‘Using Heuristics to Evaluate the Overall User Experience of Video Games and Advanced

Interaction Games’, in *Evaluating User Experience in Games*, R. Bernhaupt, Ed. Springer London, 2010, pp. 233–256.
[95] M. Csikszentmihalyi, *Flow : the psychology of optimal experience*, 1st ed. New York: Harper & Row, 1990.
[96] J. Hamari and J. Koivisto, ‘Measuring flow in gamification: Dispositional Flow Scale-2’, *Comput. Hum. Behav.*, vol. 40, pp. 133–143, Nov. 2014.
[97] F.-L. Fu, R.-C. Su, and S.-C. Yu, ‘EGameFlow: A scale to measure learners’ enjoyment of e-learning games’, *Comput. Educ.*, vol. 52, no. 1, pp. 101–112, Jan. 2009.
[98] T. P. Novak, D. L. Hoffman, and Y.-F. Yung, ‘Measuring the Customer Experience in Online Environments: A Structural Modeling Approach’, *Mark. Sci.*, vol. 19, no. 1, pp. 22–42, Jan. 2000.
[99] G. M. Wilson, *Investigating the Impact of Audio Degradations on Users: Subjective vs. Objective .*
[100] R. L. Mandryk and K. M. Inkpen, ‘Physiological Indicators for the Evaluation of Co-located Collaborative Play’, in *Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work*, New York, NY, USA, 2004, pp. 102–111.
[101] J. M. Carroll, ‘Beyond Fun’, *interactions*, vol. 11, no. 5, pp. 38–40, Sep. 2004.
[102] P. M. A. Desmet, ‘A multilayered model of product emotions’, *Des. J. AlderShot*, vol. 6, p. 2003, 2003.
[103] A. Rafaeli and I. Vilnai-Yavetz, ‘Instrumentality, aesthetics and symbolism of physical artifacts as triggers of emotion’, *Theor. Issues Ergon. Sci.*, vol. 5, no. 1, pp. 91–112, Jan. 2004.
[104] *Evaluating User Experience in Games - Concepts and Methods*.
[105] B. Cowley, D. Charles, M. Black, and R. Hickey, ‘Toward an Understanding of Flow in Video Games’, *Comput Entertain*, vol. 6, no. 2, p. 20:1–20:27, Jul. 2008.
[106] K. Isbister, *Better Game Characters by Design: A Psychological Approach*. Taylor & Francis, 2006.
[107] K. Bessière, A. F. Seay, and S. Kiesler, ‘The Ideal Elf: Identity Exploration in World of Warcraft’, *Cyberpsychol. Behav.*, vol. 10, no. 4, pp. 530–535, Aug. 2007.
[108] M. G. Jones, ‘Creating Electronic Learning Environments: Games, Flow, and the User Interface.’, Feb. 1998.
[109] E. H. C. Gámez, P. Cairns, and A. Blandford, *Assessing the Gaming Experience using Puppetry*. .
[110] ‘BAMZOOKi’. [Online]. Available: http://www.bbc.co.uk/cbbc/shows/bamzooki.
[111] ‘Solid Edge’. [Online]. Available: http://www.plm.automation.siemens.com/en_us/products/solid-edge/.
[112] B. Shackel, ‘Usability - Context, Framework, Definition, Design and Evaluation’, *Interact Comput*, vol. 21, no. 5–6, pp. 339–346, Dec. 2009.
[113] G. Cockton, ‘From doing to being: bringing emotion into interaction’, *Interact. Comput.*, vol. 14, no. 2, pp. 89–92, Feb. 2002.
[114] L. E. Nacke, M. Kalyn, C. Lough, and R. L. Mandryk, ‘Biofeedback Game Design: Using Direct and Indirect Physiological Control to Enhance Game Interaction’, in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, New York, NY, USA, 2011, pp. 103–112.
[115] J. L. Andreassi, *Psychophysiology: Human Behavior and Physiological Response*. Lawrence Erlbaum, 2007.

[116] 'On Methodology of EEG Analysis...' [Online]. Available: http://www.ece.uah.edu/~jovanov/papers/EEGConsc/. [Accessed: 01-Nov-2016].
[117] J. N. Demos, *Getting Started with Neurofeedback*. W. W. Norton & Company, 2005.
[118] S. Sanei and J. A. Chambers, *EEG Signal Processing*. Chichester, England ; Hoboken, NJ: Wiley-Blackwell, 2007.
[119] R. W. Picard and J. Klein, 'Computers that recognise and respond to user emotion: theoretical and practical implications. Interacting with', *Computers*, vol. 14, pp. 141–169, 2002.
[120] 'Nexus-32'. [Online]. Available: http://www.mindmedia.info/CMS2014/products/systems/nexus-32.
[121] R. L. Mandryk and M. S. Atkins, 'A Fuzzy Physiological Approach for Continuously Modeling Emotion During Interaction with Play Technologies', *Int J Hum-Comput Stud*, vol. 65, no. 4, pp. 329–347, Apr. 2007.
[122] M. B. Kostyunina and M. A. Kulikov, 'Frequency characteristics of EEG spectra in the emotions', *Neurosci. Behav. Physiol.*, vol. 26, no. 4, pp. 340–343, Jul. 1996.
[123] 'Usability Metrics'. [Online]. Available: https://www.nngroup.com/articles/usability-metrics/. [Accessed: 11-Aug-2017].
[124] N. Lazzaro and K. Keeker, 'What's My Method?: A Game Show on Games', in *CHI '04 Extended Abstracts on Human Factors in Computing Systems*, New York, NY, USA, 2004, pp. 1093–1094.
[125] N. Bevan and M. Macleod, 'Usability measurement in context', *Behav. Inf. Technol.*, vol. 13, pp. 132–145, 1994.
[126] D. Kieras, *A Guide to GOMS Task Analysis*. 1994.
[127] 'GOMs'. [Online]. Available: http://www.usabilitybok.org/goms.
[128] 'Nasa TLX'. [Online]. Available: http://humansystems.arc.nasa.gov/groups/tlx/.
[129] T. Tullis and W. Albert, *Measuring the User Experience: Collecting, Analyzing, and Presenting Usability Metrics*. Morgan Kaufmann, 2010.
[130] R. Horlings, D. Datcu, and L. J. M. Rothkrantz, 'Emotion Recognition Using Brain Activity', in *Proceedings of the 9th International Conference on Computer Systems and Technologies and Workshop for PhD Students in Computing*, New York, NY, USA, 2008, p. 6:II.1–6:1.
[131] A. Schorr, 'Subjective measurement in appraisal research: present state and future perspectives', in *Appraisal processes in emotion: Theory, methods, research*, K. R. Scherer, A. Schorr, and T. Johnstone, Eds. New York, NY, US: Oxford University Press, 2001, pp. 331–349.
[132] T. W. Rolf Mahnke, 'Flow Experience on the Web: Measurement Validation and Mixed Method Survey of Flow Activities', pp. 1–18, 2012.
[133] D. Norman, 'Emotion & Design: Attractive Things Work Better', *interactions*, vol. 9, no. 4, pp. 36–42, Jul. 2002.
[134] T. Partala and V. Surakka, 'Pupil Size Variation As an Indication of Affective Processing', *Int J Hum-Comput Stud*, vol. 59, no. 1–2, pp. 185–198, Jul. 2003.
[135] Y. Liu, J. M. Ritchie, T. Lim, Z. Kosmadoudi, A. Sivanathan, and R. C. W. Sung, 'A fuzzy psycho-physiological approach to enable the understanding of an engineer's affect status during CAD activities', *Comput.-Aided Des.*, vol. 54, pp. 19–38, Sep. 2014.

[136] Y. Liu, Z. Kosmadoudi, T. Lim, S. Louchart, and J. Ritchie, 'Capture User Emotions during Computer- Aided Design Research', *Interact. Des.*, vol. 3, p. 65.
[137] B. R. Thomas, 'Effects of conducting peer behavioral observations on the observer's correct use of discrete trial teaching procedures', *Res. Dev. Disabil.*, vol. 34, no. 7, pp. 2143–2148, Jul. 2013.
[138] G. Simpson and J. Ritchie, *Engineering Applications: A Project Resource Book*. Oxford ; Boston: Butterworth-Heinemann, 1998.
[139] A. Sivanathan, T. Lim, S. Louchart, and J. Ritchie, 'Temporal Synchronisation of Data Logging in Racing Gameplay', in *Virtual Worlds for Serious Applications (VS-GAMES'12)*, Genoa, Italy, 2012.
[140] 'Tobii Eye Tracker'. [Online]. Available: http://www.tobii.com/.
[141] E. Niedermeyer and F. H. L. da Silva, *Electroencephalography: Basic Principles, Clinical Applications, and Related Fields*. Lippincott Williams & Wilkins, 2005.
[142] 'Matlab'. [Online].
Available: http://www.mathworks.co.uk/products/matlab/.
[143] 'TTEST'. [Online].
Available: http://learntech.uwe.ac.uk/da/Default.aspx?pageid=1439.
[144] 'The ANOVA Procedure'. [Online].
Available:http://support.sas.com/documentation/cdl/en/statug/63033/HTML/default/viewer.htm#anova_toc.htm.
[145] D. Rowntree, *Statistics without Tears: An Introduction for Non-Mathematicians*, New Ed edition. London: Penguin, 2000.
[146] H. Abdi and P. Molin, *1 Overview Lilliefors/Van Soest's test of normality*. .
[147] D. Salvatore and D. Reagle, *Schaum's Outline of Statistics and Econometrics, Second Edition*, 2 edition. New York: Schaum's Outlines, 2011.
[148] Z. Kosmadoudi, T. Lim, J. Ritchie, Y. Liu, and R. C. W. Sung, 'Game AI architecture for teaching the engineering design process', in *eLearning and Software for Education*, Bucharest, Romania, 2013, pp. 48–54.
[149] A. Newell, 'The knowledge level', *Artif. Intell.*, vol. 18, no. 1, pp. 87–127, Jan. 1982.
[150] 'Player-Centred Game Design: Player Modelling and Adaptive Digital Games - Ulster Institutional Repository'. [Online].
Available: http://uir.ulster.ac.uk/8279/. [Accessed: 16-Mar-2018].
[151] M.-L. Ryan, L. Emerson, and B. J. Robertson, *The Johns Hopkins Guide to Digital Media*. JHU Press, 2014.
[152] M. H. Göker, 'The effects of experience during design problem solving', *Des. Stud.*, vol. 18, no. 4, pp. 405–426, Oct. 1997.
[153] K. Alexiou, T. Zamenopoulos, J. H. Johnson, and S. J. Gilbert, 'Exploring the neurological basis of design cognition using brain imaging: some preliminary results', *Des. Stud.*, vol. 30, no. 6, pp. 623–647, Nov. 2009.
[154] O. T. Zander and C. Kothe, 'Towards passive brain-computer interfaces: Applying brain-computer interface technology to human-machine systems in general', *J. Neural Eng*, vol. 8, pp. 1–5, 2011.
[155] P. Antonenko, F. Paas, R. Grabner, and T. van Gog, 'Using Electroencephalography to Measure Cognitive Load', *Educ. Psychol. Rev.*, vol. 22, no. 4, pp. 425–438, 2010.
[156] 'eConnectome'. [Online].
Available: http://econnectome.umn.edu/.
[157] E. Başar, 'A review of alpha activity in integrative brain function: Fundamental physiology, sensory coding, cognition and pathology', *Int. J. Psychophysiol.*, vol. 86, no. 1, pp. 1–24, Oct. 2012.

[158] E. Başar and B. Güntekin, ‘A short review of alpha activity in cognitive processes and in cognitive impairment’, *Int. J. Psychophysiol.*, vol. 86, no. 1, pp. 25–38, Oct. 2012.
[159] M. Benedek, S. Bergner, T. Konen, A. Fink, and A. C. Neubauer, ‘EEG alpha synchronization is related to top-down processing in convergent and divergent thinking’, *Neuropsychologia*, vol. 49, no. 12, pp. 3505–3511, Oct. 2011.
[160] W. Klimesch, B. Schack, M. Schabus, M. Doppelmayr, W. Gruber, and P. Sauseng, ‘Phase-locked alpha and theta oscillations generate the P1-N1 complex and are related to memory performance’, *Brain Res. Cogn. Brain Res.*, vol. 19, no. 3, pp. 302–316, May 2004.
[161] H. Laufs *et al.*, ‘EEG-correlated fMRI of human alpha activity’, *NeuroImage*, vol. 19, no. 4, pp. 1463–1476, Aug. 2003.
[162] H. U. Amin, A. S. Malik, N. Badruddin, and W.-T. Chooi, ‘Brain activation during cognitive tasks: An overview of EEG and fMRI studies’, in *2012 IEEE EMBS Conference on Biomedical Engineering and Sciences (IECBES)*, 2012, pp. 950–953.
[163] S. K. Card, T. P. Moran, and Newell, ‘The model human processor: an engineering model for human performance’, in *Handbook of Perception and Human Performance*, NY: Wiley, 1986.
[164] G. Marchetti, ‘Attention and working memory: two basic mechanisms for constructing temporal experiences’, *Front. Psychol.*, vol. 5, Aug. 2014.
[165] B. Karlin, S. Koleva, J. Kaufman, A. Sanguinetti, R. Ford, and C. Chan, *Energy UX: Leveraging multiple methods to see the big picture*. 2017.
[166] S. Engeser and F. Rheinberg, ‘Flow, performance and moderators of challenge-skill balance’, *Motiv. Emot.*, vol. 32, no. 3, pp. 158–172, Sep. 2008.
[167] W. Admiraal, J. Huizenga, S. Akkerman, and G. ten Dam, ‘The concept of flow in collaborative game-based learning’, *Comput. Hum. Behav.*, vol. 27, no. 3, pp. 1185–1194, May 2011.
[168] K. Procci, A. R. Singer, K. R. Levy, and C. Bowers, ‘Measuring the flow experience of gamers: An evaluation of the DFS-2’, *Comput. Hum. Behav.*, vol. 28, no. 6, pp. 2306–2312, Nov. 2012.
[169] C. K. J. Wang, W. C. Liu, and A. Khoo, ‘The Psychometric Properties of Dispositional Flow Scale-2 in Internet Gaming’, *Curr. Psychol.*, vol. 28, no. 3, pp. 194–201, May 2009.
[170] ‘Development and Validation of a Scale to Measure Optimal Experience: The Flow State Scale’, *ResearchGate*. [Online]. Available:https://www.researchgate.net/publication/232497595_Development_and_Validation_of_a_Scale_to_Measure_Optimal_Experience_The_Flow_State_Scale. [Accessed: 11-Aug-2017].
[171] K. Kiili, T. Lainema, S. de Freitas, and S. Arnab, ‘Flow framework for analyzing the quality of educational games’, *Entertain. Comput.*, vol. 5, no. 4, pp. 367–377, Dec. 2014.
[172] ‘Microsoft Reaction Card Method (Desirability Testing)’, *Wikipedia, the free encyclopedia*. 26-Feb-2016.
[173] ‘QT’. [Online]. Available: http://www.qt.io/.
[174] J. Kumar, *Gamification at Work: Designing Engaging Business Software*. 2013.
[175] ‘Typeform’. [Online]. Available: https://www.typeform.com/.

Appendix A: Data tables from first experimental study

Table A1 Effectiveness data

Effectiveness

		Num. Iterations		Iteration difference
Group	**Subject**	**CADT**	**CADG**	
A	1	8	5	3
	2	16	10	6
	3	5	24	19
	4	8	9	1
	5	19	12	7
	6	28	5	23
	7	18	5	13
Mean		14.57	10.0	
B	8	19	30	11
	9	6	22	16
	10	12	14	2
	11	10	14	4
	12	13	25	12
	13	27	11	16
	14	14	13	1
	15	41	28	13
	16	3	31	28
Mean		16.11	20.89	
Combined totals				
Mean		15.44	16.13	10.9375
Std. Dev.		9.97	9.14	7.869789943

TTESTs

Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1: Effectiveness CADT vs CADG	10.94	7.870	0.20	0.84
Test 2 (CADT-CADG): Effectiveness CADT first vs CADG second (Group A)	CADT: 14.57 CADG: 10.00	-	0.93	0.39
Test 2 (CADG-CADT): Effectiveness CADG first vs CADT second (Group B)	CADG: 20.89 CADT: 16.11	-	1.03	0.33

Table A2 Efficiency data

Efficiency				
		Time of completion (sec)		Difference (sec)
Group	Subject	CADT	CADG	
A	1	751	660	91
	2	557	303	254
	3	688	924	236
	4	1394	786	608
	5	2235	768	1467
	6	1056	468	588
	7	1383	827	556
Mean		1152.00	676.57	
B	8	531	222	309
	9	2465	1961	504
	10	1417	400	1017
	11	639	255	384
	12	587	234	353
	13	331	1087	756
	14	709	343	366
	15	1782	499	1283
	16	812	1298	486
Mean		1030.33	699.89	
Combined totals				
Mean (sec)		**1083.56**	**689.69**	**578.625**
Std. Dev.		637.40	468.24	**370.1219183**
Mean (minutes)		18.06	11.49	
Std. Dev. (minutes)		10.62	7.80	

TTESTs

Test	Means	Std. Dev.	t	p < 0.05
Test 1: Efficiency CADT vs CADG	578.62	379.12	1.99	0.06
Test 2 (CADT-CADG): Efficiency CADT first CADG second (Group A)	CADT: 1152.00 CADG: 676.57	-	2.34	0.06
Test 2 (CADG-CADT): Efficiency CADG first CADT second (Group B)	CADG: 699.89 CADT: 1030.33	-	1.55	0.16

Table A3 Satisfaction data

Satisfaction

		Scales		Difference (scale)
Group	Subject	CADT	CADG	
A	1	10	8	2
	2	8	8	0
	3	7	8	1
	4	8	6	2
	5	3	6	3
	6	5	5	0
	7	6	6	0
Mean		6.714285714	6.714285714	
B	8	5	5	0
	9	8	5	3
	10	5	5	0
	11	7	10	3
	12	5	5	0
	13	5	5	0
	14	7	8	1
	15	6	10	4
	16	9	7	2
Mean		6.33	6.67	
Combined totals				
Mean		6.5	6.7	1.3125
Std. Dev.		1.8	1.8	1.356408401

TTESTs				
Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1: Satisfaction CADT vs CADG	1.31	1.35	0.29	0.77
Test 2 (CADT-CADG): Satisfaction CADT first vs CADG second (Group A)	CADT: 6.71 CADG: 6.71	-	0	1
Test 2 (CADG-CADT): Satisfaction CADG first vs CADT second (Group B)	CADG: 6.67 CADT: 6.33	-	0.45	0.65

Table A4 Cognitive load data

Cognitive load

		TLX Scales		Difference
Group	**Subject**	**CADT**	**CADG**	**(scale)**
A	1	41	31.66666667	9.333333333
	2	20	18.66666667	1.333333333
	3	11	13.66666667	2.666666667
	4	49.66666667	46.33333333	3.333333333
	5	47.66666667	50	2.333333333
	6	62.33333333	32	30.33333333
	7	23	19.33333333	3.666666667
Mean		36.38095238	30.23809524	
B	8	26.33333333	30.33333333	4
	9	54.66666667	65.33333333	10.66666667
	10	21.33333333	43.33333333	22
	11	35.33333333	21.33333333	14
	12	66	39.66666667	26.33333333
	13	74.66666667	59	15.66666667
	14	20.66666667	25.33333333	4.666666667
	15	45	31.66666667	13.33333333
	16	38.66666667	48	9.333333333
Mean		42.52	40.44	
Combined totals				
Mean		39.8	36.0	10.8125
Std. Dev.		18.7	15.0	8.699432253
		TTESTs		
Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1: Cognitive load CADT vs CADG	10.81	8.7	0.64	0.53
Test 2 (CADT-CADG): Cognitive load CADT first vs CADG second (Group A)	CADT: 36.3 CADG: 30.23	-	0	0.20
Test 2 (CADG-CADT): Cognitive load CADG first vs CADT second (Group B)	CADG: 40.44 CADT: 42.52	-	0.45	0.70

Table A5 Engagement data

Engagement

		Scales		Difference (scale)
Group	**Subject**	**CADT**	**CADG**	
A	1	9	9	0
	2	8	8	0
	3	8	8	0
	4	8	8	0
	5	7	4	3
	6	3	3	0
	7	3	5	2
Mean		6.571429	6.428571	
B	8	3	3	0
	9	8	8	0
	10	3	3	0
	11	7	10	3
	12	3	3	0
	13	3	3	0
	14	5	4	1
	15	9	7	2
	16	9	7	2
Mean		5.555556	5.333333	
Combined totals				
Mean		6.0	5.8	0.8125
Std. Dev.		2.6	2.5	1.130196333

TTESTs

Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1: Engagement CADT vs CADG	CADT: 6 CADG: 5.81	CADT: 2.6 CADG: 2.5	0.20	0.84
Test 2 (CADT-CADG): Engagement CADT first vs CADG second (Group A)	CADT: 6.57 CADG: 6.42	-	0.25	0.80
Test 2 (CADG-CADT): Engagement CADG first vs CADT second (Group B)	CADG: 5.33 CADT: 5.55	-	0.45	0.66

Table A6 Challenge data

Challenge

		Scales		Difference (scale)
Group	**Subject**	**CADT**	**CADG**	
A	1	8	6	2
	2	3	4	1
	3	2	4	2
	4	6	7	1
	5	10	8	2
	6	8	8	0
	7	3	5	2
Mean		5.714285714	6	
B	8	2	2	0
	9	6	7	1
	10	2	2	0
	11	7	5	2
	12	2	2	0
	13	2	2	0
	14	3	3	0
	15	9	7	2
	16	9	7	2
Mean		4.666666667	4.111111111	
Combined totals				
Mean		**5.1**	**4.9**	1.0625
Std. Dev.		3.0	2.3	0.899218411

TTESTs

Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1: Challenge CADT vs CADG	CADT: 5.12 CADG: 4.93	CADT: 3.0 CADG: 2.3	0.19	0.84
Test 2 (CADT-CADG): Challenge CADT first vs CADG second (Group A)	CADT: 5.71 CADG: 6.0	-	0.44	0.67
Test 2 (CADG-CADT): Challenge CADG first vs CADT second (Group B)	CADG: 4.11 CADT: 4.67	-	1.47	0.18

Table A7 Frustration data

Frustration

		Scales		Difference
Group	**Subject**	**CADT**	**CADG**	**(scale)**
A	1	1	2	1
	2	2	2	0
	3	1	3	2
	4	6	6	0
	5	10	10	0
	6	10	10	0
	7	5	2	3
Mean		5	5	
B	8	2	2	0
	9	2	8	6
	10	2	2	0
	11	5	2	3
	12	2	2	0
	13	2	2	0
	14	2	4	2
	15	1	7	6
	16	10	2	8
Mean		3.111111111	3.444444444	
Combined totals				
Mean		3.9	4.1	1.9375
Std. Dev.		3.4	3.0	2.536452986

TTESTs

Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1: Frustration CADT vs CADG	CADT: 3.93 CADG: 4.12	CADT: 3.4 CADG: 3.0	0.16	0.87
Test 2 (CADT-CADG): Frustration CADT first vs CADG second (Group A)	CADT: 5.0 CADG: 5.0	-	0	1.00
Test 2 (CADG-CADT): Frustration CADG first vs CADT second (Group B)	CADG: 3.44 CADT: 3.11	-	0.23	0.82

Appendix B: Data tables for first experimental study iteration – GOAP & brain activation

Table B1 Effectiveness data (GOAP)

Effectiveness (GOAP)

		Num. Iterations		
	Subject	**CADT-GroupA-first**	**CADG-GroupB-first**	**CADGnoGOAP**
	1	8	30	29
	2	16	22	13
	3	5	14	3
	4	8	14	3
	5	19	25	5
	6	28	11	6
	7	18	13	11
	8		28	1
	9		31	7
	10			7
	11			1
Mean		14.57	20.89	7.82
Std. Dev.		8.08	7.98	7.61
		TTESTs		
Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1 (CADT-CADGnoGOAP): Effectiveness CADT first vs CADGnoGOAP (Group A)	CADT: 14.57 CADGnG: 7.81	CADT: 8.08 CADGnG: 7.61	1.73	0.1
Test 2 (CADG-CADGnoGOAP): Effectiveness CADG first vs CADGnoGOAP (Group B)	CADG: 20.89 CADGnG: 7.81	CADG: 7.98 CADGnG: 7.61	3.64	0.002

Table B2 Efficiency data (GOAP)

Efficiency (GOAP)

		Time of completion (sec)		
	Subject	**CADT-GroupA-first**	**CADG-GroupB-first**	**CADGnoGOAP**
	1	751	222	1389
	2	557	1961	492
	3	688	400	1403
	4	1394	255	597
	5	2235	234	1013
	6	1056	1087	356
	7	1383	343	1176
	8		499	1054
	9		1298	275
	10			628
	11			510
Mean		1152.00	699.89	808.39
Std. Dev.		580.83	612.27	391.21
Mean (minutes)		19.20	11.66	13.47
Std. Dev. (minutes)		9.68	10.20	6.52

TTESTs

Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1 (CADT-CADGnoGOAP): Efficiency CADT first vs CADGnoGOAP (Group A)	CADT: 1152 CADGnG: 808.39	CADT: 580.83 CADGnG: 391.21	1.36	0.2
Test 2 (CADG-CADGnoGOAP): Efficiency CADG first vs CADGnoGOAP (Group B)	CADG: 699.89 CADGnG: 808.39	CADG: 612.27 CADGnG: 391.21	0.45	0.65

Table B3 Satisfaction data (GOAP)

Satisfaction (GOAP)

		Scale		
	Subject	CADT-GroupA-first	CADG-GroupB-first	CADGnoGOAP
	1	10	5	8
	2	8	5	10
	3	7	5	7
	4	8	10	9
	5	3	5	6
	6	5	5	10
	7	6	8	9
	8		10	10
	9		7	8
	10			6
	11			9
Mean		6.71	6.67	8.36
Std. Dev.		2.29	2.18	1.43

TTESTs

Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1 (CADT-CADGnoGOAP): Satisfaction CADT first vs CADGnoGOAP (Group A)	CADT: 6.71 CADGnG: 8.36	CADT: 2.29 CADGnG: 1.43	1.68	0.12
Test 2 (CADG-CADGnoGOAP): Satisfaction CADG first vs CADGnoGOAP (Group B)	CADG: 6.67 CADGnG: 8.36	CADG: 2.18 CADGnG: 1.43	1.98	0.06

Table B4 Cognitive load data (GOAP)

Cognitive load (GOAP)

		TLX Scale		
	Subject	**CADT-GroupA-first**	**CADG-GroupB-first**	**CADGnoGOAP**
	1	41	30.3333333	49.66666667
	2	20	65.3333333	73.66666667
	3	11	43.3333333	64.66666667
	4	49.6666667	21.3333333	67.66666667
	5	47.6666667	39.6666667	45.66666667
	6	62.3333333	59	54
	7	23	25.3333333	66
	8		31.6666667	73.33333333
	9		48	55.66666667
	10			69.66666667
	11			64.66666667
Mean		36.38	40.44	62.24
Std. Dev.		18.67	15.01	9.09
		TTESTs		
Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1 (CADT-CADGnoGOAP): Satisfaction CADT first vs CADGnoGOAP (Group A)	CADT: 6.71 CADGnG: 8.36	CADT: 2.29 CADGnG: 1.43	1.68	0.12
Test 2 (CADG-CADGnoGOAP): Satisfaction CADG first vs CADGnoGOAP (Group B)	CADG: 6.67 CADGnG: 8.36	CADG: 2.18 CADGnG: 1.43	1.98	0.06

Table B5 Engagement data (GOAP)

Engagement (GOAP)

		Scale		
	Subject	**CADT-GroupA-first**	**CADG-GroupB-first**	**CADGnoGOAP**
	1	9	3	8
	2	8	8	10
	3	8	3	8
	4	8	10	9
	5	7	3	8
	6	3	3	10
	7	3	4	10
	8		7	9
	9		7	6
	10			7
	11			7
Mean		6.57	5.33	8.36
Std. Dev.		2.51	2.69	1.36
		TTESTs		
Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1 (CADT-CADGnoGOAP): Engagement CADT first vs CADGnoGOAP (Group A)	CADT: 6.57 CADGnG: 8.36	CADT: 2.51 CADGnG:1.36	1.73	0.12
Test 2 (CADG-CADGnoGOAP): Engagement CADG first vs CADGnoGOAP (Group B)	CADG: 5.33 CADGnG: 8.36	CADG: 2.69 CADGnG: 1.36	3.07	0.01

Table B6 Challenge data (GOAP)

Challenge (GOAP)

		Scale		
	Subject	**CADT-GroupA-first**	**CADG-GroupB-first**	**CADGnoGOAP**
	1	8	2	7
	2	3	7	10
	3	2	2	7
	4	6	5	8
	5	10	2	8
	6	8	2	1
	7	3	3	8
	8		7	9
	9		7	4
	10			8
	11			7
Mean		5.71	4.11	7.00
Std. Dev.		3.09	2.37	2.49

TTESTs				
Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1 (CADT-CADGnoGOAP): Challenge CADT first vs CADGnoGOAP (Group A)	CADT: 5.71 CADGnG:7.00	CADT: 3.09 CADGnG:2.49	0.92	0.37
Test 2 (CADG-CADGnoGOAP): Challenge CADG first vs CADGnoGOAP (Group B)	CADG: 4.11 CADGnG: 7.00	CADG: 2.37 CADGnG: 2.49	2.65	0.01

Table B7 Frustration data (GOAP)

Frustration (GOAP)

		Scale		
	Subject	**CADT-GroupA-first**	**CADG-GroupB-first**	**CADGnoGOAP**
	1	1	2	8
	2	2	8	6
	3	1	2	4
	4	6	2	2
	5	10	2	7
	6	10	2	1
	7	5	4	7
	8		7	7
	9		2	2
	10			10
	11			6
Mean		5.00	3.44	5.45
Std. Dev.		3.92	2.40	2.84

TTESTs				
Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1 (CADT-CADGnoGOAP): Frustration CADT first vs CADGnoGOAP (Group A)	CADT: 5.00 CADGnG: 5.45	CADT: 3.92 CADGnG: 2.84	0.26	0.79
Test 2 (CADG-CADGnoGOAP): Frustration CADG first vs CADGnoGOAP (Group B)	CADG: 3.44 CADGnG: 5.45	CADG: 2.40 CADGnG: 2.84	1.71	0.10

Tests of Between-Subjects Effects

Dependent Variable:Strength_R

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	14.983[a]	153	.098	2.033	.000
Intercept	72.291	1	72.291	1500.851	.000
Hemisphere_R	.090	2	.045	.931	.394
Area_R	5.063	35	.145	3.003	.000
CAD	.117	2	.058	1.214	.297
Hemisphere_R * Area_R	1.081	30	.036	.748	.836
Hemisphere_R * CAD	.197	4	.049	1.025	.393
Area_R * CAD	2.106	38	.055	1.150	.243
Hemisphere_R * Area_R * CAD	2.260	38	.059	1.235	.154
Error	164.971	3425	.048		
Total	1332.103	3579			
Corrected Total	179.955	3578			

a. R Squared = .083 (Adjusted R Squared = .042)

Figure B1 SPSS output on Resources (R)

Tests of Between-Subjects Effects

Dependent Variable:Strength_EV

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	17.631[a]	161	.110	2.308	.000
Intercept	44.584	1	44.584	939.769	.000
Area_EV	7.192	39	.184	3.887	.000
Hemisphere_EV	.309	2	.155	3.258	.039
CAD	.040	2	.020	.417	.659
Area_EV * Hemisphere_EV	1.096	37	.030	.624	.963
Area_EV * CAD	2.028	38	.053	1.125	.276
Hemisphere_EV * CAD	.240	4	.060	1.264	.282
Area_EV * Hemisphere_EV * CAD	1.769	35	.051	1.065	.365
Error	150.674	3176	.047		
Total	1258.655	3338			
Corrected Total	168.305	3337			

a. R Squared = .105 (Adjusted R Squared = .059)

Figure B2 SPSS output on Enter Values (EV)

Tests of Between-Subjects Effects

Dependent Variable:Strength_T

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	5.236[a]	119	.044	.832	.864
Intercept	33.379	1	33.379	631.417	.000
Hemisphere_T	.014	2	.007	.134	.875
Area_T	1.787	30	.060	1.127	.307
CAD	.083	2	.041	.783	.458
Hemisphere_T * Area_T	.908	28	.032	.613	.938
Hemisphere_T * CAD	.139	4	.035	.658	.622
Area_T * CAD	1.441	31	.046	.879	.654
Hemisphere_T * Area_T * CAD	.311	18	.017	.327	.996
Error	10.731	203	.053		
Total	117.933	323			
Corrected Total	15.967	322			

a. R Squared = .328 (Adjusted R Squared = -.066)

Figure B3 SPSS output on Test (T)

Appendix C: Second experimental study – ICAD CADG & CADT

Table C1 Effectiveness data (ICAD)

Effectiveness (ICAD)

			Num. Iterations		Iteration difference
	Subject	**Level of expertise**	**CADT**	**CADG**	
	1	Novice	6	6	0
	2	Novice	17	3	14
	3	Novice	7	9	2
	4	Novice	9	12	3
	5	Novice	13	21	8
	6	Novice	16	10	6
	7	Novice	10	16	6
	8	Novice	11	15	4
	9	Intermediate	4	71	67
	10	Intermediate	4	5	1
	11	Intermediate	27	8	19
	12	Intermediate	54	9	45
	13	Intermediate	21	10	11
	14	Intermediate	17	4	13
	15	Intermediate	33	6	27
	16	Intermediate	25	8	17
	17	Expert	10	36	26
	18	Expert	10	16	6
	19	Expert	9	19	10
Mean			15.95	14.95	15
Std. Dev.			12.18	15.61	16.35462272

TTESTs

Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1: Effectiveness CADT vs CADG	CADT: 15.95 CADG: 14.95	CADT: 12.18 CADG: 15.61	0.22	0.83
Test 2 (CADT-CADG): Effectiveness Beginner	CADT: 11.125 CADG: 11.5	CADT: 3.98 CADG: 5.78	0.15	0.88
Test 2 (CADG-CADT): Effectiveness Intermediate	CADT: 23.125 CADG: 15.125	CADT: 16.22 CADG: 22.66	0.81	0.43
Test 2 (CADG-CADT): Effectiveness Expert	CADT: 9.66 CADG: 23.66	CADT: 0.57 CADG: 10.78	2.24	0.15

Table C2 Efficiency data (ICAD)

Efficiency (ICAD)

		Time of completion (sec)			Iteration difference
	Subject	Level of expertise	CADT	CADG	
	1	Novice	1215.333	1109.485	105.848
	2	Novice	2181.544	2179.613	1.931
	3	Novice	1216.253	1870.342	654.089
	4	Novice	2223.962	2153.969	69.993
	5	Novice	1187.364	2038.331	850.967
	6	Novice	1345.452	1472.556	127.104
	7	Novice	1496.288	561.454	934.834
	8	Novice	2200.752	910.305	1290.447
	9	Intermediate	1009.806	743.87	265.936
	10	Intermediate	900.426	2002.285	1101.859
	11	Intermediate	1138.138	1100.872	37.266
	12	Intermediate	3375.662	1205.896	2169.766
	13	Intermediate	1302.596	1385.241	82.645
	14	Intermediate	1150.422	1402.156	251.734
	15	Intermediate	2001.155	1397.742	603.413
	16	Intermediate	1124.788	2034.524	909.736
	17	Expert	1222.478	826.974	395.504
	18	Expert	1345.832	1421.282	75.45
	19	Expert	1145.326	1201.498	56.172
Mean			1514.93	1422.02	525.5102105
Std. Dev.			614.06	501.10	557.1372109
Mean (minutes)			25.25	23.70	
Std. Dev. (minutes)			10.23	8.35	

TTESTs

Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1: Efficiency CADT vs CADG	T: 1514.93 G: 1422.02	T: 614.06 G: 501.10	0.51	0.61
Test 2 (CADT-CADG): Efficiency Beginner	T: 1633.368 G: 1537.006	T: 481.154 G: 619.609	0.34	0.73
Test 2 (CADG-CADT): Efficiency Intermediate	T: 1500.374 G: 1409.073	T: 828.246 G: 434.675	0.27	0.79
Test 2 (CADG-CADT): Efficiency Expert	T: 1237.878 G: 1149.918	T: 101.136 G: 300.492	0.48	0.67

Table C3 Satisfaction data (ICAD)

Satisfaction (ICAD)

		Num. Iterations			Iteration difference
	Subject	Level of expertise	CADT	CADG	
	1	Novice	6	3	3
	2	Novice	1	5	4
	3	Novice	6	6	0
	4	Novice	6	6	0
	5	Novice	5	5	0
	6	Novice	5	6	1
	7	Novice	5	6	1
	8	Novice	6	7	1
	9	Intermediate	7	10	3
	10	Intermediate	6	9	3
	11	Intermediate	8	8	0
	12	Intermediate	8	9	1
	13	Intermediate	8	8	0
	14	Intermediate	7	9	2
	15	Intermediate	8	7	1
	16	Intermediate	6	8	2
	17	Expert	5	7	2
	18	Expert	4	6	2
	19	Expert	3	4	1
Mean			5.79	6.79	1.421052632
Std. Dev.			1.81	1.84	1.183918093

TTESTs

Test	Means	Std. Dev.	t	p < 0.05
Test 1: Satisfaction CADT vs CADG	1.31	1.35	0.29	0.10
Test 2 (CADT-CADG): Satisfaction Beginner	CADT: 5 CADG: 5.5	CADT: 1.690 CADG: 1.195	0.68	0.51
Test 2 (CADG-CADT): Satisfaction Intermediate	CADT: 7.25 CADG: 8.5	CADT: 0.886 CADG: 0.925	2.75	0.02
Test 2 (CADG-CADT): Satisfaction Expert	CADT: 4 CADG: 5.6	CADT: 1 CADG: 1.527	1.58	0.20

Table C4 Cognitive load data (ICAD)

Cognitive load (ICAD)

		TLX Scale			Iteration difference
	Subject	Level of expertise	CADT	CADG	
	1	Novice	45.67	51.67	6
	2	Novice	51.33	58.67	7.336666667
	3	Novice	45.00	54.33	9.333333333
	4	Novice	44.67	48.00	3.333333333
	5	Novice	41.33	62.00	20.66666667
	6	Novice	49.33	59.67	10.33333333
	7	Novice	51.00	58.33	7.333333333
	8	Novice	54.00	50.00	4
	9	Intermediate	51.67	39.33	12.33333333
	10	Intermediate	77.67	70.00	7.666666667
	11	Intermediate	59.67	45.00	14.66666667
	12	Intermediate	64.33	47.67	16.66666667
	13	Intermediate	53.33	47.33	5.996666667
	14	Intermediate	60.67	44.67	16.00333333
	15	Intermediate	59.00	46.67	12.33333333
	16	Intermediate	57.00	42.33	14.66666667
	17	Expert	51.67	42.33	9.34
	18	Expert	48.33	43.00	5.33
	19	Expert	44.33	42.00	2.33
Mean			53.16	50.16	9.772105263
Std. Dev.			8.62	8.26	4.928269

		TTESTs		
Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1: Cognitive load CADT vs CADG	CADT: 53.157 CADG: 50.158	CADT: 8.62 CADG:8.26	0.64	0.28
Test 2 (CADT-CADG): Cognitive load Beginner	CADT: 47.791 CADG: 55.333	CADT: 8.05 CADG: 9.36	3.21	0.01
Test 2 (CADG-CADT): Cognitive load Intermediate	CADT: 60.416 CADG: 47.875	CADT: 3.67 CADG: 0.50	2.87	0.01
Test 2 (CADG-CADT): Cognitive load Expert	CADT: 48.11 CADG: 42.443	CADT: 4.26 CADG: 5.07	2.64	0.11

Table C5 Engagement data (ICAD)

Engagement (ICAD)

		Scale			Iteration difference
	Subject	**Level of expertise**	**CADT**	**CADG**	
	1	Novice	7	6	1
	2	Novice	3	9	6
	3	Novice	7	6	1
	4	Novice	7	7	0
	5	Novice	6	6	0
	6	Novice	5	9	4
	7	Novice	6	6	0
	8	Novice	7	7	0
	9	Intermediate	4	10	6
	10	Intermediate	7	8	1
	11	Intermediate	5	7	2
	12	Intermediate	7	7	0
	13	Intermediate	6	8	2
	14	Intermediate	6	6	0
	15	Intermediate	7	7	0
	16	Intermediate	6	7	1
	17	Expert	6	8	2
	18	Expert	5	7	2
	19	Expert	6	6	0
Mean			5.95	7.21	1.473684211
Std. Dev.			1.13	1.18	1.874157244

TTESTs

Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1: Satisfaction CADT vs CADG	1.31	1.35	0.29	0.10
Test 2 (CADT-CADG): Satisfaction Beginner	CADT: 5 CADG: 5.5	CADT: 1.690 CADG: 1.195	0.68	0.51
Test 2 (CADG-CADT): Satisfaction Intermediate	CADT: 7.25 CADG: 8.5	CADT: 0.886 CADG: 0.925	2.75	0.02
Test 2 (CADG-CADT): Satisfaction Expert	CADT: 4 CADG: 5.6	CADT: 1 CADG: 1.527	1.58	0.20

Table C6 Challenge data (ICAD)

Challenge (ICAD)

	Subject	Level of expertise	Scale CADT	Scale CADG	Iteration difference
	1	Novice	9	7	2
	2	Novice	9	5	4
	3	Novice	9	4	5
	4	Novice	8	3	5
	5	Novice	8	8	0
	6	Novice	7	4	3
	7	Novice	7	4	3
	8	Novice	7	5	2
	9	Intermediate	5	4	1
	10	Intermediate	7	8	1
	11	Intermediate	9	5	4
	12	Intermediate	5	5	0
	13	Intermediate	5	5	0
	14	Intermediate	6	4	2
	15	Intermediate	8	5	3
	16	Intermediate	5	6	1
	17	Expert	6	4	2
	18	Expert	5	6	1
	19	Expert	5	5	0
Mean			6.84	5.11	2.052631579
Std. Dev.			1.57	1.37	1.60504744

TTESTs

Test	**Means**	**Std. Dev.**	**t**	**p < 0.05**
Test 1: Satisfaction CADT vs CADG	1.31	1.35	0.29	0.10
Test 2 (CADT-CADG): Satisfaction Beginner	CADT: 5 CADG: 5.5	CADT: 1.690 CADG: 1.195	0.68	0.51
Test 2 (CADG-CADT): Satisfaction Intermediate	CADT: 7.25 CADG: 8.5	CADT: 0.886 CADG: 0.925	2.75	0.02
Test 2 (CADG-CADT): Satisfaction Expert	CADT: 4 CADG: 5.6	CADT: 1 CADG: 1.527	1.58	0.20

Table C7 Frustration data (ICAD)

Frustration (ICAD)

		Scale			Iteration difference
	Subject	Level of expertise	CADT	CADG	
	1	Novice	2	8	6
	2	Novice	9	4	5
	3	Novice	3	4	1
	4	Novice	4	3	1
	5	Novice	5	2	3
	6	Novice	7	4	3
	7	Novice	7	4	3
	8	Novice	6	3	3
	9	Intermediate	7	5	2
	10	Intermediate	9	2	7
	11	Intermediate	2	5	3
	12	Intermediate	4	5	1
	13	Intermediate	5	4	1
	14	Intermediate	6	4	2
	15	Intermediate	4	3	1
	16	Intermediate	6	5	1
	17	Expert	3	2	1
	18	Expert	3	2	1
	19	Expert	3	3	0
Mean			5.00	3.79	2.368421053
Std. Dev.			2.16	1.47	1.84135323

TTESTs

Test	**Means**	**Std. Dev.**	**t**	**$p < 0.05$**
Test 1: Satisfaction CADT vs CADG	1.31	1.35	0.29	0.10
Test 2 (CADT-CADG): Satisfaction Beginner	CADT: 5 CADG: 5.5	CADT: 1.690 CADG: 1.195	0.68	0.51
Test 2 (CADG-CADT): Satisfaction Intermediate	CADT: 7.25 CADG: 8.5	CADT: 0.886 CADG: 0.925	2.75	0.02
Test 2 (CADG-CADT): Satisfaction Expert	CADT: 4 CADG: 5.6	CADT: 1 CADG: 1.527	1.58	0.20

Table C8 Flow data (ICAD)

Flow (ICAD)

	Subject	Level of expertise	CADT	CADG	Iteration difference
		Scale			
	1	Novice	2.9	1.4	1.5
	2	Novice	1.7	3.1	1.4
	3	Novice	2.6	2.3	0.3
	4	Novice	3.2	3.4	0.2
	5	Novice	2.2	3.9	1.7
	6	Novice	2.3	4.5	2.2
	7	Novice	2.5	3.4	0.9
	8	Novice	2.8	3.5	0.7
	9	Intermediate	2.8	3.5	0.7
	10	Intermediate	1.8	3.6	1.8
	11	Intermediate	2.7	3.7	1
	12	Intermediate	3.4	3	0.4
	13	Intermediate	3.3	3.1	0.2
	14	Intermediate	2.9	3.4	0.5
	15	Intermediate	2.5	3.5	1
	16	Intermediate	2.7	3.2	0.5
	17	Expert	2.5	3.9	1.4
	18	Expert	2.4	3.5	1.1
	19	Expert	2.2	2.9	0.7
Mean			2.60	3.31	0.957894737
Std. Dev.			0.45	0.65	0.563182488

TTESTs

Test	Means	Std. Dev.	t	p < 0.05
Test 1: Flow CADT vs CADG	CADT: 2.60 CADG: 3.31	CADT: 0.45 CADG: 0.65	3.89	0.00
Test 2 (CADT-CADG): Flow Beginner	CADT: 2.525 CADG: 3.188	CADT: 0.47 CADG: 0.95	1.77	0.11
Test 2 (CADG-CADT): Flow Intermediate	CADT: 2.77 CADG: 3.375	CADT: 0.50 CADG: 0.24	3.12	0.01
Test 2 (CADG-CADT): Flow Expert	CADT: 2.37 CADG: 3.43	CADT: 0.15 CADG: 0.50	3.51	0.06

Table C9 Game dimensions data (ICAD)

Game dimensions (ICAD)				
		Scale		
	Dimensions	Novice	Intermediate	Expert
	Directed goals	3	3	5
		3	3.5	5
		1.5	5	4
		3.5	4	
		5	4.5	
		3.5	5	
		3	5	
		3.5	3	
	Autotelic Experience	1	4	3
		4.5	4.5	3
		2	4.5	3
		3	4	
		4	4.5	
		4	4.5	
		4	4	
		4.5	3	
	Unambiguous feedback	3.5	4	4
		3	5	5
		3.5	5	4
		4.5	4.5	
		5	5	
		4	5	
		4	4.5	
		5	4	
	Playability	1	4.5	5
		4	4	4.5
		3.5	4	4
		4.5	3.5	
		4	4	
		4	4	
		4.5	3.5	
		4	4	4

ANOVA

Test	Means	F	p < 0.05
Directed goals	2.74	3.50	0.05
Unambiguous feedback	1.83	2.21	0.14
Autotelic experience (rewards)	0.63	1.75	0.20
Playability	0.72	1.13	0.35

Appendix D: ICAD log file example

File Capture for recording users mouse actions					
Starting Capture at 14:53:33.770					
Date of capture Thu 7 April 2016					
User Name	/				
User Age	/				
User Level	Novice				
Cad System	CADG				
==					
Time	Action	Mouse X	Mouse Y	Notes	
--					
1011	Selected bra	1840	186		
Progress 10%					
24343	Select Arm 2	2574	323		
Progress 20%					
24345	Select Arm 2	2574	323		
24800	Select Arm 3	2586	338		
24810	Select Arm 3	2586	338		
Progress 30%					
Progress 40%					
25701	Select Hole 5	2626	504		
25701	Select Hole 5	2626	504		
Progress 50%					
28384	Test Run	2418	867	results to follow	
Test Results are					
Bracket Failed with 6					
Stress = 1					
Tensile = 1					
Weld = 0					
Cost = 57.12					
User trying experiment again					
1946415	Selected info	1681	184		
2209176	Selected bra	1821	178		
2230833	Test Run	2449	869	results to follow	
Test Results are					
Bracket Failed with 6					
Stress = 1					
Tensile = 1					
Weld = 0					
Cost = 57.12					
User trying experiment again					

Figure 91 Example of timestamp log file from second experimental study – ICAD CADG & CADT

Appendix E: Questionnaires & stakeholder timetables

Table E1 Stakeholder interviews' schedule

Institute / Company	Dates	Times slots	Experience CAD level
Heriot Watt (academic with industrial experience stakeholders)	20/09/2009	12:00-13:00 13:00-14:00	Low Intermediate
Renishaw (industrial stakeholders)	21/09/2009	12:00-13:00 13:00-14:00	Expert Expert
Renishaw (industrial stakeholders)	22/09/2009	13:00-14:00	Intermediate

Table E2: Stakeholders interviews' questionnaire

Where there any game elements you liked to be applied in CAD?
What are your thoughts on the 'visual 'feedback given while working on the task?
Was performance affected with the 'scoring' mechanism?
What are your thoughts on leader-boards in engineering design with CAD?

Cognitive Load: Tick the appropriate box that best describes your state bellow.

Mental Demand

How mentally demanding was the pace of the task using the given interface?

Very Low Very High

Temporal

How hurried or rushed was the pace of the task with the given interface?

Very Low Very High

Performance

How successful were you in accomplishing what you were asked to do using the given interface?

Very Low Very High

Effort

How hard did you had to work to accomplish your level of performance with the given interface?

Very Low Very High

Frustration

How *insecure*, *discourage* were you working with the given interface for the specified task?

Very Low Very High

Figure E1 TLX form (part 1)

Place the following in a hierarchical order from the one affected the least (1) on your overall workload to the one affected the most (5)...

Mental Demand

How mentally demanding was the pace of the task using the given interface?

Temporal Demand

How hurried or rushed was the pace of the task with the given interface?

Performance

How successful were you in accomplishing what you were asked to do given the interface?

Effort

How hard did you had to work to accomplish your level of performance with the given interface?

Frustration

How *discourage* were you working with the given interface for the specified task?

Figure E2 TLX form (part 2)

Accessible	Creative	Fast	Meaningful	Slow
Advanced	Customizable	Flexible	Motivating	Sophisticated
Annoying	Cutting edge	Fragile	Not Secure	Stable
Appealing	Dated	Fresh	Not Valuable	Sterile
Approachable	Desirable	Friendly	Novel	Stimulating
Attractive	Difficult	Frustrating	Old	Straight Forward
Boring	Disconnected	Fun	Optimistic	Stressful
Business-like	Disruptive	Gets in the way	Ordinary	Time-consuming
Busy	Distracting	Hard to Use	Organized	Time-Saving
Calm	Dull	Helpful	Overbearing	Too Technical
Clean	Easy to use	High quality	Overwhelming	Trustworthy
Clear	Effective	Impersonal	Patronizing	Unapproachable
Collaborative	Efficient	Impressive	Personal	Unattractive
Comfortable	Effortless	Incomprehensible	Poor quality	Uncontrollable
Compatible	Empowering	Inconsistent	Powerful	Unconventional
Compelling	Energetic	Ineffective	Predictable	Understandable
Complex	Engaging	Innovative	Professional	Undesirable
Comprehensive	Entertaining	Inspiring	Relevant	Unpredictable
Confident	Enthusiastic	Integrated	Reliable	Unrefined
Confusing	Essential	Intimidating	Responsive	Usable
Connected	Exceptional	Intuitive	Rigid	Useful
Consistent	Exciting	Inviting	Satisfying	Valuable
Controllable	Expected	Irrelevant	Secure	
Convenient	Familiar	Low Maintenance	Simplistic	

Figure E3 Production reaction cards

The introductive questions, the emotion-rating and flow (Flow Short Scale (FSS)) questionnaires were administrated using the online interactive tool 'Typeform' [175].

The questions are listed below:

Table E3 Flow / FSS questionnaire

CAD UI/UX questionnaire **Let's talk about the application you just interacted with today**
Introductive questions: 1. What is your experience using CAD (in years of use and type of CADs)? 2. What do you remember from the task you just completed, what stood out? **Rate your emotions accordingly, using the scale 1 (not at all) – 10 (very much):** 1. After working on the task, how satisfied was you, interacting with the given interface? 2. Overall, how challenged are you completing this task with the given interface? 3. During the activity how engaged you thick you were with the task working with the given interface? 4. Overall how frustrated you were during the task while working with the given interface **Rate the following statements using the scale 1 (strongly disagree) – 5 (strongly agree):** 1. I felt just the right amount of challenge 2. My thoughts/activities ran fluidly and smoothly 3. I did not notice time passing 4. I had no difficulty concentrating 5. My mind was completely clear 6. I was totally absorbed in what I was doing 7. I was totally absorbed in what I was doing 8. I knew what I have to do each step of the way 9. I felt that I had everything under control 10. I was completely lost in thought 11. It was really clear to me how my performance was going 12. I had a good idea while I was performing about how well I was doing 13. I really enjoyed the experience with the user interface 14. I found the interaction experience extremely rewarding 15. I had a strong sense of what I wanted to accomplish 16. My goals were clearly defined 17. The user interface was easy to use 18. The controlling of the user interface was intuitive

For the users that worked on the **ICAD GM**, the **additional** questions were:

Introductive questions:

1. What particular User Interface (UI) elements you liked and why?
2. Select the ones you most liked for the task you worked with the given interface: