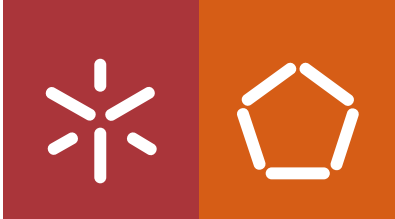




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**The Role of Prototypes in the Product
Design and Development Process**

Universidade do Minho
Escola de Engenharia





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The Role of Prototypes in the Product Design and Development Process

Dissertação de Mestrado
Mestrado em Engenharia do Produto

Trabalho efetuado sob a orientação do(a)
Professor Doutor António J. Pontes
Professor Doutor Álvaro M. Sampaio

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Resumo

O Papel dos Protótipos no Processo de Design e Desenvolvimento de Produto

Os protótipos desempenham um papel crucial no design e desenvolvimento de produtos, servindo como ferramentas para expressar e validar ideias, e permitindo aos intervenientes fornecer feedback (Gero, 1990). No entanto, ao longo do tempo surgiram desafios relacionados com a sua classificação e utilização. Os protótipos variam desde modelos de baixa fidelidade em papel até versões de pré-produção de alta fidelidade, no entanto, o consenso sobre a sua classificação continua elusivo devido a perspetivas divergentes (Pei et al., 2010, 2011; Coughlan et al., 2007; Jensen et al., 2016). Inúmeros estudos têm explorado o impacto da fidelidade dos protótipos na experiência e perceção do utilizador. Alguns estudos sugerem que protótipos de baixa fidelidade podem alcançar resultados semelhantes aos de alta fidelidade (Catani & Biers, 1998; Sauer et al., 2008; Wiklund et al., 1992). Pelo contrário, estudos como os conduzidos por Deininger et al. (2017) e Jensen et al. (2018) concluíram que os protótipos de alta fidelidade são preferidos pelos utilizadores e mais fáceis de entender. No entanto, esses estudos frequentemente focam-se apenas na eficácia e satisfação, deixando uma abertura na literatura para estudar a eficiência.

Neste estudo foi conduzida uma atividade de “*user-experience*” onde foram avaliados seis protótipos por 33 participantes. Os participantes foram divididos em seis grupos, com protótipos representando vários níveis de fidelidade, desde V1 (menor fidelidade) até V6 (produto real). Os testes foram realizados num simulador de condução, utilizando o video-jogo “*Asseto Corsa®*” e o kit de volante e pedais “*SuperDrive SV250®*”. Os resultados revelaram que os protótipos de alta fidelidade apresentaram um desempenho superior a nível de sucesso de tarefa. No entanto, para tarefas com cargas cognitivas inferiores, resultados precisos podem ser alcançados com protótipos de baixa e média fidelidade (V1 e V4).

No geral, estes resultados clarificam a relação complexa entre a fidelidade do protótipo e a experiência do utilizador, destacando a importância de considerar tanto a complexidade como as exigências da tarefa no processo de design.

Palavras-chave: Fabrico Aditivo, Fidelidade, Protótipo, Simulação de Condução, User-Experience

Abstract

The Role of Prototypes in Product Design and Development Process

Prototypes play a pivotal role in product design and development, serving as tools to express and validate ideas, and allowing stakeholders to provide feedback (Gero, 1990). However, challenges have arisen over time regarding their classification and usage. Prototypes range from low-fidelity paper models to high-fidelity pre-production versions, yet consensus on their classification remains elusive due to varying perspectives (Pei et al., 2010, 2011; Coughlan et al., 2007; Jensen et al., 2016). Despite this, it is agreed that differences in complexity are referred to as fidelity or resolution, and determining the timing, methodology, and context of their application is crucial in the design process.

Numerous studies have explored the impact of prototype fidelity on user experience and perception. Some research suggests that lower fidelity prototypes can achieve similar results to high-fidelity ones (Catani & Biers, 1998; Sauer et al., 2008; Wiklund et al., 1992). Conversely, studies like those conducted by Deininger et al. (2017) and Jensen et al. (2018) found that higher-fidelity prototypes are preferred by users and easier to understand. However, these studies often focus solely on efficacy and satisfaction, leaving an opening in the literature to study efficiency.

In this study, a user experience experiment assessed six prototypes by 33 participants. Participants were divided into six groups, with prototypes representing various levels of fidelity, from V1 (lowest fidelity) to V6 (real product). Testing took place on a driving simulator using the Asseto Corsa® video game and the SuperDrive SV250® steering wheel and pedals kit. The findings revealed that higher fidelity prototypes exhibited superior performance in task success. However, for tasks with lower cognitive workloads, precise outcomes could be achieved with lower and medium fidelity prototypes (V1 and V4).

Overall, these findings shed light on the nuanced relationship between prototype fidelity and user experience, highlighting the importance of considering both complexity and task demands in the design process.

Keywords: Additive Manufacturing, Driving-Simulation, Fidelity, Prototype, User-experience

Table of Contents

DIREITOS DE AUTOR E CONDIÇÕES DE UTILIZAÇÃO DO TRABALHO POR TERCEIROS.....	i
STATEMENT OF INTEGRITY.....	ii
Acknowledgments.....	iii
Resumo.....	iv
Abstract.....	v
1. Introduction.....	1
1.1. Investigation Background.....	2
1.2. Theoretical Framework.....	3
1.2.1. Prototype Categorization.....	3
1.2.2. Summary.....	10
1.3. Consumer Involvement.....	10
1.3.1. Comparing Prototypes with Different Resolutions.....	11
1.3.2. Summary.....	13
1.4. Case Study – Steering Wheel.....	14
1.5. Importance of the Materials and Technologies.....	15
1.5.1. Revision of Case Studies.....	15
1.5.2. Rapid Prototyping Technologies.....	17
1.5.2.1. Subtractive Manufacturing.....	17
1.5.2.2. Additive Manufacturing.....	19
1.6. Testing Environment.....	21
1.6.1. Tasks and Metrics.....	22
1.6.2. Participant Selection.....	23
2. Methodology.....	27
2.1. Prototypes Development and Production.....	29
2.1.1. Design Considerations – Design for Additive Manufacturing.....	32
2.2. Testing Scenario.....	35
2.2.1. Driving Simulator.....	36
2.2.2. Data Acquisition and Bias.....	40
2.3. Assessment Planning.....	43
2.4. Summary.....	45
3. Results and Discussion.....	47
3.1. Control Prototype – V6.....	47
3.2. Low-Fidelity Prototype – V1.....	48
3.3. Low-Fidelity Prototype – V2.....	50
3.4. Medium-Fidelity Prototype – V3.....	51
3.5. Medium-Fidelity Prototype – V4.....	52
3.6. High-Fidelity Prototype – V5.....	53
3.7. Workload on Milestones.....	54
3.8. Discussion.....	55
4. Conclusion.....	59
5. Future Work.....	60
Bibliography.....	61
Appendix 1 – Citroen Steering Wheel.....	71
Appendix 2 – Best Selling Cars.....	74

Appendix 3 – HMI Comparison.....	76
Appendix 4 – Selective Laser Sintering Process.....	78
Sintering Process.....	78
Materials.....	79
Appendix 5 – Guidelines for the Driving Simulation.....	81
Appendix 6 – Informed Consent.....	85

Table of Images

Image 1: Double Diamond diagram.....	2
Image 2: Design of the low fidelity prototypes (V1 on the left and V2 on the right) and the placement jig.	29
Image 3: Design of medium fidelity prototypes (V3 on the left and V4 on the right).....	31
Image 4: Design of high fidelity prototypes (V5 on the left and V6 on the right).....	32
Image 5: Designing for SLS - Cleaning openings.....	34
Image 6: Prototypes final resolutions.....	35
Image 7: Driving Simulator scenario.....	36
Image 8: Superdrive SV250® system.....	37
Image 9: Prototype adaptation process.....	38
Image 10: Space measurements.....	39
Image 11: Studied circuits on Asseto Corsa®.....	40
Image 12: Fiat 500 Abarth 595 SS on Asseto Corsa®.....	40
Image 13: Camera 's point of view.....	41
Image 14: Milestone track section on Asseto Corsa®.....	44
Image 15: Video editing software, used to assess reaction time.....	47
Image 16: Reaction Time comparison.....	56
Image 17: Tasks Success Comparison.....	57
Image 18: Lowest fidelity prototypes commands.....	57
Image 19: Original Steering Wheel.....	71
Image 20: Scanning process.....	71
Image 21: Fixture placement and surface goal.....	72
Image 22: Rectified button layout.....	72
Image 23: Iterative process for the airbag fixture.....	73
Image 24: Toyota HMI.....	76
Image 25: Mercedes HMI.....	76
Image 26: Porsche HMI.....	77
Image 27: SLS sintering.....	78
Image 28: SLS Process.....	78
Image 29: Cleaning Process Stages 1 - Unpacking; 2 - Brush Clean-up; 3 - Compressed Air cleaning; 4 - Low Pressure Air Dusting.....	79

Table of Tables

Table 1: Filter Dimension (Lim et al., 2008).....	6
Table 2: Manifestation Dimension (Lim et al., 2008).....	6
Table 3: Prototypes by their Function.....	7
Table 4: Product visual representations (Pei et al., 2011).....	8
Table 5: Product Visual Representation Taxonomy (Pei et al., 2011).....	9
Table 6: Consulted literature regarding comparison of prototypes.....	12
Table 7: Case Studies.....	16
Table 8: Sales volume comparison on the Luxury car brands.....	22
Table 9: Usability Test guidelines.....	23
Table 10: The Number of Participants for Studies Involving a Binary Metric (Success, Conversion).....	24
Table 11: Analyses of 20 studies regarding the participants used.....	25
Table 12: Fidelity groups definition.....	27
Table 13: Types of biases and how they will be avoided (Natesan et al., 2016).....	42
Table 14: Performance data from V6 tests.....	48
Table 15: Performance data from V1 and comparison with control.....	50
Table 16: Performance data from V2 and comparison with control.....	51
Table 17: Performance data from V3 and comparison with control.....	52
Table 18: Performance data from V4 and comparison with control.....	53
Table 19: Performance data from V5 and comparison with control.....	54
Table 20: Milestones with lower workloads.....	58
Table 21: Correlation between fidelity and how to use it for usability assessment.....	59
Table 22: Utilitarian Cars.....	74
Table 23: Luxury Cars.....	74
Table 24: Sport Cars.....	74
Table 25: Materials and Suppliers.....	80

1. Introduction

When it comes to the user experience, the way prototypes are produced vary according to their finality. The functional aspect can be put aside (or it can be simulated) and can teams focus only on the interaction aspect and on how the consumer will experience the product. Prototypes have an important role on these interactions because these objects are the only interface that people can use to perceive how the product should or will work, and it is expected that the resolution has some effect on how the user will interpret the product. Some studies (Virzi et al. 1996; Wiklund et al. 1992) show a tendency to believe that the resolution of the prototypes have no meaningful effect on their usability, however, Sauer et al. (2008) pointed that the usability assessment must be developed in a performance scenario, and not searching for errors, as most of the literature suggest. In the other hand, Deininger et al. (2017) and Jensen et al. (2018), pointed how the fidelity affects the user perception of several points on a prototype. All these problems leads to the following question:

“Will different prototype fidelities perform the same regarding the three aspects of usability: Efficacy, Efficiency and Satisfaction?”

In this context, this work will drive into research to answer this question, deepening the knowledge surrounding the prototypes dynamics and designing a methodology capable to put on practice a way to verify and corroborate the research question. To do so, this dissertation resolute in the following objectives:

- Assess different fidelities of a prototype, regarding efficacy, to understand if there are significant differences between each resolution;
- Exploration how different prototyping technics affects the user experience.

To attend to the objectives, this work followed an adaptation of the “Double Diamond” method, (designcouncil.org.uk, 2023), one of the several methods applied by DONE Lab, a Research and Development lab situated at University of Minho, where this dissertation and research took place (donelab.pt, 2024). This method divides the investigation into four phases: Discover, Define, Develop and Delivery. Discover is the period where the research background is set. In this phase the research obtains the theoretical information to formulate the research by consulting authors, papers, articles and all scientific and non-scientific data possible on the time-frame. The Define phase happens when the researcher needs to filter the information only to the necessary to develop the work, e.g. requirements and specifications. On this dissertation this phase corresponds to the methodology, strong guideline to conduct the experimental research. Develop resides on

the design/constructions of the materials needed to run the experiment, being prototypes and/or real context scenarios. Lastly, in the Delivery period, is expected to run the experiment and analyse the data to further conclusions, being the phase where the experimental research is executed. On the image 1 there is a diagram that summarizes the whole method.

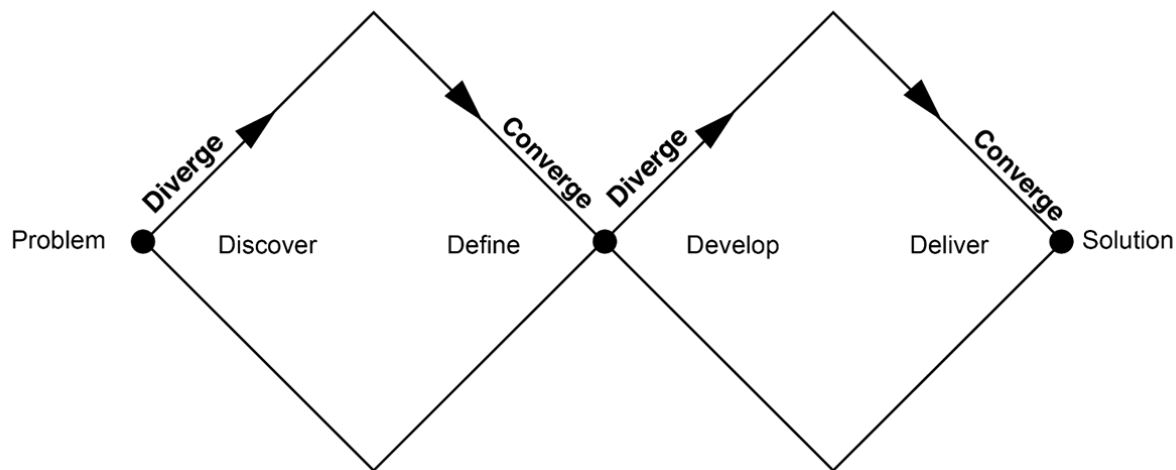


Image 1: Double Diamond diagram.

1.1. Investigation Background

Prototypes are a way to express ideas or concepts and to validate them, being next to team members, stakeholders or final users (Gero, 1990). Throughout the product development process, there are many occasions where the production of a prototype is necessary, however, through the years, some problems with the usage of these objects have been occurring. The prototype can be developed in a diversity of ways, they go from paper prototypes (like in the software industry) to pre-production, fully functioning prototypes, in their final materials (Pei et al., 2010, 2011). These differences in complexity are called fidelity or resolution and this aspect resides on one big problem: *when, how and where we apply the different fidelities in the design process?*

Several studies focus in this problematic and got to a conclusion that the fidelity of a prototype is related to the validation process that the team wants to confirm. The validation could take different forms: functional validation (mechanical or performance), where the team can assess the actual functionality of their solutions, and usability and/or perception validation from the users, where the team get to understand how the product will be received and used from the end user (Canuto da Silva & Kaminski, 2015; Coughlan et al., 2007; Lim & Stolterman, 2018; Pei et al., 2011). But there is a problem regarding the use of prototypes, in first place it is difficult to categorize prototypes, each industry as its own way to see how these objects work and, in some cases, there is no understanding on how to communicate and produce them. This problem

creates a necessity to gather these artefacts in groups, to facilitate their communication, but even those attempts are inconclusive, and each author has its way to group prototypes. However, Pei et al. (2011), brings a more structured and detailed framework to organize prototypes by their function and aspect, that can be used as a base to work this problematic.

Apart from categorization, another problem is connected to how the prototype looks. As exposed before, there are several resolutions of a prototype with different fidelities, and each form has its own challenges to be produced. In one hand, low-fidelity prototypes are easily produced with cheap materials, but they can't assess all variables of the product; the high-fidelity can be fully functional and close to the final product (either in aesthetic or function/technology) but they are expensive to produce. For that reason, some authors, (Catani & Biers 1998; Sauer et al. 2008; Wiklund et al. 1992), tried to compare side by side these different resolutions to see if, regarding the usability, it is possible to use cheapest prototypes, so they can be used earlier in the design process, or there is a need to use a high-fidelity one, to guaranty that the usability performance is effective. Other authors focus on the understanding of how the user will perceive the prototypes and how the fidelity will affect their perception (Deininger, Daly, Sienko, Lee, et al., 2017; Jensen et al., 2018).

1.2. Theoretical Framework

Using Jensen et al. (2016) as a reference, when developing and using a prototype, it is important to consider what can be learned from it, the various possibilities for obtaining knowledge from it, and how and when to use it effectively. Therefore, the primary objective of this dissertation is to compare and evaluate prototypes of different resolutions during the product development process and to comprehend the distinct data that can be evaluated from each type of prototype. To facilitate this comparative analysis, two main subjects will be considered: prototype categorization and prototype comparison.

The categorization of a prototype is an important subject because it deals with a way to arrange prototypes in specific groups, so they can be easily identified and to promote understanding between development teams. On the other hand, the use of different types of prototypes is frequent through the design process and it is important to know how and when we should use a specific prototype in a specific phase. It is also important to understand what kind of information we can take from the interaction we the user.

1.2.1. Prototype Categorization

To categorize prototypes, it is relevant to get a definition of what are those objects. Prototype comes from the Greek word "*Protos*" (first) and "*Tupos*" (image), being the prototype the first image/representation

of the product that it is been designed (tensentric.com). These objects or artefacts, according to Gero (1990), appears as a manner of communicate products for the time they are being developed, allowing the teams to materialize their ideas, assess concepts, measure performance and/or usability, or simply visualise their products. This process speeds up the design process and ensures the final product is better designed (Canuto da Silva & Kaminski, 2015; Coughlan, Suri, et al., 2007; Gero, 1990; Lim et al., 2008)

Even though the prototype is a first approach to the product, in a generalized way, the term refers to any kind of representation of the product (Jensen et al., 2016b). However, it becomes very limiting to designate any representation in this way, as there are many different types of prototypes, with different complexities and aspects, that need to be distinguished. It is generally understood that there are different fidelities concerning these objects, with high fidelity referring to prototypes with more detail and low fidelity referring to prototypes with less detail. Different fields approach prototypes in different ways, and there is some difficulty in communicating the understanding for the object "prototype" between designers and engineers, since each field of knowledge tends to catalogue the prototype in slightly different ways according to their function, as (Pei et al., 2011) shows. This set of information leads to a division on how to interpret prototypes. On the one hand there is the nature of the prototype, which reflects its intention, an idea being a more abstract but broader category (Lim et al., 2008; Odom et al., 2016). On the other hand, there is the function, a more concrete way of cataloguing prototypes, but which differs with respect to different product development practitioners (Pei et al., 2010, 2011). In order to simplify the categorization of prototypes, this chapter is divided into two groups. First, different ways of categorizing prototypes according to their nature will be explored, and then ways of cataloguing these artefacts according to their functions will be studied. This also involves exploring the interpretation of prototypes in the two areas of knowledge mentioned.

Before addressing the prototype categorizations, it is necessary to understand the main differences between the design prototype and the engineering prototype, since both areas have different views on this theme. The main difference is in the way professionals use these artefacts. In design there is a greater concern for aesthetics, shape and usability, and prototypes are often used in a more exploratory way, in order to generate more ideas for how the product will be delivered to the user. On the other hand, in engineering, there is a greater concern with the validation of functionalities and a more careful analysis with the performance, being the prototypes used in this area a way to evaluate and verify ideas, instead of exploring and generating them (Jensen et al., 2016b).

These differences raise a problem for development teams when it comes to communicating the intention for the use of a prototype, because there is no agreement on the best way to do it (Jensen et al.,

2016b; Pei et al., 2011). In this manner, several authors seek to standardize this relationship, in order to obtain a transversal understanding of what prototypes are in product development.

Prototypes by their Nature

As already mentioned, prototypes may have varied resolutions, which means, they may present several types of complexity, being referred to as low and high-fidelity prototypes. However, treating prototypes by their fidelity becomes something too generic, and it is necessary to objectify the purpose of each type of prototype. The concept of the nature of the prototype comes from its intention. This concept comes from a more abstract idea that connects the prototype to a generic functionality, e.g. low-fidelity prototypes are considered to have an exploratory nature, as their intention is to explore new forms, functionalities, aspects, or ways of use. This abstraction leaves open the physical and functional characteristics of the prototype.

When applied this ideology, there are several fields of knowledge that we can address in product and design development. Coughlan et al. (2007) sees the prototype as a manner to change the way Organizations behave, because it is part of the nature of these objects to promote critical thinking in relation to what is being done, since the prototype takes out of the equation the hypothetical side of the idea, presenting it in a tangible way. The author also argues that learning through error is very important for the development of a new product and, again, prototypes ensure that mistakes can be made without great risk to the cost of projects (Coughlan, Suri, et al., 2007). Finally, these objects are seen as a way to create dynamism in internal communication, because through a prototype it is possible to break with behavioural patterns and make people have another approach to problems without them realizing it.

This approach allows us to understand that there are certain aspects of the nature of these artefacts that are important to mention, such as the versatility that they bring to communication (Coughlan, Suri, et al., 2007; Jensen et al., 2016b), the ability to evaluate and create knowledge through them, either with the user or with the analysis of functional elements (Coughlan, Suri, et al., 2007; Jensen et al., 2016b), promoting different ways of thinking and seeing the problem. However, in addition to these characteristics, Jensen et al. (2016) still highlights the ability that prototypes have for the integration of complex systems with each other, giving them a more technical dimension.

Briefly, and following the example of Jensen et al. (2016), prototypes present four types of nature: communication; learning, integration and evaluation. However, these characteristics only allow perceiving prototypes as a whole, not distinguishing between them, making it difficult to choose which type to use for each context. Faced with this problem, the author Lim et al. (2008), defined a way to allow differentiating the different types of prototypes, based on their natures. The authors bring the concept of "Prototype Anatomy",

where they separate prototypes into two dimensions (Jensen et al., 2016b; Lim et al., 2008): filter dimension and manifestation dimension. The filter dimension addresses the physical and functional attributes, whereas the manifestation dimension is concerned with the material attributes and with the context/objective of the prototype, tables 1 and 2.

Table 1: Filter Dimension (Lim et al., 2008).

Filter Dimension	Variables
Aspect	Size, colour, shape, weight, texture, proportion, hardness, transparency, gradation, haptics and/or sound
Information	Size of information, type of information, use of information, type of privacy, hierarchy, organisation
Functionality	Function system, functionality requirements
Interactivity	Input behaviour, output behaviour, feedback behaviour, information behaviour
Spatial Structure	Ordering of the interface or information elements, relationship between interface and information elements

Table 2: Manifestation Dimension (Lim et al., 2008).

Manifestation Dimension	Definition	Variables
Material	Material used to develop the prototype	Paper, wood, plastic; Tools used to shape the material; Rapid prototyping tools;
Resolution	Level of detail of what is manifested (corresponding to fidelity)	Precision in performance; Appearance details; Interactivity details Realistic vs. Simulated information;
Scope	Scope of what is covered to be manifested	Level of contextualisation;

Through this concept, it becomes possible to develop and identify prototypes and then understand how they will materialise for a better result in their application. Applying the prototype choice based on its nature becomes a very interesting exercise on the part of the teams, as this form of selection creates more openings for the use of the objects, not being limited only to the more conventional prototyping in which the prototypes are constantly being evaluated in order to mature the product. Here, these artefacts can be used with a view to knowledge acquisition. Odom et al. (2016) reinforces this idea by referring to research prototypes. Objects that behave as something unique, rather than for the purpose of progressing the development of a product, allowing information to be gathered that can generate ideas for new products, and

not to help the development of an existing product. Therefore, the nature of prototypes is based on what can be learned from them, rather than the concrete function of that prototype.

Prototypes by their Function

Choosing the prototype according to its function requires that there is a set of characteristics associated with the prototypes that allows them to be easily identified, allowing the team to develop the object in a more direct way. As already mentioned, prototypes allow to evaluate and explore ideas, to test functionalities and performance and to communicate with stakeholders or final users, however there are divergences between professional areas regarding the representation of the product through prototypes. Several authors, and other sources, seek to catalogue prototypes according to their function, creating major identifying groups. The main prototype cataloguing groups separate them into conceptual prototypes, functional prototypes and final prototypes, table 3.

Table 3: Prototypes by their Function

Conceptual Prototype	Concept prototypes arise from the need to evaluate an idea/concept in order to help generate new ideas and better develop those being tested. In these cases, the shape, size and possible sensations by the user are usually evaluated. These prototypes are seen as mock-ups, helping to accelerate the initial ideation process (Canuto da Silva & Kaminski, 2015; tensentric.com, 2023)
Functional Prototype	Functional prototypes aim to evaluate isolated or interconnected functions of the product, allowing the complexity of the analysis to be reduced to simpler elements, making the process easier and reducing the risk of time and resources. At some point it becomes necessary to start evaluating the product as a whole, integrating all the technologies involved in it. Even at these times, the prototype does not have to resemble the final product, being only necessary to demonstrate its functionality (Canuto da Silva & Kaminski, 2015; tensentric.com, 2023)
Final Prototype	Final prototypes are used to demonstrate the product in its final form, bringing together all its aesthetic, ergonomic and functional elements. In many cases these prototypes are not developed in their final materials, being prepared only to resemble them, however, in some industries there is the need to prototype small series of the final product, before entering into scale production (Canuto da Silva & Kaminski, 2015; tensentric.com, 2023)

This segmentation is a very common approach in product development. In other hand, this division is too generic, pointing to a specific type of functionality, but ignoring the level of detail (resolution) that the prototype should have. Pei et al. (2010) tries to solve this problem through a questionnaire with professionals in the areas of engineering and design, trying to find a set of characteristics that would allow the development of a taxonomy for prototypes, making it much easier to identify them.

The authors quickly realized that the word prototype could not be used to identify all the types of representations that emerged, for this reason they ended up adopting the expression "Visual Product Representation" in order to be able to make a detailed division of all the representations (Pei et al., 2011, p6). In table 4, it is possible to observe the division carried out by the authors.

Table 4: Product visual representations (Pei et al., 2011).

Sketch	Quick representation of an idea, without definition or much detail.
Drawing	Formal representation of the product, designed according to standardised representation rules. High level of structure in its representation.
Model	Used to represent in a rudimentary way the functionality, appearance or performance of a product. Generally used at an early and exploratory stage of the project.
Prototype	Prototypes are used to validate the various aspects of the product, being more faithful to the final representation.

Within this division, the authors also considered the different interpretations between engineering and design professionals, detailing each group as much as possible into smaller subgroups with more information, depicted on table 5 (Pei et al., 2011).

Table 5: Product Visual Representation Taxonomy (Pei et al., 2011).

Group		Sub-Group	Visual Representation
2D Representation	Sketches	Personal Sketches	Idea sketch Study sketch Reference sketch
		Shared Sketches	Coded sketch Information sketch
		Persuasive Sketches	Rendering Inspiration sketch
		Delivery Sketches	Prescriptive sketch
	Drawings	Design Drawings	Concept drawings Presentation drawings Scenario and storyboard
		Engineering Drawings	Diagram Single view drawing Multi-view drawing General arrangement drawing Technical drawing Illustrative drawing
3D Representations	Models	Design Models	3D Sketch Development model Aesthetic model
		Engineering Models	Functional model Operation model Production model Assembly model Service model
	Prototypes	Design Prototypes	Aesthetic prototype Alpha Prototype Prototype Beta Prototype pre-production
		Engineering Prototypes	Experimental Prototype System prototype Final hardware prototype Prototype machining Post-production prototype

As it is possible to observe in this table, each representation has a function and a specific type of visualisation, with specific characteristics, which allows a better selection of prototypes when there is the need to develop them. Unlike the selection according to nature, the work of Pei et al. (2011), allows a very concrete

and detailed dataset of what the representations are, however, segregate the development areas studied, opening space to a more inclusive taxonomy.

1.2.2. Summary

These two methods to refer to prototypes have a common ground, however, the nature of a prototype is a more intuitive way to get to what is needed, and not a method to categorize the type of prototype that will be developed, as the use of the taxonomy presented by Pei et al. (2011), makes the process of selecting prototypes (visual representations) much clearer, since each type is divided by its functions and physical characteristics. However, something that none of the consulted literature demonstrated, was the type of information that each representation allows to be taken from the consumer.

1.3. Consumer Involvement

In product development, user involvement is a key point for the product to be successful. By studying the user, it is possible to understand their needs regarding the product that the team is developing (Campbell & Evans, 2019; Carthy et al., 2021; dos Santos et al., 2021). Another important aspect, is the involvement of the user in very preliminary stages of the project. Several authors argue that introducing the user factor in the project, from the beginning, can contribute to a development more oriented to their needs. Campbell et al. (2014) presents the concept of "customer designer", where he argues that the user should have input in the design phase, helping teams to define earlier the form and certain characteristics of the product. However, this involvement should raise certain questions and should be well organized to make the most of it.

The authors Carthy et al. (2021) and dos Santos et al. (2021), tried to understand, through two studies, to what extent is the involvement of users important for companies and what is the importance of the prototype in this set of activities. It was then realized that the first step to involve users, involves identifying the nature of their involvement, understanding if the project will really benefit from the involvement activities. Next, it is important to establish what is going to be taken from the user and to what extent they will be involved in the different phases of the development. Finally, involving users allows you to understand their emotional needs, something that is not possible without close contact (Carthy et al., 2021). dos Santos et al. (2021), studied 46 case studies that allowed understanding the added value of involving the user in the project, with the support of prototypes. The authors realized that there are four major matters when it comes to the use of the prototype. First is the purpose of the prototype, where it is important to understand whether it will be used to validate an idea, measure requirements priorities, evaluate product functionality or user experience. Next it is important to define what benefits the prototype will bring to the project, if it will allow refining the product, if

it will speed up the decision-making process or if it will contribute to generate knowledge. Finally, it is important to understand if the prototype will be used as a means of communication or a way to capture the user's feelings/emotions (dos Santos et al., 2021).

These ideas are in line with what was explored in the previous chapter, where the way to categorise, prototypes are related to their functions or natures. In this way, by defining the purpose of what the prototype will be used for, it is much easier to choose the type of prototype to be used, which returns to the same problem of there being no standard way of characterising prototypes, especially when they are related to usability.

In order to be able to associate usability metrics to a resolution of prototypes, it is necessary to compare them side by side and understand the user's perception of each one. To do so, for the same product the different types of prototypes should be compared in the same temporal space, with different people, in order to ascertain the potential of each one and cross-reference them with the reference taxonomy, thus being able to start generating a new form of knowledge.

In this sense, a collection of case studies was made that compare different resolutions of prototypes in the same temporal space, allowing to have previous indications of what can be expected from the users. Another important factor is to understand at what stage of the project these prototypes are developed and compared and what the different stages imply in the perception of the prototype.

1.3.1. Comparing Prototypes with Different Resolutions

In the context of the literature comparing prototype resolutions, it was found that the number of studies carrying out this comparative analysis is quite small. It was also possible to note that most of these cases address prototype comparison in the software development field, focusing on user interaction (UI) comparison, between paper prototypes and digital prototypes. In this particular studies, authors simulated interaction scenarios, either with paper mockups and software prototypes. It was also possible to note that the information on this theme is dated (between 1996 and 2009), except for one article that dates back to 2013, being this an issue that has not been addressed in current times. Based on this information a table was prepared, table 6, where the authors and the type of prototype they analyse can be consulted.

Table 6: Consulted literature regarding comparison of prototypes.

Authors	Compared Prototypes	Type of Prototype	Prototypes Materials
Catani & Biers (1998) and Nielsen (1990)	3	Software (UI)	Paper; Digital
Säde et al. (1998)	2	Physical Product	Cardboard
Sauer & Sonderegger (2009)	3	Software (UI) with Physical Product	Paper; Digital; Physical Product
Sauer et al. (2008)	3	Physical Product	Paper; Physical Product
Sefelin et al. (2003)	2	Software (UI)	Paper; Digital
Uebelbacher et al. (2013)	2	Software (UI)	Digital
Virzi et al. (1996)	2	Physical Product	Paper; Physical Product
Walker et al. (2002)	4	Software	Paper; Digital
Wiklund et al. (1992)	5	Software (UI) with Physical Product	Digital; Physical Product
Deininger et al. (2017)	4	Sketch with Physical Product, Software (UI) with Physical Product	Paper; Cardboard; 3D Model; Additive Manufacturing
Jensen et al. (2018)	4	Physical Product	Paper; MDF; Additive Manufacturing; Metal

The studies presented seek to understand if there is a difference between low-fidelity and high-fidelity prototypes through user testing. As can be seen in table 6, many of the tests were focused on software products, where there is a great need to develop paper prototypes in order to minimise costs and development time to validate concepts (Sauer & Sonderegger, 2009; Walker et al., 2002). In some cases, the physical product is prototyped through a digital interface, in order to promote usability issues.

The focus of the studies lies on finding usability errors in the different prototype types. The results are common to all these studies: there are no significant differences in usability performance between low and high-fidelity prototypes. However, during some of these studies some interesting data related to the users' perception of the prototypes were noted. In the study carried out by Sauer & Sonderegger (2009), it was possible to notice that the appearance of the prototype had a greater relevance in the previous perception of

the product, when compared to the post-use, with more positive initial evaluations. This may be due to the conclusions drawn by S  de et al. (1998), who noticed that people tend to forget about the appearance when they are focused on a specific task. In the same study, it was also found that participants tend to like digital prototypes more than the physical one. Sauer & Sonderegger (2009) predict that this phenomenon happens due to the fact that users form a mental image of what the product could be, where the real thing does not always correspond to that idealisation.

In the case of Sefelin et al. (2003), it was noted that there is a greater tendency to criticise the higher resolution prototypes (in this context the graphical aspects of the software) than the lower resolution ones, as there is more openness to suggestions from the participants. In contrast, when confronted with this question, participants preferred the use of the higher resolution prototype (computer) as it did not involve the moderator of the experiment so directly.

In relation to prototype comparison models for physical products, the little literature that exists comes to the same conclusion that was reached in software, there are no significant differences in the usability performance of prototypes (S  de et al., 1998; Virzi et al., 1996), however, Sauer et al. (2008), states that the analysis carried out by all types of tests may not be the most appropriate, because what is being tested are usability errors and not product efficiency. According to the authors, efficiency encompasses several factors, such as test scenarios, physical and social environments, etc. Thus, even if the tests found in the literature so far point out that the use of low-fidelity prototypes may be the most appropriate, in the cost-information ratio obtained, there are certain parameters that are not being tested and need to be assessed in order to draw these conclusions.

In a different perspective, Deininger et al. (2017) and Jensen et al. (2018), drawn an opposite conclusion. Similarly to an observation made by Wiklund et al. (1992), when assessing the satisfaction parameter, the fidelity of the prototypes have a considerable impact in the user perception. Lower fidelities tend to be less clear regarding their function, tending to have a poor performance, as the highest fidelities, because they tend to have more detailed information, generates more satisfaction and less frustration and confusion in the user.

1.3.2. Summary

The studies reviewed herein primarily aim to discern disparities between low-fidelity and high-fidelity prototypes through user testing. Notably, many of these assessments focus on software products, where the development of paper prototypes is common to minimize costs and expedite concept validation. In some

instances, physical products are prototyped via digital interfaces to address usability concerns. The overarching focus of these studies center on identifying usability errors across various prototype types. While the results consistently indicate no significant disparities in usability performance between low and high-fidelity prototypes, intriguing insights regarding user perceptions of prototypes have been gleaned. For instance, (Sauer & Sonderegger, 2009) observed that prototype appearance carries greater relevance in pre-use perceptions compared to post-use evaluations, potentially attributed to users forming idealized mental images of the product. Additionally, participants tend to favour digital prototypes over physical ones, possibly due to discrepancies between mental idealizations and actual products.

Regarding physical product prototype comparisons, the scant literature available echoes similar conclusions to those drawn in software assessments, highlighting no significant differences in usability performance. However, (Sauer et al., 2008) posit that existing analyses may not fully capture efficiency, emphasizing the need to consider additional factors such as test scenarios and environmental variables. In contrast, (Deininger, Daly, Sienko, Lee, et al., 2017; Jensen et al., 2018) offer divergent perspectives, asserting that prototype fidelity significantly impacts user satisfaction. Lower fidelity prototypes may exhibit less clarity in function, resulting in low performance, while higher fidelity prototypes, with more detailed information, engender greater satisfaction and reduced user frustration and confusion.

1.4. Case Study – Steering Wheel

From all the products that could be chosen to enroll on this work, the Steering Wheel (SW) was selected as the test product. The reason for this choice is related with the HMI (Human Machine Interaction) problems that the steering wheel has. As pointed by Stouffer et al. (2015), an HMI is a “*[...] hardware or software through which an operator interacts with a controller. An HMI can range from a physical control panel with buttons and indicator lights to an industrial PC with a color graphics display running dedicated HMI software*”, and these types of systems are involved with several major issues involving drivers workloads and distraction.

Driving distraction is the cause of several number of accidents. According to a study by Dingus et al. (2006), in 100 cars studied, 80% of crashes and 65% of near-misses are caused by drivers distraction. Also, in 2010, were reported that 41600 people were injured and 3092 were killed due to accidents provoked by distracted drivers (NHTSA, 2012). Car HMI is a source of distraction for the user (Murata & Moriwaka, 2005; Shakeri et al., 2016), and part of the responsibility is the amount of technology and buttons integrated on the steering wheels (Döring et al., 2011; Murata & Moriwaka, 2005; Quintal & Lima, 2022), that causes a visual workload to the driver. Also, a study conducted by (G Markkula & J Engström, 2006), pointed that visual load

on the driver provokes a drastic steering wheel movement (between 2 to 6 degrees), in the moment the person switches the eyes from the HMI to the road.

All this data showcases an extreme usability scenario regarding SW usage, once the user is interacting with the HMI while driving, having to perform secondary tasks on top of a critical task (being focused on the road), leading to conflicts on the performance, either of driving, either the given tasks in hand. This kind of workload related to the product makes it suitable to run a performance usability study.

1.5. Importance of the Materials and Technologies

As explored before, there is a problematic surrounding the prototypes and their resolution. However, there is also a problem related to the materials used in those prototypes. Most of the studies showed a comparison between paper – digital – end product prototypes, being difficult to assess how expensive and how limitative a prototype can be if the product is a physical object. In that sense this chapter will focus on exploring how different fidelities of prototypes are built and, if possible, how much were spent on each one, in order to understand if/or how the materials affect the performance and the cost of these artefacts.

1.5.1. Revision of Case Studies

In order to understand the materials used in prototype development, several case studies were consulted and analysed to verify if there is some common ground on the various teams. On table 7, it is possible to verify the studies, the type of materials used, the fidelity of the prototypes and their goals. As it is possible to confirm, most of the materials used on earlier prototypes are foams, cardboard (and paper as in the last chapters), wood compounds, like plywood and MDF and easily moulded plastics, like PVC sheets or tubes and Corrugated Plastic. As we can verify, these materials are cheap and easy to work with, being in line with the idea that early prototypes have an exploratory nature, that also comes from the materials used. As the complexity increases, technologies like additive manufacture, start to get used more often, increasing the resolution of the prototypes. These technologies are used when a more precise functionality is needed, so the prototype can perform better.

Table 7: Case Studies.

Author	Study Description
(Brooks et al., 2021)	The product is a robot developed to assist individuals with disabilities. It has a low fidelity, meaning it is non-functional in its current state. The materials used include corrugated plastic, plywood, and PVC pipe. The goal of this project is to understand patient home object preferences through input from healthcare professionals. The costs associated with this project are not available. Additionally, the use of low fidelity allows participants to contribute to the product's development.
(M. Evans et al., 2005)	This work studies a toaster and focuses on exploring various forms with low fidelity and assessing textured components with high fidelity. Styrofoam is used for initial form exploration, while additive manufacturing (potentially stereolithography) is employed for textured component assessment. The primary goal is to prevent dirt ingress by designing a mechanism to close the bread slots, while also testing Free-form Technology of haptic modelling. The evaluation process aims to understand the speed at which prototypes can progress from a basic styrofoam form to more intricate designs, utilizing different materials to achieve complexity.
(M. A. Evans & Ian Campbell, 2003)	The work deals with a grass trimmer, and involves the development of visual prototypes with varying levels of fidelity, aiming for both medium and high performance. Materials such as MDF and polyurethane are utilized for medium-level prototypes, while SLA (accuDur100) and electrical components are incorporated for higher fidelity versions. The design objective is to create a grass trimmer with the motor positioned near the handle to optimize equipment balance. Costs for the project range from 2020,36€ for medium fidelity to 3195,64€ for high fidelity prototypes. Each prototype undergoes sanding and painting to resemble the end product, ensuring that user perception and testing are not influenced by the prototype's appearance. This approach aims to maintain a seamless transition from prototype to final product in the user's experience.
(Fang & Ainsworth, 2012)	This study focuses on shape exploration with low fidelity of a steering wheel, aiming for a medium to high level of functionality and aesthetic appeal. Utilizing a polystyrene foam core and additive manufacturing (possibly FDM), the project aims to design a steering wheel integrated with gesture-enabling technology. Although specific costs are not provided, the primary goal of the study is to evaluate the feasibility of incorporating gesture technology through prototyping. By exploring this technology, the project seeks to enhance user interaction and functionality within the automotive context, potentially revolutionizing steering wheel design and user experience.
(Deokar et al., 2019)	This work prioritizes functionality and aesthetics at a high level of a steering wheel prototype, utilizing materials such as epoxy resin, MDF, and NC putty. The primary focus is on developing a steering wheel integrated with banana fibers to achieve weight reduction. The prototype, costing approximately 425 Rs or 5€, serves as a platform to investigate the application of natural fiber composites in steering wheel design. While the initial prototype shows promise in reducing weight, there are areas for improvement to enhance performance and durability. Future iterations will likely refine the design and material composition to achieve optimal results in weight reduction while maintaining structural integrity and user satisfaction.
(Akaoka et al.,	The Interaction Objects study, focuses on creating low-fidelity prototypes using materials

2010)	like styrofoam, cardboard, and digital pellets. The primary aim is to enhance the usability of these prototypes through digital interaction, ultimately resulting in the development of a multi-dimensional prototype. Although specific costs are not provided, the project's conclusion highlights the suitability of this method for evaluating conceptual ideas in the early phases of development. By leveraging low-fidelity prototypes and digital interaction, the project demonstrates an effective approach to exploring and refining conceptual designs, laying the foundation for further development and iteration in future stages of the project.
(Mok et al., 2017)	This work prioritizes low fidelity while aiming for high functionality of a transforming steering wheel. Utilizing a polystyrene foam core and SLA (Stereolithography) technology, the project's primary objective is to develop a steering wheel designed for semi-automated cars. Specific costs are not provided for this endeavor. By focusing on transforming features, the project aims to enhance user experience and control within the context of evolving automotive technologies. While the details of the transformation mechanism are not specified, the project holds promise for contributing to advancements in vehicle ergonomics and driver assistance systems.
(Hofmann et al., 2016)	This Prosthetic for Playing Violin study explores a combination of low fidelity and high functionality, utilizing materials such as Lego, styrofoam, clay, and FDM (Fused Deposition Modeling) technology. The primary focus is on leveraging additive manufacturing (AM) techniques to reduce the production costs of prosthetics. Specific costs are not provided for this initiative. Furthermore, the project aims to inspire others to explore do-it-yourself (DIY) solutions for similar applications. By embracing innovative materials and manufacturing processes, the project seeks to make prosthetic instruments more accessible and affordable, ultimately enhancing the quality of life for musicians with limb differences.

1.5.2. Rapid Prototyping Technologies

Throughout this dissertation it is possible to understand that there are two main ways to produce a prototype. The first ones are hand crafted technics, where the designers build their prototype in an “old fashion” way, using hand or power tools to transform their raw materials. The second one, that is been growing in the recent years (statista.com, 2021a, 2021b), are rapid prototyping technologies, either additive or subtractive manufacturing.

1.5.2.1. Subtractive Manufacturing

Subtractive manufacturing is a term used on various methods of controlled machining. The tasks performed are, generally, cutting, boring, drilling and grinding. All those operations perform remotion of material from a solid block of raw material. The process of control machining is called computer numerical control (CNC) and it operates on top of a CAD model, where the software (CAM) analyses the part to be produced and simulates how the machine will actually remove the material to end up with the part (formlabs.com, 2022a). The most common processes of subtractive manufacturing are CNC machining, Electrical Discharge Machining (EDM), Laser Cutting and Water Jet Cutting.

- **CNC Machining**

- CNC, as said previously, is a process that allows to control a machine precisely. However, CNC by itself only describes how the machine works, not a specific technology (3erp.com, 2022). However, CNC machining is a cutting material process that allows the machine to, slowly, transform a block of solid material on a specific shape. To acquire the needed part, there are several main operations that can be used:
- CNC Milling – This operations allows the machine to remove the material;
- CNC Drilling – This process allows the machine to perforate the part, either to insert a screw hole or an aesthetic look.
- CNC Grinding – In this process, the machine uses an abrasive tool to smooth the surface of the part.
- CNC Routing – Routing allows the machine to turn the part on the x, y and z axes, without losing accuracy.
- This technology is very versatile because it allows to work with a complete range of materials, being metal, plastics, alloys and wood.

- **EDM**

- Electrical Discharge Machining is a process that utilizes thermal energy instead of a mechanical tool to remove the material. It is used to overcome the limitations of the CNC machining. This technology allows to manufacture parts with a tight tolerance (0,012mm) and does not require post process finishing. These characteristics comes from the way the technology removes the material, a quick electrical discharge that occurs recurrently through the part (get-it-made.co.uk, 2022; udm.edu, 2022). EDM is also an excellent process to get micro-hole drilling, sharp internal corners, and rotary forms.
- Like the CNC machining, this method is divided in several possible processes to achieve the result expected (Boissonneault, 2021). Those processes are:
- Wire EDM – A electric charged wire passes trough the material, removing small fractions until it is cut-off;
- Plunge EDM – Allows to cut holes with different geometric shapes by using a graphite, copper or tungsten electrodes to erode the part;

- Fast Hole EDM – Using a thin copper electrode (0.25 to 4.7mm), it allows to drill precise holes the size other technologies can't produce.
- **Laser Cutting**
 - Laser cutting technology uses a dense laser to go through the material to cut by melting, vaporizing or burning it. Unlike CNC machining or EDM, laser cut only works with sheets of material, cutting through the whole sheet or engraving it (xometry.eu, 2022). The thickness of the materials used in this process can range from less than 1mm to 24mm and could be use in metal, plastic, wood, paper and foam (engineeringstudent.uk, 2018).
- **Water Jet Cutting**
 - Water jet cutting is a process that uses water pressurized at 392 MPa, delivering a stream of liquid that reaches three times the speed of sound. The water is released from a precision nozzle and in his pure form it is used to cut through soft materials as wood, plastics, foam and rubber, but with the usage of abrasive materials it can be used to cut through hard metals (iqsdirectory, 2022). Because the water jetting allows tight tolerances and clean cuts, it is used in several industries as aerospace, automotive, medicine, glass, electronics and fibreglass (iqsdirectory, 2022).

1.5.2.2. Additive Manufacturing

Instead of removing material, as in subtractive manufacturing, additive manufacturing (or 3D printing) builds an object by adding material, layer by layer, bonding each one in a solid final part. Similarly to the CNC process, 3D Printing takes a CAD model and prepares it to be manufactured through a software called slicer. After the CAD model is "sliced", there are several technologies that can produce the component: Stereolithography (SLA), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), Material Jetting, Binder Jetting, Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM). Some of those technologies are available in desktop machines, that are easier to use and affordable to the general public (formlabs.com, 2022b).

- **SLA**
 - SLA is a type of additive manufacturing technology that works around liquid resin to produce the parts. The principle is simple, using a light source, the printer cures the liquid resin into a hard plastic. This process is called polymerization, where the

molecules react to the light wavelength and solidify the raw material (formlabs.com, 2022d). SLA is very appealing due to the wide range of material properties that other technologies can't offer. The parts produced with this process are very accurate and a higher surface smoothness and detail. Also, the resins used in this technology have the ability to imitate the properties of well-established materials, like ABS, PC or Silicone (formlabs.com, 2022d; protolabs.co.uk, sem data)

- **SLS**

- Similar to SLA, SLS is a technology that uses a laser beam to sinter polymer powder into a solid part. This process is a favourite from several industries because of the high performance materials used to produce the parts, the low cost per unit and the capability to produce small series of products. Unlike any other technology, this process does not require support material, because the unfused powder supports each layer. This allows for a more complex geometries that are harder to produce otherwise (formlabs.com, 2022c). The materials used for this technology are different grades of polyamide (PA), commercially known as Nylon, and each one offers different mechanical properties to suit different applications (formlabs.com, 2022c). By the end of the production, the leftover material is recyclable.

- **FDM**

- FDM printing is one of the most common technologies available in the world. The way it works is simple: the machine runs a filament material through a hot head and deposits fused material, layer by layer, on a print bed to produce the desired part. FDM machines are built in a various number of designs and are affordable to the common user (all3dp.com, 2022). Some up sides of this technology are the range of thermoplastics available as raw material, from polylactic acid (PLA), one of the most common and easy to work materials, to carbon fibre or glass fibre filaments, with higher properties (all3dp.com, 2022, 5/072022). The down sides are the heavily maintenance required to daily basis usage and the poor surface finishing and tolerances (all3dp.com, 2022).

- **DMLS**

- DMLS follows the same principle as any other additive manufacturing technology, it uses a 3D model, slices it and produces layer by layer. This process also uses a powerful laser

to sinter a metal powder into a solid part. This technology can produce object directly in pure metal, alloys or materials mixtures, having a wide range of raw materials to work with. The properties are similar to products produced in a conventional technology and, as in SLS, the leftover material can be recycled (all3dp.com, 2021).

- **EBM**

- This technology is very similar to DMLS in concept, but instead of a laser, it uses an electron beam to fuse conductive metals, layer by layer, creating a high-density part at the end. Due to its high mechanical properties, it is used in several industries like aerospace and implants (Loth, 2021). One big difference to DMLS is the capability to stack objects like SLS, not requiring support materials. In the other hand, due to the size of the beam, the surface finishing is poor and post processing is needed (Loth, 2021).

1.6. Testing Environment

The assessment of a product's usability can be evaluated by two parameters, namely performance and satisfaction (Tullis & Albert, 2013). Performance refers to the user's ability to complete a given task, while satisfaction refers to the user's emotional response towards the product. Efficiency and efficacy are two aspects of performance, with efficacy pertaining to the successful completion of a task and efficiency referring to the quality of the accomplishment (dictionary.com, 2021). In the existing literature, researchers have predominantly focused on the efficacy of prototypes by identifying errors in their designs, which led them to conclude that there were no significant differences in prototype resolution. However, it was pointed out by (Sauer et al., 2008) that the efficiency of prototypes was not measured, highlighting the need to conduct performance usability tests in real-life scenarios to validate the efficacy of the prototypes. Some researchers, i.e. Deininger et al., 2017 and Jensen et al., 2018, have also explored the satisfaction aspect of the product and found that prototype fidelity has an impact on users' satisfaction.

The literature presents a gap, in which there is a lack of pertinent studies towards measuring efficiency on multiple prototype resolutions. In that regard, 2 major requirements need to be take into account: the metrics to be used and the participants that will be tested.

1.6.1. Tasks and Metrics

Choosing metrics and tasks are a crucial step of any usability activity, since those are the parameters that allows the product to be evaluated (Tullis & Albert, 2013). In this case study, it is important to understand what similarities most steering wheels have, in order to create a group of activities to better assess the

efficiency of the prototypes fidelity on a steering wheel. To do so, it was performed a research of the best selling/best rated cars of three categories: utilitarian cars, luxury cars and sport cars. The research based itself in consulting magazines and blogs about the thematic and trace the most reviewed cars. By doing that research, it is possible to compare side by side the steering wheel of each car typology and conclude what the similarities in the HMI's where, and choose a SW based on the common features that won't be strange to the majority of users/participants.

In Appendix 2 – Best Selling Cars, are three comparative tables of each car category and, as it is possible to assess, the results are the following: the best rated/sold cars in the utilitarian category were the Toyota Corolla and Toyota R4AV. By comparing the sales volume of both cars, the steering wheel of Toyota R4AV is the selected one of this category (92 854 R4AV - 85 036 Corolla) (newsroom.toyota.eu, 2022). Regarding the luxury cars, the most wanted are Audi A8, BMW 7-Series, Porsche Panamera and Tykan and Mercedes E-Class. When comparing the sales volume, the Mercedes E-Class is the car with most sales volume, being it 's steering wheel the selected to compare in this category, table 8, (Demandt, 2022). Lastly, in the sport cars category, the most sold/rated cars are the Porsche 911 and the Jaguar F-Type. When compared the sales volume, the selected steering wheel to be compared is the Porsche 911, with a total of 15 705 sales in 2021 (Demandt, 2022, p. 911), compared to 2363 of Jaguar (Demandt, 2022).

Table 8: Sales volume comparison on the Luxury car brands.

Car Brand	Sales Volume 2021 (units)
Mercedes E-Class	53 654
Porsche Tykan	16256
BMW 7-Series	5235
Porsche Panamera	5097
Audi A8	2865

Upon analysing the selected steering wheels, and as demonstrated on Appendix 3 – HMI Comparison, it is evident that the primary functionalities are infotainment control (including multimedia, dashboard, and cellphone functions) and cruise control, particularly Dynamic Radar Cruise Control (DRCC), enabling speed management relative to the leading vehicle (Calgary, 2022; Napoles, 2021; USA, 2017; valdostatoyota.com, 2022). However, aligning with the study's objectives, simulating dashboard or cruise control behaviours diverges from the research focus, since the goal is not to test the car response but the user response,

therefore a more direct approach entails simulating volume adjustments and call responses, which can be easily simulated without the participant needing a software confirmation.

As the experiment aims to compare different prototype resolutions on steering wheels, secondary driver tasks serve as the dependent variables for evaluation, with steering wheel resolution serving as the independent variable (Tullis & Albert, 2013). Secondary tasks involve activities drawing driver attention away from driving, such as interacting with cellphones, radios, or talking with passengers (Engström et al., 2005; G Markkula & J Engström, 2006). These tasks demand visual or cognitive loads, involving eye deviation from the road or engaging in hands-free activities (Engström et al., 2005).

In assessing prototypes through performance tasks, a binary evaluation is deemed ideal, wherein participants either pass or fail the task (Tullis & Albert, 2013). The parameters defining task success are crucially established. Given the driving simulator context, driver reaction time serves as a paramount metric. Driving at 88 km/h (55 miles/h) for 4.6 to 5 seconds equates to traversing the length of a football stadium, highlighting the potential severity of distractions during this time-frame (Gardner, 2018; Schlechta, 2022). Studies indicate varying reaction times: 0.7 seconds for expected obstacles, 1.25 seconds for anticipated yet sudden events (e.g., front car braking), and 1.5 seconds for unforeseen surprises (Green, 2021). Therefore, for this work, based on previous data, successful task completion time should not exceed 1.5 seconds consecutively, aligning with the worst-case scenario of a surprise reaction time, table 9. Any duration exceeding this reference will be considered a failure. Additionally, pressing the right buttons is also crucial to pass the test, any action in contrary will be considered a failure.

Table 9: Usability Test guidelines.

Task	Task Success (s)	Possible Errors
Up the Volume	≤1,5	Surpassing the time; not clicking the right buttons
Down the Volume	≤1,5	
Answer a Call	≤1,5	
Decline a Call	≤1,5	

1.6.2. Participant Selection

Acquiring participants is a crucial task in any usability scenario, however, determining the appropriate sample size for a study is a matter of discussion. Tullis & Albert (2013), propose two types of evaluations to consider when engaging in a user experience activity. If the study is formative and involves iterative testing of several prototypes to refine the design and detect usability issues, a sample of 5 to 8 users per iteration is enough. However, in the case of a summative study, where the product is tested to determine whether it meets the project goals, a sample size of 30 to 50 users is expected. Although some authors, e.g. (Spillers, 2019),

caution against the use of smaller sample sizes, claiming that they may not yield a satisfactory level of confidence, table 10, the method described by Tullis & Albert (2013) appears to be widely accepted by several research teams and has been adopted for the present work. Additionally, an analysis of several studies has revealed that 5 out of 20 authors, table 11, have divided their larger sample sizes into smaller test groups, resulting in fewer users per test. For instance, Nelson & Menold, (2020), divided 37 teams into groups of 3 to 4 people. Does studies show that, in certain scenarios, the use of fewer participants is functional and its used often. Therefore, based on this range of studies, and due to time restraints, the present work will use a smaller sample size approach considering 6 to 7 users per test. As the number of prototypes intended to assess are 6, is expected a sample from 30 to 40 participants.

Table 10: The Number of Participants for Studies Involving a Binary Metric (Success, Conversion).

	Confidence Level	Margin of Error	Participants
Low Risk – Good Precision	95%	15%	39
Low Risk – Fair Precision	95%	20%	21
Medium Risk – Good Precision	90%	15%	28
Medium Risk – Fair Precision	90%	20%	15

Table 11: Analyses of 20 studies regarding the participants used.

Authors	Nº of Participants	Ages	Types of users	Group division
(Brooks et al., 2021)	6	35 - 49	Occupational, Speech and Physical therapists	
(Canuto da Silva & Kaminski, 2015)	34		Different companies positions	
(Catani & Biers, 1998)	30		Undergraduate students	
(Deininger, Daly, Sienko, Lee, et al., 2017)	45		Healthcare professionals	
(Jensen et al., 2018)	66	13 - 48	Users of locker rooms	
(Nelson & Menold, 2020)			Students	37 teams, 3 to 5 students
(Säde et al., 1998)	20	10 - 65	Supermarket users	
(Sauer & Sonderegger, 2009)	60	19 - 41	Mobile phone users	
(Sauer et al., 2008)	34	16 - 66	Different working experience	
(Sefelin et al., 2003)	48			4 groups
(Uebelbacher et al., 2013)	80	16 - 65	General public and students	
(Virzi et al., 1996)	20		University students	
(Walker et al., 2002)	28		No prior experience with user testing	2 groups, 16 and 12 users
(Wiklund et al., 1992)	50		University students	5 groups
(R. Li et al., 2021)	36	25 - 29	Different levels of fatigue (SSS scale), healthy, no coffee or alcohol 24h before the test	2 groups
(Ma et al., 2020)	24	20 – 45	Different Mileages (from 3000 to over 20000Km)	

(Tinga et al., 2022)	18	21 - 66	Having drivers license, no history of epilepsy	
(Matsuda et al., 2022)	24		Novice drivers, frequent drivers	
(X. Li et al., 2020)	36	18 - 65	Having drivers license, passing motion sickness test	

Also, as seen in table 11, for each study there are specificities on the participants used, specially on the studies regarding steering wheel assessment, i.e. (R. Li et al., 2021; X. Li et al., 2020; Ma et al., 2020; Matsuda et al., 2022; Tinga et al., 2022), where the participants must have driving license, no health problem has epilepsy, in order to use driving simulators, and range from different driving experiences. This work followed the same idea, all participants must have driving license and should be healthy.

2. Methodology

To structure the user experience investigation and address the research question, the following methodology that will guide the entire process. To this end, this chapter is segmented according to the principal themes of the investigation: the formulation and execution of the prototypes' design and development, the arrangement of the testing environment and driving simulator, and the delineation of the assessment strategy.

As seen in the literature, most of the authors only test three prototypes of each fidelity, being those low, medium and high fidelity. By consulting the taxonomy proposed by (Pei et al., 2011), it is possible to perceive that each fidelity of prototypes could have a range of different resolutions, as they are presented as models and prototypes, and even sketches are considered in some cases. For these reasons, this work considered an upgrade of resolution on each fidelity typology, being reasonable to develop 6 prototypes, 2 low-fidelity, 2 medium-fidelity and 2 high-fidelity, to further assess if the smallest change in resolution can impact the usability of the prototype. With this approach is expected to understand the impact of resolution changes, particularly in the transition from low to medium fidelity and medium to high.

To better understand different fidelity groups, the following table demonstrates what this dissertation intends by Low, Medium and High fidelity, strongly based on (Pei et al., 2011), altogether with the showcased authors.

Table 12: Fidelity groups definition.

Fidelity	Global Literature Definition	Pei´s Definition	Authors
Low-fidelity	Conceptual Prototype or Design Models	3D Sketch and Development Model.	(Canuto da Silva & Kaminski, 2015; Pei et al., 2011; tensentric.com, 2023)
Medium-fidelity	Conceptual and Functional Products or Design and Engineering Models	Aesthetic Model and Functional Model	(Canuto da Silva & Kaminski, 2015; Pei et al., 2011; tensentric.com, 2023)
High-fidelity	Final Prototype and Design and Engineering Prototype	Beta Prototype and Postproduction Prototype	(Canuto da Silva & Kaminski, 2015; Pei et al., 2011; tensentric.com, 2023)

In this context, it is proposed two resolutions for each fidelity level. Each fidelity offers different levels of detail, allowing us to evaluate user perceptions of these changes. This approach helps us determine the specific characteristics each prototype should have to gain valuable usability insights. In the context of this work, all prototypes were 3-dimensional, as the tests needed a certain degree of interaction that a bidimensional prototype can't have (as grabbing and moving the object) and they followed these characteristics:

- **Low-fidelity:** The low-fidelity was produced essentially in two materials, cardboard and polyurethane. The cardboard prototype should be the lowest fidelity (V1) one and it must have all the components in that material. The HMI is the only exception, and was developed in paper (with drawn buttons). This was possible because the whole structure of the steering wheel is 3-dimensional and the user can grab the prototype, this way it was possible to assess a prototype with completely flat interface. Regarding the second resolution (V2), the use of polyurethane enabled the creation of a fully three-dimensional prototype, including the buttons. However, these low-fidelity prototypes did not have functional buttons or HMI. As described in the literature, they were exploratory, low-cost prototypes.
- **Medium-fidelity:** The medium-fidelity prototypes introduced the Additive Manufacturing. The first resolution (V3) was a mix medium, having some structural components as the HMI buttons. The goal was to present the user with an object with more robustness, but at the same time with a low cost and rough aspect. This prototype has movable/interactive buttons, but they don't click or function as they should. In the other hand, the second resolution (V4) in the medium-fidelity category, is a fully 3D printed prototype, aiming to have a consistent prototype, regarding the materials, and create distinction in colours and infography. This prototype, as the one before, has movable/interactive buttons, but they don't function either, being this object more oriented to the aesthetic, rather than function.
- **High-fidelity:** The prototypes considered for the high-fidelity are fully functional prototypes, with similar looks and material (also produced by additive manufacturing but it can have post processing to achieve the material likeness goal) and the real product (steering wheel). The goal of the high-fidelity (V5) prototype is trying to have a similar look and feel as the final product but having in mind that some aspects could not be achieve and the user is expected to notice. One final prototype (V6) will be the real steering wheel, where all the prototypes were based on, that must be used as the control prototype on the study.

2.1. Prototypes Development and Production

As previously mentioned, a steering wheel has been chosen as the focal object for this dissertation due to its elevated usability degree. In this regard, a Citroen Xsara, Appendix 1 – Citroen Steering Wheel, was acquired for the purpose of conducting the assessment tests. The prototype development was based on the decomposition of the steering wheel into six different prototype resolutions, 2 low-fidelity, 2 medium-fidelity and 2 high fidelity prototypes, that consequently were named V1 to V6.

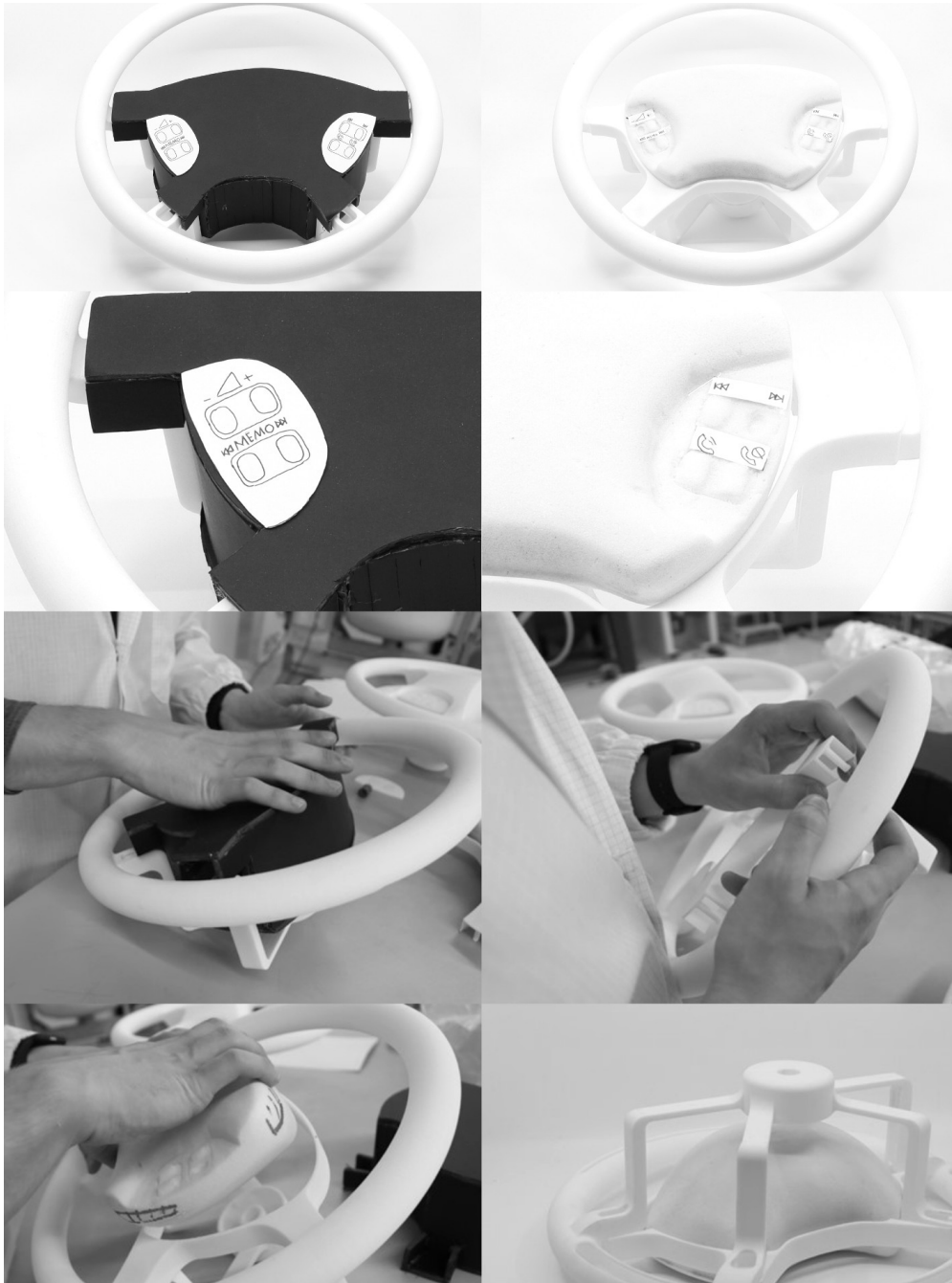


Image 2: Design of the low fidelity prototypes (V1 on the left and V2 on the right) and the placement jig.

The first prototype, V1, was designed in foam board and hand drawn infographic commands to replace the buttons. As this model represents a first exploratory iteration, the overall shape was unrefined, without smooth curves and edges, focusing on the basic measurements and volume, image 2. Also, the buttons were designed flat, regarding only their area and placement. The second prototype upgrades from paper-foam to polyurethane foam. This material allows more exploration regarding the shape, having in consideration the smoothest curvature of the steering wheel. This prototype has its buttons sculpted directly on the raw material, exploring the volumetric confirmation for the user, however the accuracy on size and shape differs from the real buttons, image 2. In this context, the written information maintains its handwritten nature, as both prototypes require a low cost aspect. Additionally, for the low-fidelity prototypes (and for the first medium fidelity resolution) was designed a structure to secure and place the objects to a steering wheel frame. This way, the same part holds the three models, minimizing material waste and development time and costs (later it was very useful during the assessment). This feature was divided in two parts, the steering wheel grip and the holding frame, which snap-fits on the grip and holds the foam models. The paper foam prototype fits directly onto the grip, image 2. Also, this jig imposes the same gripping size and feeling for every prototype, regarding that the objects of the study are the commands, not the gripping and driving satisfaction.



Image 3: Design of medium fidelity prototypes (V3 on the left and V4 on the right).

Similar to the low fidelity group, the medium fidelity prototypes encompass two resolutions, V3 and V4. The initial resolution prototype adopts a mixed technology approach, incorporating a polyurethane foam core while employing additive manufacturing (SLS) for the buttons. These buttons closely approximate the final size and shape requirements. Information regarding to the buttons was computer-generated and fixed with transparent tape. The following resolution, image 3, consists in a full SLS prototype, having a more refined aesthetic. In this case, the command buttons have an upgrade regarding the previous ones. The buttons have a physical movement in order to allow the user to have an increased degree of confirmation when executing the tasks, image 3.

The last group has the most aesthetic and functional prototypes, V5 and V6. First of all, the prototype that represents the highest fidelity is the acquired steering wheel that, for the purpose of this work, is considered a post-production prototype. In that regard, the resolution bellow, V5, is also a fully SLS production, image 4, however, this prototype differs in three aspects form the previous one. To start, the overall shape is

closer to the final product, representing a more definitive look as it is usual in a design process. Second, the command buttons, even not functional, are designed to be clickable, so the confirmation is accentuated by the click sensation, image 4. For the last, the prototype is painted in black, having a closer look to the final steering wheel.



Image 4: Design of high fidelity prototypes (V5 on the left and V6 on the right).

2.1.1. Design Considerations – Design for Additive Manufacturing

Selective Laser Sintering is a technology based on powder deposition, meaning that, for each layer, Polyamide – PA powder is spread on the printing bed and then synerized by a laser, forming a solid part. As the printing proceeds, the parts stay surrounded by PA powder, not needing support or infill material, demanding prototypes to be hollow in order to save material and reducing weight, Appendix 4 – Selective Laser Sintering Process. Regarding this specificity, the steering wheels prototypes were designed to

accommodate such considerations. In order to maintain the part hollow and facilitate the cleaning process, the back of the parts was open, so the compressed air could expel the trapped powder. To do so, the three SLS prototypes incorporated three different approaches.

- **Placement Jig:** The placement Jig was designed to incorporate the first prototypes, having a modular architecture. As seen before, this prototype is composed by two parts, the main body and the fitting frame. The main body has a tubular part, to simulate the steering wheel gripping area and a structural element to connect to the steering column. The tubular part has openings so the powder can easily be removed, however, the structure is thinner, only requiring openings in fewer areas, image 5. Differently, the fitting frame was designed as an injection mould part, with uniform thin walls, not requiring following the same rules to be produced.
- **Medium-Fidelity:** As the fourth prototype is a fully 3D printed product, the complexity to place the cleaning opening were more challenging. The idea for this object was to maintain it as similar as the steering wheel, therefore reducing the amount of openings in its surface. In that regard, only a few holes were placed on the back of the prototype, specially to help the powder to escape the main volume. Then, two holes on the bottom body, two openings on the tubular area, allowing the powder to escape both from the gripping element and the main body and two more holes were open right under the commands. The opening for the connection to the driving simulator was the only expected opening from the original drawing. All the holes and openings were given more than 10mm of diameter.
- **High-fidelity:** Similar to the previous prototype, the high-fidelity steering wheel was fully 3D printed, however, as the medium-fidelity strategy to clean the part failed (in a sense that the holes were not enough to clean the prototype) the higher resolution was designed with an opening pattern on the bottom body, allowing for more air flow on the inside. The tubular element followed a similar design as the Placement Jig. In conclusion, this prototype had a more ventilated architecture, facilitating its cleaning process without losing the steering wheel identity and aesthetic.

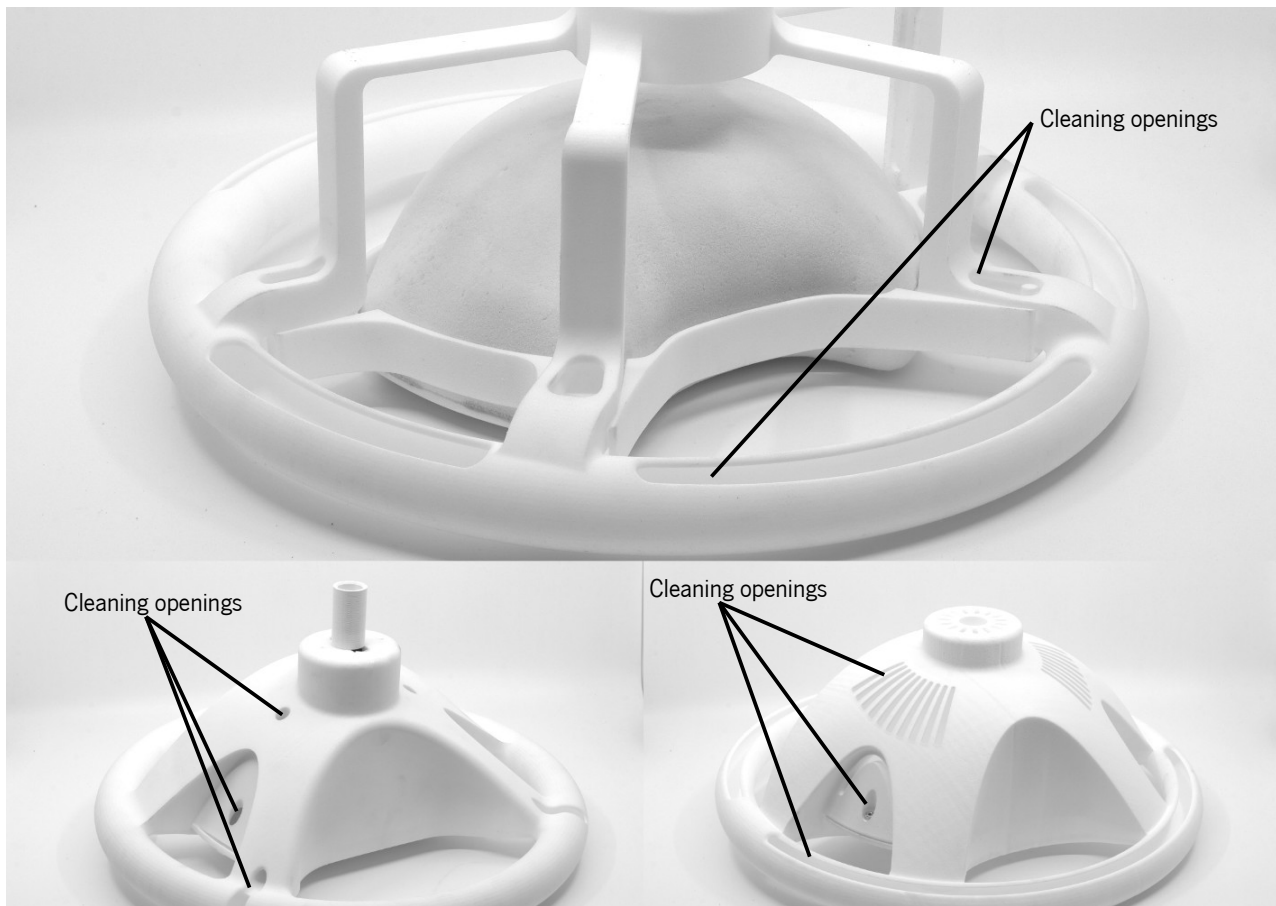


Image 5: Designing for SLS - Cleaning openings.

The following considerations were concerned with the haptic confirmation of the buttons itself. A fully functional steering wheel has, as its basis, a clicking button that allows the user to feel they press something, followed by the corresponding action of that button. In this context, that feedback action will not be considered, being the prototypes designed to accommodate the haptic feedback only. Following the same idea that a first prototype should not have a completed aesthetic and function, the buttons were developed by the following order: a paper, hand drawn command, representing the placement and button size only, demanding the user to have a visual confirmation to know if the task is correct, as depicted in image 6. Secondly, the buttons upgrade to a foam sculpted representation, allowing a degree of tactile feedback. This prototype is followed by a fully 3D printed command, representing the same idea, but instead of sculpted buttons, the third prototype approaches the volume and shape of the original, with accuracy. The following steering wheels have the same concept, but with a small difference. Both have clickable buttons, in order to give the user action feedback, however, the fifth prototype incorporates real mechanical buttons, giving it the sound and vibration of a real button.



Image 6: Prototypes final resolutions.

2.2. Testing Scenario

In the consulted literature, most of the authors performed tests in a controlled room, however, (Sauer et al., 2008) pointed that to really assess a prototype usability it is needed a testing scenario, where the participants are confronted with a more realistic context of use of the assessed products. Addressing that problem, this section explores in detail the planning of the usability conditions to enrol on a steering wheel assessment, going from the context in which the prototypes were assessed, to the participants and potential bias and how to avoid them.

2.2.1. Driving Simulator

Since the selected product is a steering wheel, the most logical scenario to assess these types of prototypes, regarding performance, is a driving simulator, a testing instrument designed to test participants on a context of driving experience, without harming anyone if anything goes sideways. Although the University of Minho has a professional driving simulator that would be optimal for this kind of study, due to access and time-frame constraints, a more simplistic simulator had to be designed. To do so, it was opted to use a gaming simulator, that included steering wheel and pedals, to simulate a driving experience to some extent, and a video-game on the “Simulator” category, that allows for a low level of customization and realistic behavior of the car, image 7.



Image 7: Driving Simulator scenario.

The acquired products for this purpose were the *Superdrive SV250®*, a gaming setup with as steering wheel and pedals kit, image 8, and the video-game *Asseto Corsa®*, a racing simulator that brings a considerable amount of cars and circuits variety, based on the real ones. After the acquisition of those two

products, the Simulation Setup needed to be prepared and adapted to the designed prototypes, either the physical interface and the digital interface.



Image 8: Superdrive SV250® system.

- **Physical Interface:** the first idea to adapt the SW prototypes to the *Superdrive SV250®*, was to disassemble the steering wheel and directly adapt the prototypes to the steering column, however the main board was installed into the steering wheel itself, turning useless the rest of the interface without it. To resolve this problem, an intermediate part was designed to be placed on top of the main steering wheel, allowing for the prototypes to be assembled in place, image 9.



Image 9: Prototype adaptation process.

Then, the steering wheel was placed on top of an office table and in front of a computer monitor and the pedals on the ground, right below the prototypes. To ensure the setup would be equal to every participant, all the components were given a specific marking on the table, to be easier to reassemble everything if the space suffered any change. Regarding the ergonomic aspects, the placement of the elements did not follow any particular defined metric, however, two extreme participants were used to ensure that everything could be used. The setup was placed allowing a 1.98m height male and a 1.52m height female (Gomes da Costa & M. Arezes, 2005) to be in a comfortable enough position that the elements could stay in the same position, without adjusting any measurement. The schematics of the setup are represented in image 10.

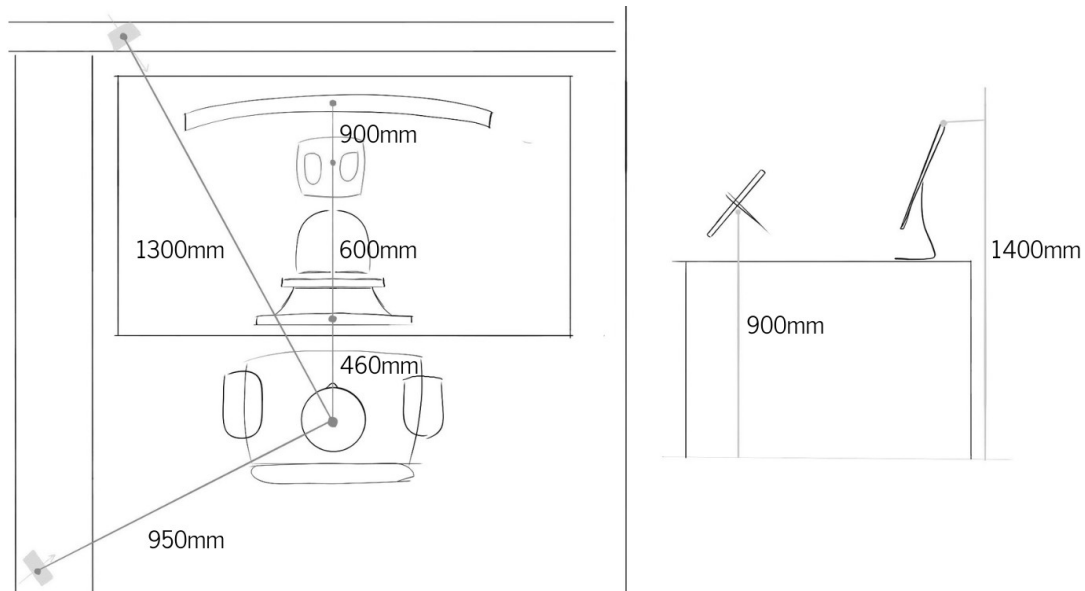


Image 10: Space measurements.

- Digital Interface:** The digital setup was the most challenging part of the process, in a way that this dynamic should respond to a group of requirements to ensure the success of the tests. First, the time frame of the project was tight, and the circuit should be short enough to allow a considerable number of tests accordingly and long enough to run the tasks in the two sets of situations previously considered. The second requirement was the amount of visual information on the circuit. As specified, the tasks must be performed in specific milestones, in order to be repeated by every participant on the same position and because the video-game do not allow to programming specific messages during the driving, the monitor should have a considerable amount of detail to use as milestones. Lastly, with the lack of driving sensations (e.g. vibrations of the car and the sound of the surroundings), it is easy to drive at undesirable speeds, which brings undesirable accidents during the tests, so the third requirement regarded the type of car used being limited on it's top speed and driving behavior. Facing those challenges the following part was divided in selecting the circuit and selecting the car. To select the circuit, the first steps to do was to select small circuits with a variety of straight roads and curves, allowing for diversity when assigning the tasks.

The main circuits reviewed were Silverstone International (3619m length), Silverstone National (2638 length) and Red Bull Ring National (2336m length), image 11, which have similar lengths and similar time per lap of 3 to 5 min, at speeds of 70 to 100 km/h on average. All of them also have trail sections that brings significant workload to the users, without being too demanding or distracting, meaning these trail sections were simple enough to allow the users to interact with the HMI without the risk of an accident or going of rail. Although these circuits had several conditions on their favor,

only Red Bull Ring National offered the amount of visual content to easily define milestones through the test. Apart from the circuit, the selection of the car was of great importance.



Image 11: Studied circuits on Aseto Corsa®.

Again, one major problem with this simulator was, as said, the lack of sensations, being easy to go off tracks frequently. To avoid this problem, the selected car for this study was a Fiat 500 Abarth 595 SS, demonstrated on image 12, with only 32bhp and 130km/h max speed, facilitating the users to better control the car. All this process was tested with 3 users, altogether with the moderator, in order to

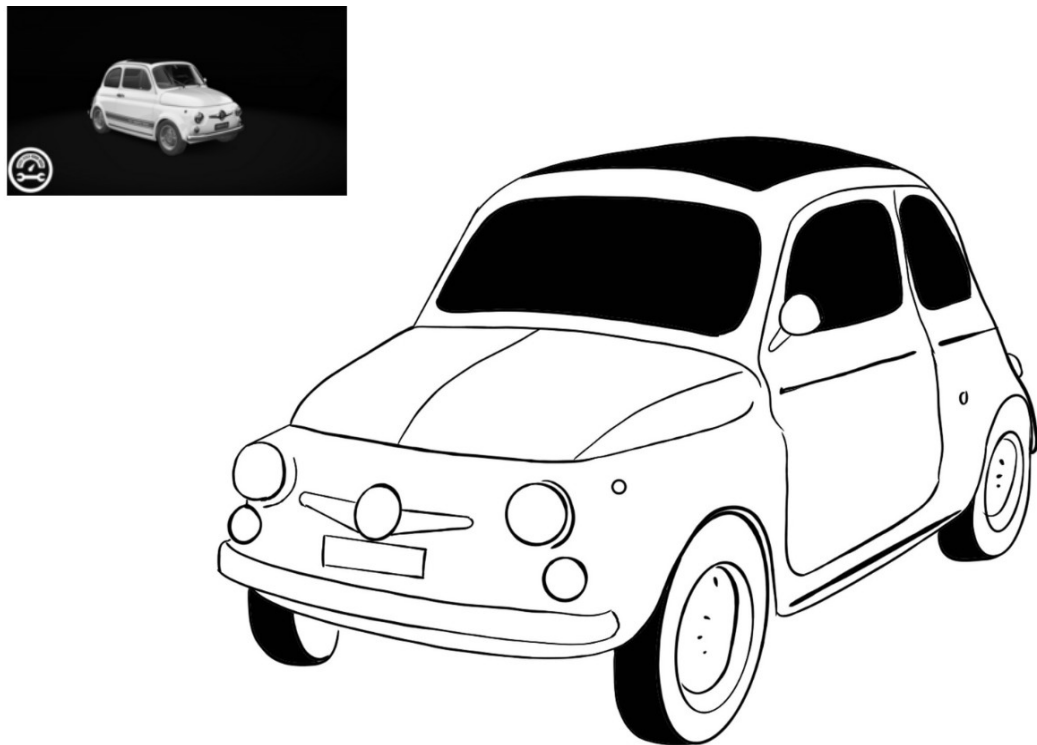


Image 12: Fiat 500 Abarth 595 SS on Aseto Corsa®.
select the optimal solution.

2.2.2. Data Acquisition and Bias

The best way to acquire this data must be using an eye-tracking device, that will indicate for how long and where the participants are looking. As the equipment is not available to use, the participants will be recorded to later analyse the video and verify the time of distraction. The hands of the participant will also

need to be recorded to verify if the person uses the right button and to measure if there is any physical difficulty to use the buttons, as represented on image 13.



Image 13: Camera 's point of view.

Finally, to ensure the assessment will run without external implications, the monitor must be aware to avoid any biases as possible. Biases, or Cognitive Biases, are behaviour and tendencies that the monitors and/or the participants have that may interfere with the usability tests, encompassing a distortion or misinterpretation of the tasks on hand, leading to faulty or inaccurate results. Those can be placed in two categories, such as Information Biases, related to the manipulation of the exiting information to create shortcuts, intended to be more efficient, and Ego Biases, regarding emotional response to the tests and environment (Natesan et al., 2016; Taylor, 2013). Although biases cannot be fully avoided, they can be mitigated through the design of the usability scenario and attention to behaviour (Tullis & Albert, 2013). On the following table, table 13, it is possible too see the 8 principal biases, according to Natesan et al., 2016, and how they were avoided in this dissertation.

Table 13: Types of biases and how they will be avoided (Natesan et al., 2016).

Types of Biases	Description	How to Avoid (Dissertation)
Experimenter Effect	The moderator reveal errors mistakes that are expected to happen.	<ul style="list-style-type: none"> Pilot tests to anticipate unwanted mistakes in order to avoid corrections during tests. Maintaining a cordial and polite attitude towards the participants, without being emphatic regarding any of the tasks.
Confirmation Bias	The moderator/participant search to attend their expectations and not to conduct the study accordingly to the plan.	<ul style="list-style-type: none"> Making sure to reveal only the necessary information regarding the session in specific. Ignore questions from the participants, when the person wants to know specific intel about the direction of the study.
Hawthorne Effect	Participants behave differently when observed.	<ul style="list-style-type: none"> Although the participants are being recorded, the cameras are away of the focal view. The activity itself do not catch the individuals attention for the observation part of the data collection.
Social Desirability Bias	Participants intend to impress the monitor by exaggerating the reported data, or the extreme opposite.	<ul style="list-style-type: none"> Participants are not expected to speak during the tests, only executing the given tasks.
Priming Effect	Participants act differently according to the way the moderator expresses the questions/tasks.	<ul style="list-style-type: none"> The tasks are given using the same speech and monochord tone.
Recency Effect	Participants learn how to perform the tasks during the sessions/tests	<ul style="list-style-type: none"> Between-Subject study: each participant only test once, never repeating the study throughout the whole range of prototypes.
Task-Selection Bias	Participants try to force or invent a solution, trying to impress the moderator.	<ul style="list-style-type: none"> The study is designed in the way that this bias would not occur. Each task is performed during a straight section of the circuit and on a curve, avoiding the tendency

		to do a task with less workload.
Bandwagon Effect	Participants share the same beliefs or opinions regarding the study.	<ul style="list-style-type: none"> Each participant is alone with the moderator, not having space to share opinions during the tests. The study is designed in the way that this bias would not occur.
Hindsight Bias	Participants predict what may happen during the sessions.	<ul style="list-style-type: none"> If there is a line of participants waiting to perform the tests, the moderator asks to each participant to not share the experience with the others. The participants test in small groups at different periods to avoid conversation between them.

2.3. Assessment Planning

The planning of the assessment scenario is crucial to ensure every aspect reported before is executed. There are 3 relevant factors regarding the simulation, being the room organization, the timing and place of the tasks milestones and the reception and integration of the participants on the Driving Simulation scenario.

- **Room Organization:** As mentioned before, the simulations were conducted on the EC.2.11, at University of Minho. The setup was mounted on the corner, next to a window, where the tests will always be run with the curtains down, in order to maintain an equivalent level of light throughout the sessions. It is worth to mention that all the tests were assigned randomly from 9AM to 3PM, on the periods with most daylight. Also, all the equipment was promptly labelled, ensuring that everything can be placed back on position if moved.
- **Milestones:** It is defined that every task is demanded on a specific place on the selected circuit. This way the simulation adapts to each participant driving style. The following image, image 14, showcases the milestones of the Redbull National circuit. The image do not represent the accurate place where the task is demanded, rather a reference so the moderator had to pay attention (Appendix 5 - Guidelines for the Driving Simulation). Regardless of the image, the milestones were organized in the represented order and each one is associated with the following tasks:
 - Milestone 1: Answer and Deny a Call on a curve;
 - Milestone 2: Higher the Volume on a straight track section;

- Milestone 3: Lower the Volume on a curve;
- Milestone 4: Higher the Volume on a curve;
- Milestone 5: Lower the Volume on a straight track section;
- Milestone 6: Answer and Deny a Call on a straight track section.



Image 14: Milestone track section on Asseto Corsa®.

- **Participants:** As soon as they arrive to the room, the participants signed a Consent Form, Appendix 6 – Informed Consent, where they agree to be recorded and is assured that any of the data is confidential and will not be public. Then, each one fill in a socio-demographic questionnaire intended to verify their experience behind the wheel, as well if there is any kind of health problem that can injure them during the simulation, e.g. epilepsy. Followed by those forms, the participants were indicated to sit in front of the prototype and invited to drive one lap to get used to the simulator dynamic. After that, the simulation is reset, and the participants were explained the following rules:
 - *“You will run for 2 laps and, during the test, I will command you to interact with the steering wheel, which you must do immediately. I will tell you when to stop”;*
 - *“The speed limit is 70km/h. Be specially carefull on the curves”;*
 - *“Keep your hands on the sides of the steering wheel during the assessment”.*

After these instructions, participants started the simulation. As it is expected some participants to get enthusiastic during the laps, it will be considered a failure every participant that goes off track or crushes the car during a task, if the speed limit is not respected.

2.4. Summary

Setting the methodology was one of the most important steps for this work, because it lays a guide in which the practical component was set upon.

Socio-demographic Questionnaire: Participants were recruited through a socio-demographic questionnaire that included questions about their age, nationality, gender, and occupation. Participants were also asked about their health problems and epilepsy.

Participants: For this study, 33 participants were randomly recruited, 27 on the academic community, 82% - 55% students and 27% researchers, and 4 outside this community, 12%. The participants ranged from 18 to 58 years old with a mean of 23.7 years ($SD=7.4$), being 73% from 18 to 23 and 27% from 24 to 58, and 61% were male and 39% were female. Regarding their driving experience, 52% of the participants were on their first 3 years, which means that, according to Portuguese legislation, they are on their probation period (segurancarodoviaria.pt, 2024), as 48% of participants were on their regular periods. Additional, 94% of the participants reported not having health problems such as epilepsy and 6% were not aware.

Prototypes: Six prototypes were produced for this study, with two prototypes for each level of fidelity: low (V1 and V2), medium (V3 and V4), and high (V5 and V6). The low-fidelity were produced in cardboard foam and polyurethane, focusing on overall dimensions and shape. The medium-fidelity prototypes considered the type of information displayed and some degree of functionality, while the high-fidelity prototypes resembled the real product in terms of aesthetic, feel, and function. The highest fidelity prototype was the real product, as a post-product prototype and the control for the further assessment.

Research Plan: The objective of this study is to evaluate the impact of prototype fidelity on user experience efficiency, specifically focusing on comparing the performance of participants across six different prototype resolutions, ranging from paper to the final product, for a Citroen Xsara steering wheel. In this context, the independent variable is the prototype resolution. Participants were randomly assigned to one of six groups, and will be required to complete designated tasks while driving the car along a predetermined route. The metrics employed for this study will be time on task and binary evaluations, where participants will be assessed based on their task completion time and accuracy in pressing the correct button. The study will be a Between-subjects study design, i.e. a person can only be exposed to a single user interface, to avoid learnability.

Procedure: Prior to participating in the study, all participants were required to provide informed consent, which outlined the confidentiality and protection of data collected. Data collection was individual and took

place in a driving simulator located at the University of Minho, where each participant was tested individually within their respective group. Participants began by driving for a lap, to acclimate to the simulator, followed by 2 laps. During the ride, participants were prompted to adjust the volume and answer or decline incoming calls, at specific milestones. Each task was performed on a straight track section and a curve. Two cameras were employed to monitor the amount of time participants divert their eyes from the road, as well as their level of accuracy when pressing the buttons. The test was considered failed if the participant's eyes are off the road for more than 1.5 seconds individually, or if they fail to click the button altogether. All the participants performed the same tasks; however, the different prototypes fidelities will be sorted by the six groups, i.e. the first group assessed the low-fidelity prototype (V1), the second group the low-fidelity prototype (V2), the third group the medium-fidelity prototype (V3), the forth group the medium-fidelity prototype (V4), the fifth group the high-fidelity prototype (V5) and the sixth group the final product (V6). The participants were commanded to respect a speed limit of 70km/h and to keep their hands close to the button commands. If any participant committed a mistake due to avoid the speed limitations, the task in question was considered a failure.

3. Results and Discussion

The first three groups were constituted by 6 participants each and the last three by 5 participants each. After all the tests were finished the data was analysed on a video editing software so the record could be paused at specific frames and the reaction times could be counted at a milliseconds scale, as shown on image 15.

The following sections will present the average performance of each prototypes and further compare them to the control steering wheel, V6. To facilitate the analyses, the milestones for the Answer and Deny Call tasks, represented by Milestones 1 and 6, are subdivided into M1.1/M1.2 and M6.1/M6.2. This is because each action has a distinct reaction time, even though the tasks are related (it is impossible to deny a call without answering it first).



Image 15: Video editing software, used to assess reaction time.

3.1. Control Prototype – V6

As mentioned before, this study did not aim to design a new steering wheel or any HMI of some sorts, instead is focused on studying an existing product and simulate it's development stages to compare the different prototypes resolutions, for this reason, the higher fidelity prototype (real product) will be used as a

control, from which all the performances will be compared, since this resolution it is the final stage of this product and already have been used on real cars, outputting the most faithful experience. In this regard, as it is shown on table 14, this prototype had an excellent performance regarding the participants pressing the demanded buttons and task success, which means that none of the participants surpass the 1.5 seconds of Eyes of the Road, ranging from 0.8s to 1.1s ($mean = 0.95s$; $SD = 0.13$). Also, all the participants respected the simulation conditions, respecting the speed limit, which lead to an average Time per Test of 4min:50seconds, which was expected. The reaction time performance will be further assessed in a side-by-side comparison.

Overall, the data suggests a positive user experience with the prototype interface, as evidenced by the high task success rates and efficient reaction times. This prototype did not present any issue related with it's usability, all the participants perform the tasks with easy, presenting a need for more focus on the first task (M1.1) and switching for the second (M2), moments they used to study the steering wheel. The interface design resulted in a smooth and seamless interaction experience.

Table 14: Performance data from V6 tests.

Milestones	Answer/Deny Calls	Turn up the Volume	Turn down the Volume	Reaction time (s)	Task Success
M1.1	100%			1,1	100%
M1.2				0,8	
M2		100%		1,1	100%
M3			100%	0,8	100%
M4		100%		1,0	100%
M5			100%	1,0	100%
M6.1	100%			1,0	100%
M6.2				0,8	
Mean				0,95	100%

3.2. Low-Fidelity Prototype – V1

The first resolution, that is design in paper foam and with flat buttons, presents a low Task success rate, ranging from 33% to 83% ($mean = 66.7\%$; $SD = 0.18$). Although the precision on clicking the right button as a relatively high performance, having values next or targeting the 100%, there is a problem with reaction times that leads to lower tasks success. On this prototype, most participants needed to have long periods of time to analyse the HMI at each task, specially on M1.1, M2 and M6, the reaction times ranged from 0.8s to

1.68 ($mean = 1.09s$; $SD = 0.31$). Apart from missing the buttons, one participant went of rails by surpassing the speed limit, being considered a fail the Milestone 1, where that happened. The time per Test was on average 4min:41seconds. Comparing to the Control - V6, shown on table 15, we can infer that, M2 and M6 had performed equally in both prototypes and the milestone with lower consistency was M5, apart from that, V1 had, a decrease of 33% on task success. Regarding reaction time, even though the milestones 3 and 5 appeared to outperform the control prototype. The overall time increased 0,14 seconds. This data suggest more difficulty on this prototype.

Table 15: Performance data from V1 and comparison with control.

Milestones	Answer/Deny Calls	Turn up the Volume	Turn down the Volume	Reaction time (s)	Task Success
M1.1	83%			1,18	67%
M1.2				0,83	
M2		100%		1,68	33%
M3			83%	0,80	83%
M4		83%		0,98	83%
M5			67%	0,85	67%
M6.1	100%			1,4	67%
M6.2				0,9	
Mean				1,09	67%
Comparison between V6 and V1					
M1.1	-33%			0,12	-33%
M1.2				0.03	
M2		0%		0.61	-67%
M3			-17%	-0.03	-17%
M4		-17%		0	-17%
M5			-33%	-0,13	-33%
M6.1	0%			0.38	-33%
M6.2				0.10	
Mean				0,14	-33%

3.3. Low-Fidelity Prototype – V2

The second prototype, fully sculpted in foam, also shown a low Task Success rate. Contrarily to the V1, this prototype had a less reaction times beyond 1.5s, ranging from 0.7s to 1.4s ($mean = 1.01$; $SD = 0.23$), however, the precision on button clicking was significantly lower, ranging from 17% to 50% ($mean = 36\%$, $SD = 0.12$). 38% of the missing buttons on this test were caused by the participants mistaken the labels with the actual buttons, pressing on the labels instead. Apart from this mistake, no other issues were relevant on this test. Similar to V1, this prototype also shows a worst reaction time on M1.1, M2 and M6.1.s. The Time per Test was, on average, 3min:91seconds. When the V2 is compared to the V6, it is possible to see, table 16, a decrease in performance of 64% on task success. Reaction time performed better than the previous steering wheel, only increasing 0.06 seconds, table 16.

Table 16: Performance data from V2 and comparison with control.

Milestones	Answer/Deny Calls	Turn up the Volume	Turn down the Volume	Reaction time (s)	Task Success
M1.1	50%			1,13	50%
M1.2				0,7	
M2		33%		1,20	33%
M3			33%	0,92	33%
M4		17%		0,78	17%
M5			67%	0,88	50%
M6.1	50%			1,4	33%
M6.2				1,1	
Mean				1,01	36%
Comparison between V6 and V2					
M1.1	-50%			0.03	-50%
M1.2				-0.1	
M2		-67%		0.1	-67%
M3			-67%	0.12	-67%
M4		-83%		-0.22	-83%
M5			-33%	-0.12	-67%
M6.1	-50%			0.4	-50%
M6.2				0.3	
Mean				0,06	-64%

3.4. Medium-Fidelity Prototype – V3

This third prototype, a mix of foam sculpture and SLS buttons, starts to show better results, having an overall result higher than 50% of Task Success, ranging from 50% to 83% ($mean = 63.8\%$; $SD = 0.16$). However, even with better reaction times, this prototype had the same problem as the previous, where most of the errors are related to a confusion between the button and the label, more precisely 46% of the mistakes. Nonetheless, this was the most consistent issue and, differently from the other previous prototypes. The Reaction Time had more consistency on its dispersion, ranging from 0.8s to 1.3s ($mean = 0.96$; $SD = 0.18$). The Time per Task was, in average, 3min75seconds. When compared with the control, it is possible to infer that there was a decrease in performance of 36,2%, however, the reaction time was very similar to the real steering wheel, presenting only 0,01seconds on the overall test, table 17.

Table 17: Performance data from V3 and comparison with control.

Milestones	Answer/Deny Calls	Turn up the Volume	Turn down the Volume	Reaction time (s)	Task Success
M1.1	67%			1,1	50%
M1.2				0,9	
M2		83%		1,0	67%
M3			83%	0,7	83%
M4		67%		1,0	50%
M5			83%	0,8	83%
M6.1	83%			1,3	50%
M6.2				0,9	
Mean				0,96	63,8%
Comparison between V6 and V3					
M1.1	-33%			0	-50%
M1.2				0,1	
M2		-17%		-0,1	-33%
M3			-17%	-0,1	-17%
M4		-33%		0	-50%
M5			-17%	-0,2	-17%
M6.1	-17%			0,3	-50%
M6.2				0,1	
Mean				0,01	-36,2%

3.5. Medium-Fidelity Prototype – V4

The V4 steering wheel, that was the first prototype to be fully 3D printed, has a satisfactory performance. Although the reaction time on the problematic Milestones still leads to failure, the precision tends to increase and, on the rest of the Milestones was excellent, surpassing the 80% (M3, M4 and M5), ranging from 40% to 100% (*mean* = 73.3%; *SD* = 0.24). Overall, on this prototype the number of issues was almost inexistent, apart from one participant that went off rails due to exceeding the speed limits, however it wasn't on any of the milestones. As mentioned, the reaction time was problematic on Milestones M1.1, M2 and M6.1, but the other Milestones performed better than the original steering wheel, ranging from 0.56s to 1.36s (*mean* = 0.98s; *SD* = 0.33). The Time per Task was, on average, 3min8seconds. By comparing this prototype with the control, its is possible to see a decrease in performance of 26,7% and the reaction time is, on average, 0,03seconds, which is almost insignificant, table 18.

Table 18: Performance data from V4 and comparison with control.

Milestones	Answer/Deny Calls	Turn up the Volume	Turn down the Volume	Reaction time (s)	Task Success
M1.1	80%			1,36	40%
M1.2				0,56	
M2		80%		1,44	60%
M3			100%	0,98	80%
M4		100%		0,76	100%
M5			100%	0,74	100%
M6.1	80%			1,24	60%
M6.2				0,72	
Mean				0,98	73,3%
Comparison between V6 and V4					
M1.1	-20%			0,26	-60%
M1.2				-0,24	
M2		-20%		0,34	-40%
M3			0%	0,18	-20%
M4		0%		-0,24	-0%
M5			0%	-0,26	-0%
M6.1	-20%			0,24	-40%
M6.2				-0,08	
Mean				0,03	-26,7%

3.6. High-Fidelity Prototype – V5

For last, the high fidelity prototype, designed to be similar to the Control prototype, shows an excellent performance. Although it has a lower performance on the first Milestone, it recovers significantly, having 4 of the 6 milestones scoring 100%, ranging from 60% to 100% ($mean = 90\%$; $SD = 0.17$). Regarding reaction time, it is also closer to the control prototype, ranging from 0.58s to 1.32 ($mean = 0.9s$; $SD = 0.24$). The only issue noted on this test group was a participant that did not respond to the demanded task for being distracted with the driving itself. The Time per Test was, on average, 4min45second. When compared with the V6, this prototype only shows a decrease of 10% in performance regarding Task Success. The Reaction Time, overall, performed better, but not significantly, table 19.

Table 19: Performance data from V5 and comparison with control.

Milestones	Answer/Deny Calls	Turn up the Volume	Turn down the Volume	Reaction time (s)	Task Success
M1.1	100%			1,32	60%
M1.2				0,66	
M2		100%		1,04	100%
M3			100%	0,92	100%
M4		100%		0,84	100%
M5			80%	0,74	80%
M6.1	100%			1,06	100%
M6.2				0,58	
Mean				0,90	90%
Comparison between V6 and V5					
M1.1	-20%			0,22	-40%
M1.2				-0,14	
M2		-20%		-0,06	0%
M3			0%	0,12	0%
M4		0%		-0,16	0%
M5			0%	-0,26	-20%
M6.1	-20%			0,06	0%
M6.2				-0,22	
Mean				-0,06	-10%

3.7. Workload on Milestones

As delineated in the methodology section, the assessment of performance is intricately influenced by variations in workload dynamics. This study was structured to encompass two primary difficulty levels, wherein participants were tasked with executing manoeuvres along both straight and curved trajectories, denoted as the easy and hardest levels, respectively. However, these scenarios did not inherently represent the most cognitively demanding workloads. Upon scrutinizing the outcomes, it becomes apparent that the most demanding milestones were M1, M2, and M6. Challenges encountered during M1 were anticipated, given that participants were not pre-instructed on the tasks prior to testing, thereby introducing an element of surprise necessitating time for the recognition of button placement and function. Notably, during the trial lap, some participants were observed inspecting the buttons, which facilitated a swifter response during subsequent

trials. Conversely, both M2 and M6 shared a common impediment during testing, namely, the need to switch the side of button placement to execute the task. Specifically, the first and last tasks, Answering and Denying a call (M1 and M6), featured buttons situated on the right side of the steering wheel's bottom part, while Volume control (M2) necessitated manipulation of buttons positioned on the left side's upper part.

These findings revealed a notable observation: during Milestone 1 (M1), all participants were confronted with a novel task, necessitating a search for the corresponding buttons. In Milestone 2 (M2), participants not only encountered a new task but also had to navigate to the opposite side of the steering wheel to execute it. By Milestone 6 (M6), participants were concluding an entire test and once again required to transition to the opposite side of the steering wheel for action, resulting in a tendency to forget button placement and necessitating subsequent searches. These dynamics imposed greater cognitive demand than the duration of the circuit traversed by participants during the two-lap session.

3.8. Discussion

When compared side-by-side, the outcomes of this experiment shows an interesting result. By assessing the reaction times alone, image 16, it is possible to see an increase in performance as the resolution of the prototypes increases, being the V1 the prototype in which the average reaction time performance was the highest, which may indicate that, the higher the fidelity, the better it performs. However, this metric alone cannot give any information of success.

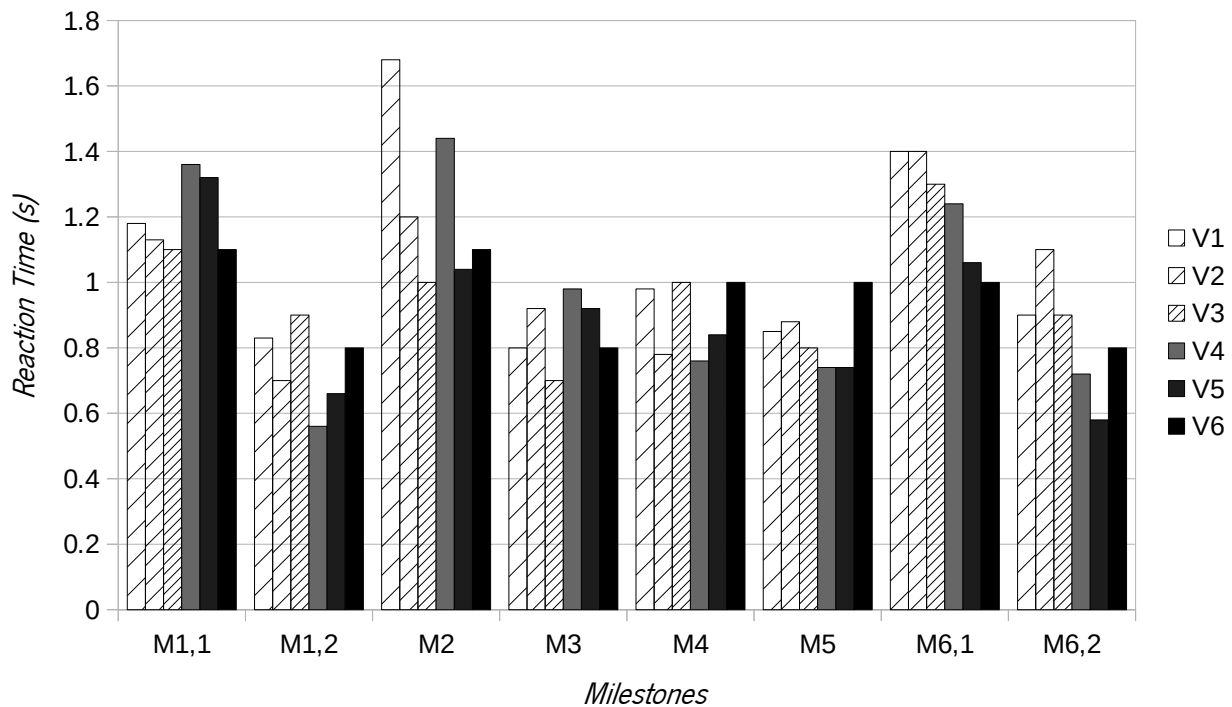


Image 16: Reaction Time comparison.

For this study, Task Success is the most significant metric to take in consideration, in a way that, to obtain these results, it was analysed the reaction time and the assertiveness in button clicking. Taking into account some of the literature, an expected outcome for this study was an increase in performance throughout the resolutions, either significant or insignificant, however, as shown on image 17, the results are quite the opposite. The medium and high-fidelity prototypes, V4 and V5, exhibit a notable enhancement in performance, as described by previous authors. These prototypes incorporate sensory feedback mechanisms, such as V4 through button movement and V5 via audible clicking sounds. Additionally, the geometric variations between the two prototypes may contribute to differing outcomes and perception of the product. However, it is noteworthy that the lower resolution prototypes demonstrate interesting results, with the lowest resolution prototype yielding superior performance. This phenomenon appears to be attributed to the design of information presentation within each prototype.

While V2 and V3 integrate three-dimensional elements, the lack of cohesion between the buttons and the prototype's body occasionally leads participants to wrong actions, such as clicking on labels instead of buttons. These mistakes are re-enforced by the contrast between the labels and the prototype's body. Conversely, the two-dimensional layout of V1 shows consistency in button and label display, facilitating a more comprehensive understanding of the prototype as a whole, image 18. Returning to the reaction time metrics, the constant increase in performance does not mean that the prototypes are performing better, but the

participants are reacting faster to a given input, and as seen in V2 and V3, participants are aiming for the labels and not for the actual buttons. These findings underscore the significance of information design in influencing user interaction and performance outcomes across different fidelity levels of prototypes.

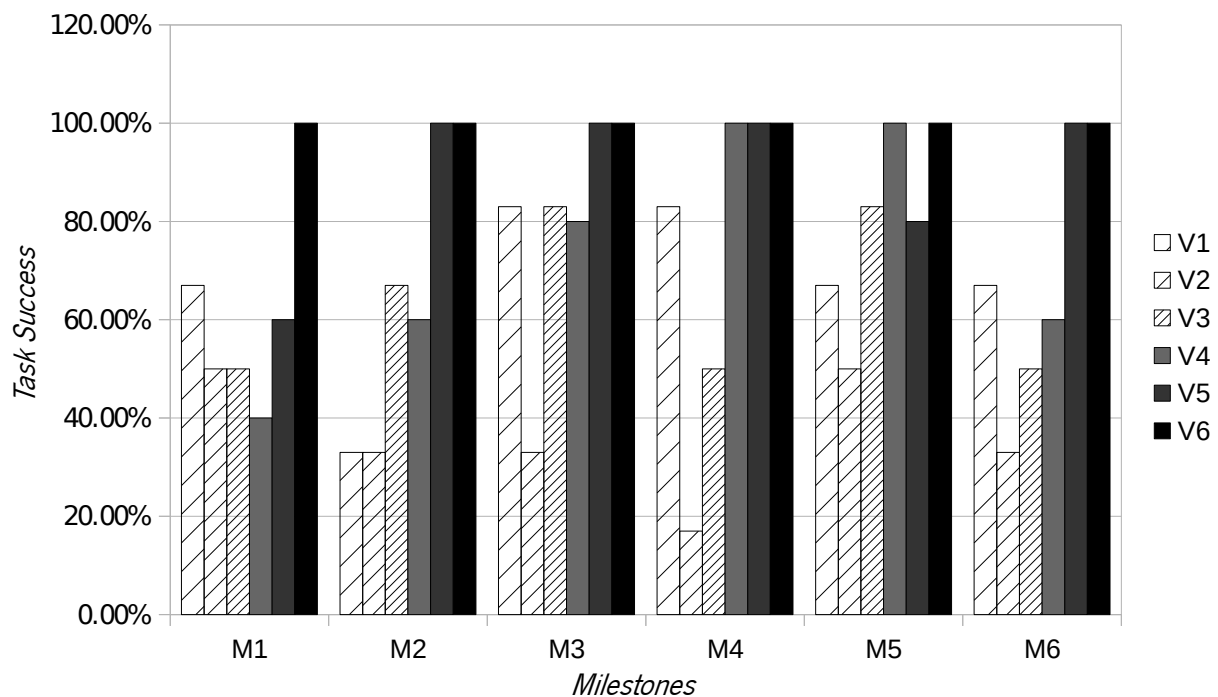


Image 17: Tasks Success Comparison.



Image 18: Lowest fidelity prototypes commands.

In addition to the interesting observations concerning low-fidelity prototypes, the tendency observed by previous authors persists: higher fidelity prototypes generally yield superior results. Consequently, it can be deduced that design teams are better equipped to evaluate performance metrics using higher fidelity prototypes. However, as previously demonstrated, the complexity of tasks and milestones significantly influences outcome results. For instance, upon isolating milestones with lower workloads for analysis, it becomes evident that these milestones exhibit higher performance outcomes, as seen in table 20. This finding

suggests that, while higher fidelity prototypes are generally more suitable for assessing performance metrics, there exists a nuanced scenario where design teams can evaluate these metrics with higher confidence levels, if the tasks are simple and with lower workloads.

Table 20: Milestones with lower workloads.

Milestones	V1	V2	V3	V4	V5	V6
M3	83%	33%	83%	80%	100%	100%
M4	83%	17%	50%	100%	100%	100%
M5	67%	50%	83%	100%	80%	100%
Mean	81%	33,3%	72%	93%	93%	100%

4. Conclusion

In conclusion, this study sought to address the research question: "Will different fidelities perform the same regarding the three aspects of usability: Efficacy, Efficiency, and Satisfaction?" The findings indicate that while different fidelity levels do not universally exhibit consistent performance across all aspects of usability, they may do so in specific contexts.

From the literature review, it is evident that efficacy and satisfaction were the primary fields of usability investigated, prompting this study to explore efficiency. The results suggest that low-fidelity prototypes can effectively validate efficacy, offering a cost-effective solution for design teams. For efficiency, higher fidelity prototypes tend to perform better, although medium-fidelity prototypes may suffice, particularly for tasks with lower cognitive workloads. Conversely, high-fidelity prototypes are recommended for assessing satisfaction, as participants demonstrate greater awareness of functionality and clarity, table 21.

Table 21: Correlation between fidelity and how to use it for usability assessment.

Fidelity Level	Definition	Field of Usability
Low-Fidelity	Conceptual Prototype or Design Models	Efficacy
Medium Fidelity	Conceptual and Functional Products or Design and Engineering Models	Efficiency – if the tasks demand lower cognitive workload
High Fidelity	Final Prototype and Design and Engineering Prototype	Satisfaction, Efficiency, Efficacy

In addition to the conducted study, this research has successfully achieved the initial objectives delineated at its outset. Firstly, the dissertation facilitated the acquisition of an extensive knowledge pertaining to user experience and usability. This knowledge acquisition facilitated the development of a comprehensive plan and methodology for designing a user experience assessment, encompassing the establishment of metrics for evaluation, the strategic delineation of testing environments—both physical and virtual—and the recruitment of participants. Finally, the culmination of this work involved the interpretation of the final product across its various developmental stages. This aspect of the research facilitated a deeper understanding of the selected technology — Selective Laser Sintering (SLS) — and entailed adept manipulation of diverse media and mixed-media formats to conceive the final prototypes. Through these endeavour, the research not only achieved its overarching goals but also engendered enriched insights into the chosen technological framework and the intricate design processes underlying prototype development.

5. Future Work

While this study yields intriguing results, there are opportunities for enhancement to refine the overall methodology. The data acquisition process employed in this study was rudimentary, potentially leading to inaccuracies in capturing reaction times and button presses due to imprecisions from the cameras in use. To mitigate these errors, the integration of an eye-tracking system linked to either the participant or the screen could provide a more precise insight into gaze deviations during simulations, facilitating the mapping of HMI interactions in relation to eye movements and enabling the precise capture of timing for these actions. Additionally, the inclusion of touch sensors on designated buttons or a motion tracking device would enhance the accuracy of button press data, allowing for the identification of specific areas touched by participants during tests. Furthermore, a critical concern pertains to the simulator environment and construction utilized in the study. The *SuperDrive SV250* interface, comprising a steering wheel and pedals connected to a computer with a 27-inch monitor, is primarily intended for the amateur video game market rather than professional driving simulation. Consequently, the driving experience deviates significantly from that of an actual car, as noted by some participants who remarked on issues such as overly sensitive steering and cramped pedal placement. Addressing these concerns, the incorporation of a more realistic driving simulator setup would enhance the ecological validity of the study, therefore improving the relevance and reliability of the findings.

Moreover, the outcomes elucidated in this dissertation pave the way for two prospective investigations centred on the derived results. Firstly, a study targeting low-fidelity prototypes could be undertaken with the principal aim of juxtaposing 2D and 3D solutions within a performance context. This endeavour seeks to elucidate whether cost-effective, 2D interfaces exhibit superior performance compared to their 3D counterparts. Also, it would be relevant to assess the dynamics of different resolutions and how does a low-cost and quick prototype be adapted to enhance the performance testing aspect of usability. Secondly, a supplementary study could be conducted to exclusively evaluate tasks with lower workloads within a performance scenario, thereby reinforcing the dataset obtained in this study. Such an inquiry aims to bolster the robustness of the collected data and provide further insights into the relationship between workload intensity and performance outcomes.

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Appendix 1 – Citroen Steering Wheel

It should be noted that the main steering wheel intended to represent the final prototype resolution ("post-production prototype"), required some rectification. Specifically, the acquired steering wheel was lacking the necessary airbag fixture, resulting in the complete exposure of this compartment, image 19.



Image 19: Original Steering Wheel

In order to address this issue, a 3D scan of the object where performed to obtain the real size dimensions of the faulting space, allowing to produce a custom cap for that specific location. The 3D scan technology used for this model was a Comet 6 8M (technical specifications see Appendix X), And the main focus was the central part of the product, image 20.

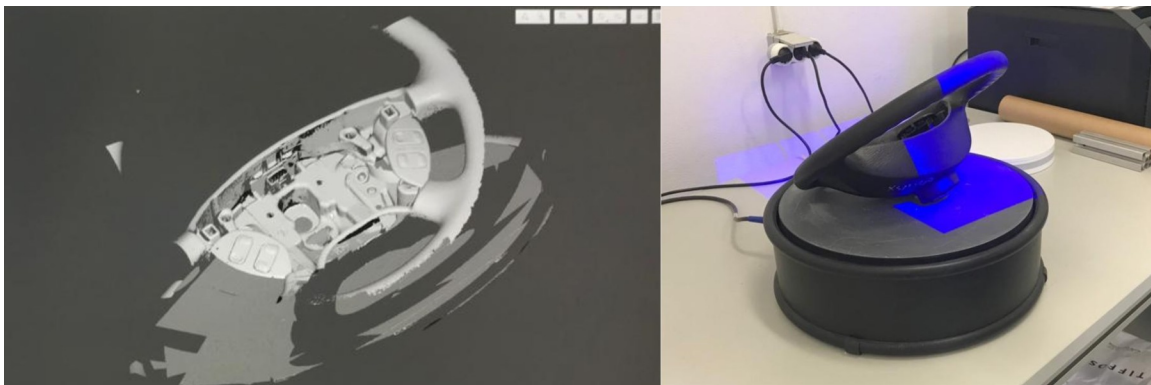


Image 20: Scanning process.

Upon completion of the scanning process, the following phase involved designing the missing component. Utilizing Computer Aided Design (CAD) software, the part was modelled with it focus in securing the part onto the pin holes at the extremity and achieving a smooth surface finish, closely resembling the authentic steering wheel as depicted in image 20. The iterative process consisted of three stages, the initial

iteration aimed to obtain accurate measurements for securing the part. It was noted in this iteration that the outer measurements were misaligned with the internal cavity. Furthermore, the main geometry exhibited surface irregularities. Consequently, the second iteration focused on refining the overall dimensions and geometry and to design a fixture for the pin holes, followed by applying the initial coat of paint. The final iteration concentrated solely on enhancing the paint finish, achieving a matte aesthetic consistent with the remaining sections of the steering wheel; image 21 depict the overall iterations. Notably, all prototypes were produced using Selective Laser Sintering (SLS) technology, with detailed technical information provided in Appendix 4.

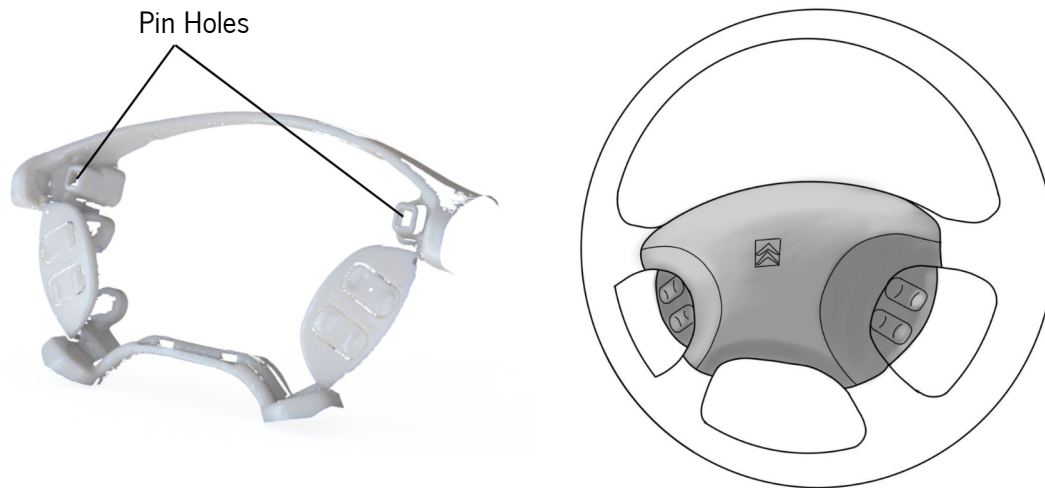


Image 21: Fixture placement and surface goal.

Apart from the production of the steering wheel cap, there were some considerations regarding the buttons information. As the demanded tasks includes answering and denying calls, it was noticed that the original steering wheel does not includes does features on the main HMI. Regarding this requirement, and because the electronic side of the product will not be used, it was decided to change the “MUTE – MODE” infography for the classic phone symbols, suiting the user experience activity better than the previous buttons, image 22.

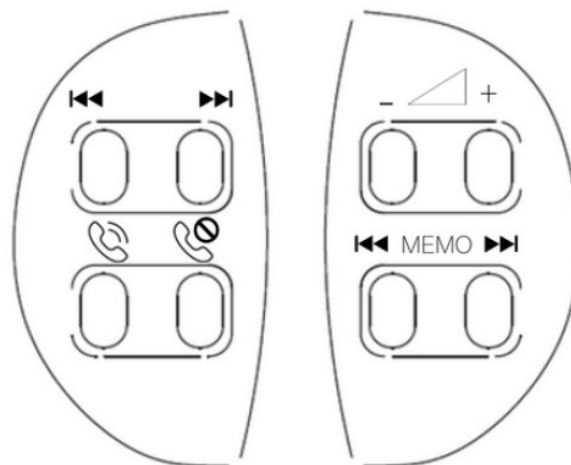


Image 22: Rectified button layout.



Image 23: Iterative process for the airbag fixture.

Appendix 2 – Best Selling Cars

In this appendix are presented the comparison between utilitarian cars, luxury cars and sport cars, in order to determine three steering wheels to compare the similarities in HMI's, table 22 and 23.

Table 22: Utilitarian Cars.

Author	(statista.com, 2023)	(Ashraf, 2022)	(Munoz, 2022)	(iol.co.za, 2022)	(sevendiesel.it, 2023)
Toyota	Corolla/ R4AV/ Carmy	Corolla/ R4AV/ Carmy		Corolla/ R4AV/ Carmy	Corolla/ R4AV
Honda	CR-Vx			CR-V	CR-V/Civic
Ford	F Series				F Series
Nissan		Nissan Centra		Nissan Centra	
Volkswagen			Golf		
Peugeot			208		
Opel			Vauxhall Corsa		
Fiat			Panda		

Table 23: Luxury Cars.

Author	(Loveday, 2022)	(car.com, 2023)	(carwow.co.uk, 2023)	(usnews.com, 2022)	(mordorintelligence.com, 2023)
Audi	A4 /A5		A8	A8	A6
KIA	Stinger				
BMW	2 Series		7 Series	7 Series	5 Series
Porsche	Tycan	911	Panamera	Panamera	Tycan
Lexus		RX		LS	
Mercedes		Benz C-Class/ Benz E-Class	S-Class		E-Class
Tesla		Model 3			
Bentley			Continental GT		
Volvo					S90

Table 24: Sport Cars.

Author	(Demandt, sem data)	(goodcarbadcar.net, 2022)	(autoexpress.co.uk, 2022)	(autocar.co.uk, 2022)	(Leslie, 2016)
Porsche	Porsche 911	Porsche 911	Porsche 911	Porsche 911/Porsche Cayman	

Jaguar	F Type		F Type	F Type	F Type
Mercedes	AMG GT				
Ferrari	Roma				
Audi	R8	TT	R8		TT
BMW		8 Series/Z4			2 Series
Polestar		1			
Caterham			Seven		
Lotus				Emira	
Chevrolet				Corvet	
Mazda					MX-5
Toyota					GT86

Appendix 3 – HMI Comparison

In this appendix are exposed the HMI's of the different steering wheels in analyses.

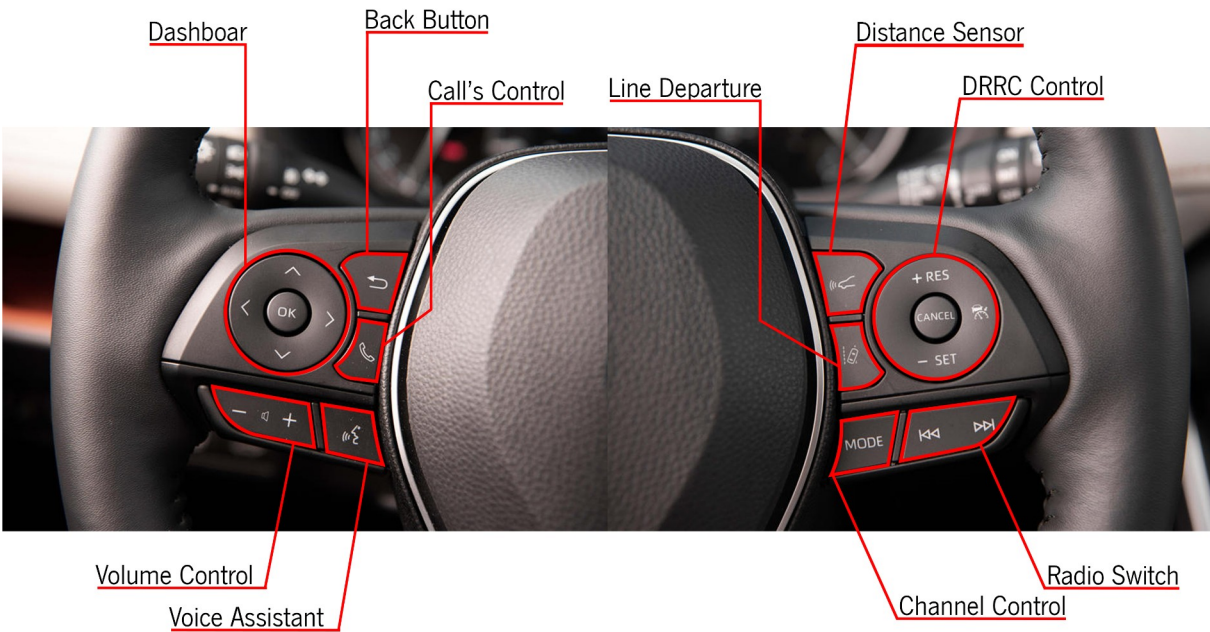


Image 24: Toyota HMI.

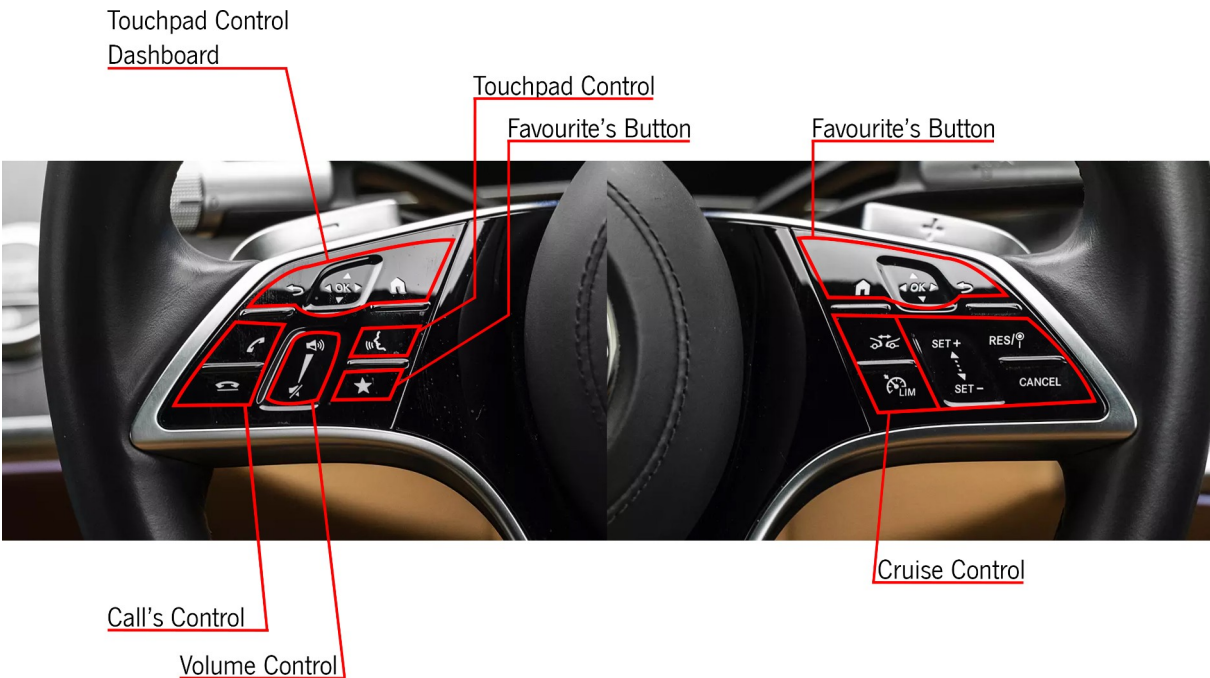


Image 25: Mercedes HMI.

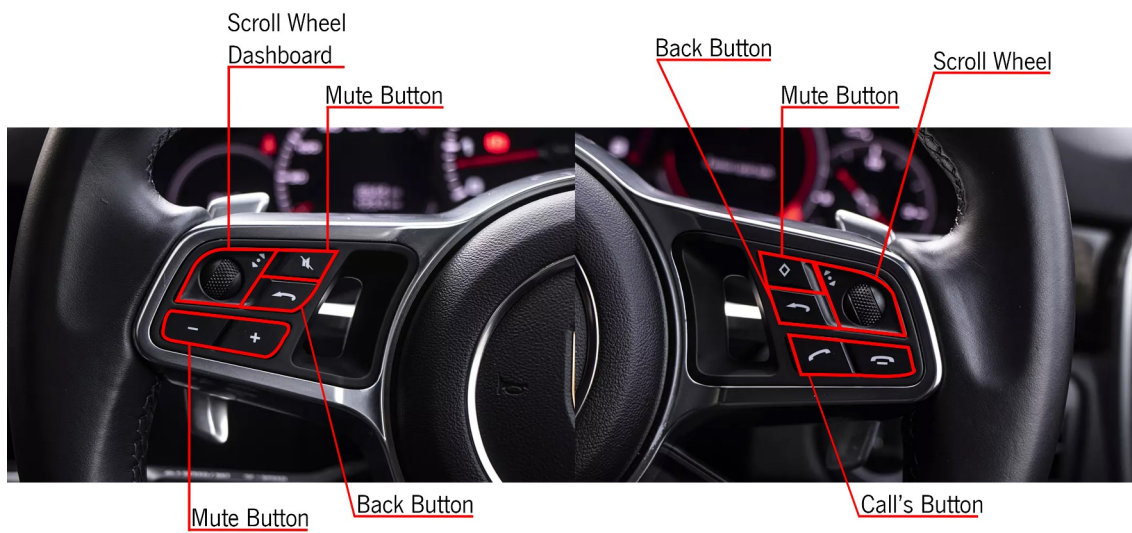


Image 26: Porsche HMI.

Appendix 4 – Selective Laser Sintering Process

Sintering Process

Selective Laser Sintering, or SLS for short, is an additive manufacturing process used to produce durable and strong parts in small batches. This technology is based on powder deposition, where a high power laser hits the powder bed and, layer by layer melts and solidifies the parts (sintering) until the printing bed is filled and the prototypes are done. In a simplified way, these machines are divided in three essential parts: the printing bed tank, the powder dispenser and the laser. As the printing goes, the machine deposits the powder on the tank and a recoater flattens the material on the bed, then the laser hits the powder and the bed recoils (between 50 and 200 microns) and the process repeats, image 28.



Image 27: SLS sintering

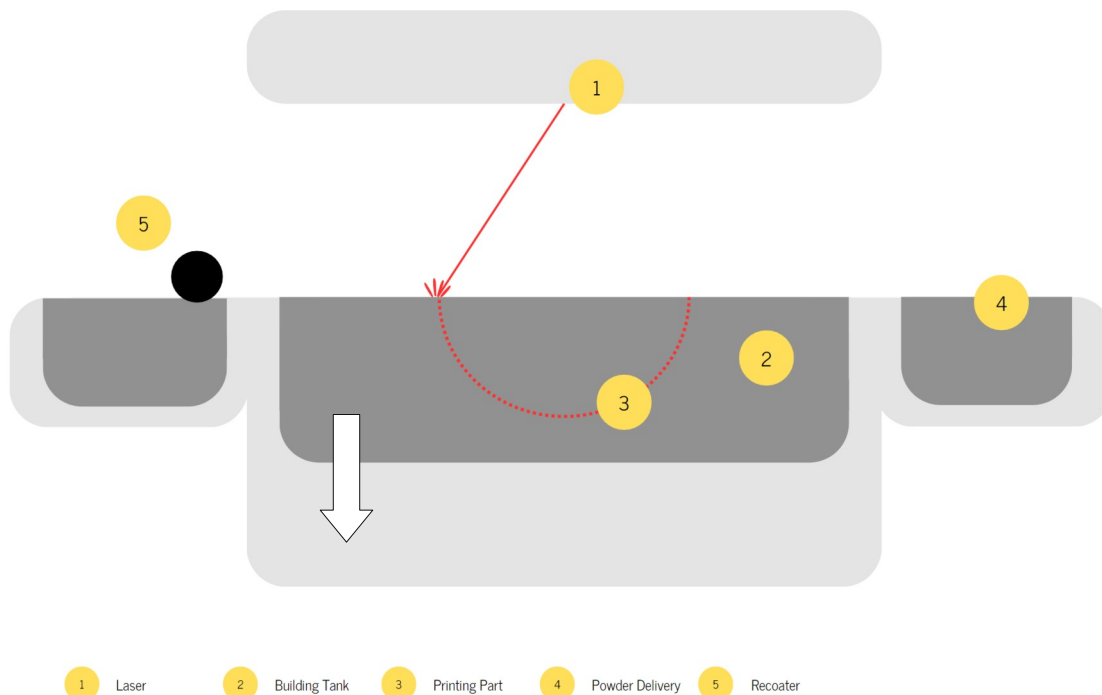


Image 28: SLS Process

Cleaning Process

This process as a great advantage, compared with other technologies, because it does not require support material. As the tank fills, the whole printing area is covered by the polymer powder, submerging the

printed parts, allowing the parts to self support. On the other hand, the end result is a compact block of powder that will need a cleaning process so each part can be separated and finished.

The cleaning process as 3 to 4 steps. First, the block needs to be turned apart, to separate all prototypes and give them a rough cleaning with a soft brush. After, the parts are fine cleaned with compressed air, allowing to clean the surface more vigorously and reach small areas that otherwise would not be possible. With the prototypes cleaned, there are situations where they can be sand dusted to achieve a certain surface finishing or to clean small holes that the compressed air cannot reach. All those processes are realized on closed chambers with protective equipment, as thick rubber gloves and masks. The final step is simply a final dust of, with lower pressure air, to clean some residual powder or sand present on the part. The final step is simply a final dust of, with lower pressure air, to clean some residual powder or sand present on the part.



Image 29: Cleaning Process Stages 1 - Unpacking; 2 - Brush Clean-up; 3 - Compressed Air cleaning; 4 - Low Pressure Air Dusting.

Materials

The selection of materials for this technology is mainly focused on Polyamide polymer (PA), either in its purest form or with addition of other materials, e.g. glass fiber, carbon fiber or aluminum powder. However, other raw materials can be used in SLS, as thermoplastic elastomers, polyaryletherketones or polystyrene. On table 1 is a list of materials and their respective suppliers:

Table 25: Materials and Suppliers.

Supplier Company	Raw Material
EOS	PA 1101; PA 2200; TPE; PAEK
3D Systems	PA 11; PA 12; TPE; Castable PS
Formlabs	PA 11; PA 11 CF; PA 12; PA 12 CF
Stratasys	PA 11; PA 11 EX; PA 11 FR; PA 12; PA 12 FR; PA 12 GF; PA 12 CF; PA 12 HST; PA 12 AF

Appendix 5 – Guidelines for the Driving Simulation

Lap 1



After the sign, on the curve, Answer a Call, Then Decline.



On the sign, Higher the Volume.



On the curve, Lower the Volume.

Lap 2



On the curve, Higher the Volume. On the sign, Lower the Volume.



On the sign Answer a Call, Then Decline.



Appendix 6 – Informed Consent

Declaration of Informed Consent

This document contains information about the dissertation "The Role of Prototypes on Product Design and Development" and the disclosure and confidentiality of the data produced from it, for the clarification of the participant. Please read the following information carefully in order to understand the details of your participation.

1. Objective of the study

The aim of this study is to evaluate the impact of prototype fidelity on efficiency in usability testing, specifically focusing on comparing the performance of participants in six different prototype resolutions, from paper to final product, for a Citroën Xsara steering wheel.

2. Description of the study, tasks and duration

Data collection will be individual and will take place in room EC2.11, located at the University of Minho. The tests will be carried out using the "Aspeto Corsa" driving simulator and the "Superdrive SV50" driving interface, on a representation of the Red Bull Ring National track. Each participant will be tested individually within their respective group. Participants will start by driving one lap around the track to get used to the simulator, followed by two laps to be considered for the study. During the journey, participants will be randomly asked to adjust the volume and answer or decline incoming calls. One camera will be used to monitor the amount of time participants look away from the road to press the appropriate buttons, and a second to confirm that they touch the appropriate button.

3. Risks associated with your participation in this research

It is expected that subjects with epilepsy may be affected, but it is not possible to test participants with this health problem.

4. Use of research results and confidentiality

No personal details of the participants will be divulged during the dissertation. All images and information collected will only be used for analysis and statistical purposes. The

images collected will be stored on the computer used for the study and promptly deleted at the end of the dissertation in question.

5. Rights of the research participant

Participation in the study is voluntary and the participant can give up at any time and leave the experiment without any harm to them.

If you wish to notify us of any aspect relating to the protection of your data, please do so in writing to the Data Protection Officer at the University of Minho (protecaodados@uminho.pt).

Thank you for taking the time to read this information and consider taking part in this study. If you wish to participate, you must sign and date the Informed Consent Form.

Consent (1st copy for the Participant)

I, _____ (full name of participant) have understood the information I have been given about the research that will be carried out. I have been given time to reflect on my participation and to ask any questions I may have about the study.

I am aware that, in accordance with the recommendations of the Declaration of Helsinki, the information or explanation given to me covered the objectives, methods, expected benefits, potential risks and possible discomfort caused by taking part in this procedure.

I understand that participation is voluntary and that I can withdraw at any time without giving any reason, without any prejudice.

I therefore consent to take part in the research procedure proposed by the researchers and authorise the data to be presented in a completely anonymous and confidential manner at public presentations, scientific conferences and publications.

Date: ____ / ____ / 20____

Participant,

Nome: _____

Signature: _____

The researcher in charge,

Name: Vitor Hugo Malheiro Pais

Signature: _____

For any clarification or questions about the information contained in this document, please contact: vpais@eaad.uminho.pt, thank you.