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VR Application for immersive prototyping for Industrial Designers

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RESUME : Dans l'industrie, la réalité virtuelle (RV) est surtout utilisée comme outil de visualisation immersif 3D de maquette de Conception Assistée par Ordinateur (CAO). Cependant, les technologies interactives comme la RV ouvrent de nouvelles possibilités créatives pour le développement de concepts and prototypes, en particulier pour les designers industriels. Cette étude examine l'utilisation de la RV comme outil de conception et d'idéation dans les premières étapes du processus de design en utilisant la modélisation 3D and le croquis en 3D. Dans un premier temps, une analyse comparative a permis de donner un aperçu de quatre applications commerciales actuelles pour créer des volumes et croquis dans des environnements immersifs 3D. Les conclusions de cette analyse permettent de déduire des besoins et d'identifier les outils essentiels pour modéliser en 3D et faire des croquis en RV. Ensuite, une première session de test avec des participants a permis de mesurer l'expérience utilisateur de chacune de ces applications. L'étude a débouché sur une application interactive pour la transmission d'idées en RV visant à déterminer si cette technologie peut améliorer la créativité, la perception des formes and réduire le temps nécessaire au designer industriel pour créer, visualiser and développer des prototypes. En dernière partie, la solution développée proposée a été testée pour évaluer si l'expérience utilisateur a été améliorée, puis elle a été comparée avec un logiciel de modélisation 3D et un logiciel CAO lors d'une seconde session avec participants.

MOTS CLES : Réalité Virtuelle, Design, Prototypage Virtuelle, Interaction, Dessin immersif, modélisation, croquis, 3D.

Abstract

In industry, Virtual Reality (VR) is mostly used as a 3D immersive visualisation tool. However, immersive technologies like VR open new creative possibilities for concept development, especially for industrial designers. This study investigates the use of VR as a design tool in the early stages of the design process by using three-dimensional modelling and sketching methods. At first, a comparative analysis offered insights on four current commercial applications that exist for immersive sketching and the creation of three-dimensional shapes in VR, which then could be used to derive a requirement's catalogue. Moreover, an experiment with participants was conducted to measure the user experience of the selected applications. Evaluation of the advantages and limitations of industrial designers who use VR as a content creation tool was conducted. The study resulted in an interactive 3D modelling and sketching application in VR. Investigation of immersive design tool for improve creativity, perception of scale and reduce the time needed by the industrial designer to create, visualise, and develop concepts was made. In the final part, the newly developed application was tested with participants following the same procedure as with the commercial application in a second session. Lastly, all VR applications were compared to desktop-based Computer-Aided Design (CAD) applications.

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1 Introduction

1.1 Problem statement and motivation

During the design process, products, equipment, and installations are tested with physical mock-ups and require expensive development time to be reliably manufactured (Heufler, 2012). Thanks to VR and digital mock-ups, time and money can be saved (Berg & Vance, 2017). Since communication between people can be improved thanks to VR, use cases are found in various fields such as military, entertainment, education, industry (Berg & Vance, 2012). Vehicles, aircraft or boats are complex products, and their development involves a large number of actors from various fields. Mock-ups are the links between these stakeholders. Unfortunately, physical mock-ups present many deficiencies from the perspective of costs, time and service (Fillatreau et al., 2013):

- High costs since components must be manufactured, assembled and decorated.
- High time consumption since there is a need to manufacture the prototype.
- Ongoing development since there is the possibility that a newer version of the product is already available while a prototype is manufactured.
- Maintenance for physical mock-ups.

Therefore, there is a need for new digital tools in the design office of companies in manufacturing industries. With the use of virtual and interactive environments such as Powerwall[1], CAVE[2] (Wilson & D'Cruz, 2006) or Head-Mounted Displays (HMD)**,** new collaborative work methods bring people with or without technical background together (Kan et al., 2001). Moreover, design concept iterations can be improved by VR with the use of 3D models displayed at real scale and interactive features. For instance, VR long-distance and multi-user cooperation can be used. The use of innovative technologies with an immersion in a 3D virtual environment offers designers a new tool to communicate, ideate, evaluate and interact with the product and create new concepts with a different workflow than conventional design methods (BMW, 2018). VR offers designers the ability to immerse themselves into the 3D model or sketch and solve the 2D visualisation and spatial issues experienced with Computer-Aided Design (CAD) and 3D modelling applications. Besides, to reduce the delay between the early stage of designing products and its sale, companies want to innovate and

[1] Stereoscopic 3D wall with a system of rear projection or front projection with one or multiple projectors.
[2] Immersive virtual reality environment with between three and six projectors directed to the walls of a room-sized cube.

being able to get first ideas more quickly and with more details to limit mistakes of conception and manufacturing (Berg & Vance, 2017).

1.2 Objectives of the thesis

The goal of this thesis is to build a VR application in which a user can develop concepts and variants by using sketching and 3D modelling tools. Evaluation of commercial 3D modelling and sketching solutions to the current market will be conducted to evaluate the usability and to do modification on the developed VR design application. The developed VR design application will then be evaluated with participants thanks to usability tests. The conclusion will be drawn on the viability of using VR as a design tool based on the comparison of the newly created VR application with commercial VR applications and desktop-based modelling applications. The following questions are considered during the development of the VR design application for industrial designers:

1. How can VR be incorporated into the design stage?
2. What advantages does VR applications (i.e. the developed VR design application) offer for industrial designers?
3. What are the limitations of such VR applications?
4. Does VR increase creativity for industrial designers while creating 3D models?

1.3 Methodology

This report is organised in 5 main parts.

1. The first part focuses on the design phase and compares current methods that are used in different industries at the early stage of the design phase.
2. The second part focuses on a study of different solutions for creating and manipulating geometries and strokes in VR. A literature review is conducted on how VR is currently used for CAD, 3D modelling, and sketching.
3. The third part concerns the first iteration. It includes research and identification of current commercial VR design applications for sketching and CAD that are available in the market, which allows creative concept generation differently in a 3D virtual environment. First modules are developed as an output of this first analysis.
4. The fourth part focuses on tests with participants (n=16) to evaluate existing commercial VR design applications. VR design applications are selected that manage 3D objects modelling and sketching in a 3D environment. System Usability Scale (SUS) and functionality questionnaire are used for the evaluation. According to the SUS, a score above 68 is considered above the average, and anything below 68 is below average. Each item is a statement (positive or negative), and a rating on a five-point Likert scale from ‘Strongly Disagree’ to ‘Strongly Agree’ (Likert, 1932). Parameters like the time to complete a task (simple 3D models to recreate), a number of questions asked, and feedback are considered.

   The feedback and results of the tests with participants function as a requirement catalogue. They are used as a basis for the development and improvement of assets and functionality to create concepts and variants.
5. The fifth part is the evaluation and subsequent optimisation of the developed application. The tests with the participants are conducted for this application and desktop-based 3D modelling applications. The same method as in part 4 is used.

1.4 TUMCREATE

TUMCREATE is a research institute that focuses on the improvement of Singapore's public transportation, mainly on the development of an electric autonomous public transport system. The mission of TUMCREATE is to seek the ultimate public transport system with high comfort and positive travel experience, including human-centred system, environmental system, urban system and energy system (TUMCREATE, 2019). Researchers and engineers from the Technical University Munich (TUM) and Nanyang Technological University work together and are funded by Singapore's National Research Foundation as part of the Campus for Research Excellence and Technological Enterprise (CREATE).

The central concept developed by TUMCREATE is DART (Dynamic Autonomous Road Transit). It is a system that would supplement Singapore's public transport by filling the 'gap' between the rail-based high-capacity MRT (Mass rapid transit) system and the slow, low capacity but densely distributed, road-based bus system.

Since 2016, six multidisciplinary research teams work together. This master's thesis is conducted in the Design for Autonomous Mobility (DAM) team. The role of DAM is to design Autonomous Vehicles (AVs) for public transport and their related infrastructure (e.g. stations) with a focus on users' needs. The research areas of DAM include:

- The development of the vehicle's exterior and interior.
- The development of transit hubs and stations including future dynamic guidance systems.
- Human Factors for the development of a fully autonomous public transport system.
- Human-machine interfaces for passengers, pedestrians and other road users.
- User perception and acceptance.
- The usage of VR during the stages of the design process.

DAM investigates the advantages of new tools like VR and pedestrian simulations that are not yet widely used within the designer community (Stadler et al., 2019). The goal is to investigate the impact VR can have on the design of future mobility concepts and which features of DART can be designed within VR.

2 The Design Phase

2.1 Definition of the design phase

VR is known as a reliable tool for industry 4.0[3] and allows product manipulation to accelerate design iterations/refinement and avoid mistakes while manufacturing (Mujber et al. 2004). Errors of conception are reduced from the design to the maintenance phase of the product. VR can be implemented at every step of the product life cycle (Blümel et al., 2004) and find different use cases applied to various stages.

The thesis focuses on the design phase in the early stages where two use cases, 3D modelling and sketching are identified in the industry (Figure 1). The primary usage targets the design and reviews of shapes, textures or ergonomic aspects (Barbieri et al., 2008). Secondly, modelling and sketching are used for the design phase for creating and manipulating 3D objects and environments while immersed in VR. The recent implementation of VR for such applications offered the potential to re-evaluate the design process and open new opportunities for businesses to design, manufacture, market and maintain products. Arroyave-Tobón (2015) identified that it is essential to use a tool such as VR during the early conceptual phase and that influences the quality and cost of the product as well as its time to market.
Moreover, it provides a first evaluation of ergonomics and scale before the production phase. Although VR does not offer enough precision with the resolution of displays, it can be an interesting tool in the early stage of conceptualising (Kiyokawa et al., 1998). Before detailed modelling, the creation of 3D primitives and rough outlines of the product in VR as the first step in the design phase is investigated in the present study.

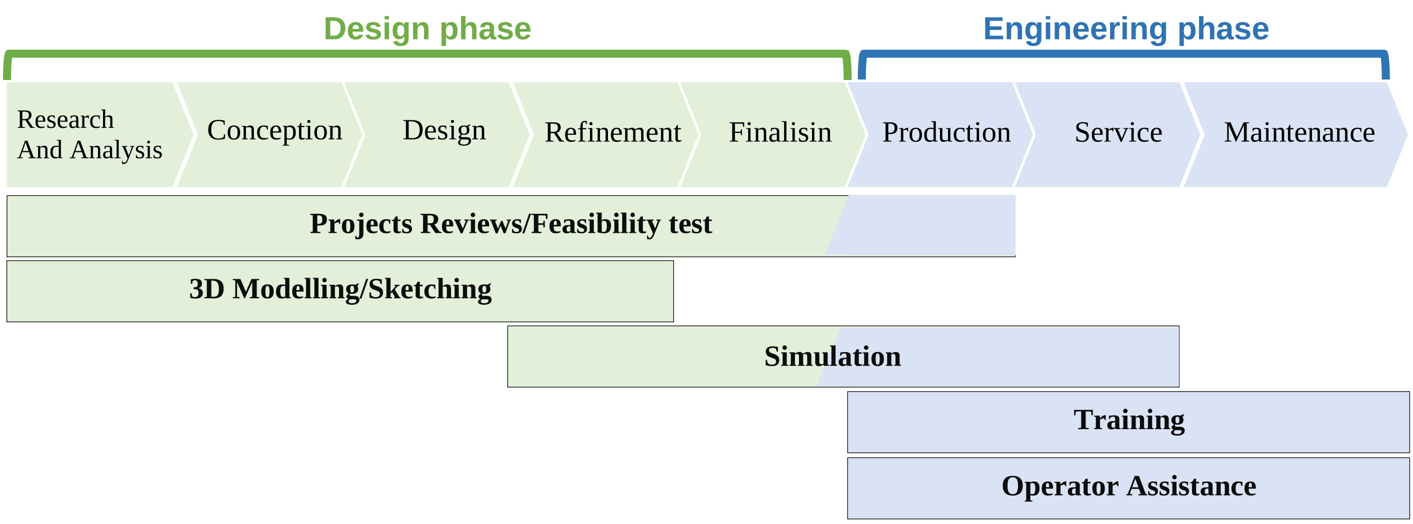


Figure 1: The different phases in the product life cycle where VR can be used

[3] Industry 4.0 refers to the 4th Industrial Revolution which aims to be interconnected and communicating by introducing digital technologies.

2.2 Methods for creating, evaluation and communicating design

Techniques for creating, evaluating and communicating concepts during the design process are continuously evolving. CAD has been a game-changer in the field of design and can refine the way designer work and collaborate with others (Fuh & Li, 2005). The first phase of the product life cycle and most importantly, at the early stage of product design, is almost entirely digitalised nowadays (Zhou, 2013). Therefore, CAD tools are essential for any industrial company (The Talley Group, 2012). Several alternative methods for evaluating and communicating design proposals exist such as sketch drawing, tape drawing, 2D CAD, sketch of physical model, physical prototype, 2D render from a 3D model and VR. VR technology is the one evaluated in this thesis. Table 1 highlights the advantages and disadvantages of each one.

Table 1: Comparison of methods for evaluating and communicating design decisions (Stacey et al., 199), (Dong & Agogine, 1998), (BMW group, 2018)

Method-technology	Advantages	Disadvantages
Mental imagery[4]	Very fast	Limited detail, accuracy, realism cannot be shared
Sketch drawing	Quick	Low detail, low accuracy, moderate realism
Tape drawing	Quick, real scale	Low detail, low accuracy, moderate realism
2D CAD	Accuracy and detail, fast to adjust and draw	Limited 3D information, required technical skill to be read
Sketch physical model	Facilitates group discussions, quick	Limited realism, hard to update
Physical prototype (clay, foam)	Facilitates group discussions, realism	Hard to update, time-consuming
2D render from the 3D model	High resolution, High potential realism, shared easy	The restricted field of view
3D CAD	Can be edited quickly can move around freely	The visual field of view does not match with real-life, limited realism, not stereoscopic
VR	Field of view getting close to real life, head tracking, high potential realism, can move around freely, no linear workflow, size does not matter, allows to get inside the model, can be modified easily	Can be limited in terms of realism, low accuracy due to hardware limitations (Field of view, resolution), can be time-consuming.

[4] Mental imagery can be defined as pictures in the mind or a visual representation in the absence of environmental input.

2.3 The usage of VR within the design process

The needs are different for each use case and specific for each phase of the product life. Thus, the requirements for the design steps are the evaluation of the shapes at real scale, the review of materials, textures, and the modification and addition of components in real-time, the study of the feasibility, the study of ergonomics and assembly of complex products. VR in design reduces development time and physical prototypes, which can be a considerable improvement in the industry (Galvin & Levac, 2011). Problem-solving, as well as the communication of ideas, is accelerated due to the technology. For instance, in the nuclear sector (Orano, 2018), physical prototyping results in contaminated waste, dangerous for humans and the environment. The use of virtual prototyping became essential to manufacture with increased security for humans and the environment.

Besides the benefits of VR for real scale visualisation of digital mock-ups, this technology unlocks new possibilities and new interactions perspectives with 3D models. A variety of input devices can be used, such as haptic gloves with included force feedback[5] (Hosseini et al., 2018), texture feedback and heat feedback (HaptX, 2019) or haptic robotic arm and controllers like those of the HTC VIVE and Xbox. Hand recognition systems can also be used for real-life simulation gesture more naturally like the leap motion (Du et al., 2017).

[5] Haptic force-feedback devices provide the human operator with tactile cues, adding the sense of touch to existing visual and auditory interfaces.

3 VR Literature Review

VR is an evolving technology used across multiple industries and academic disciplines to empower decision-making in design, evaluation, and training processes (Berg & Vance, 2017). It provides a unique way to interact inside a three-dimensional environment. Current literature focuses on the technical aspect of how to communicate in VR more than systematise and quantify the use of VR today for the industrial designer.

3.1 VR and CAD

Technological advancements of HMDs have spurred public and industrial interest in utilising this technology for design applications (Smparounis et al., 2008). The real-time immersive 3D representation can support a new way to design and can lead to an improved spatial understanding (Bowman & McMahan, 2007).
VR offer advantages that CAD applications do not offer. First, in terms of interactions, the use of input devices allows interactivity in the virtual world. Secondly, VR is a real-time system which allows the user to navigate and interact in a none-static environment. Moreover, stereoscopic vision increases realism. With VR, navigation in CAD applications is not limited to regular isometric view anymore. The user can, for example, experience a car's interior in real scale.

But limitations exist, for instance exchange links of data from CAD to VR and VR to CAD are the main problems since they are time-consuming tasks. Metadata of the 3D model is lost during the conversion to VR that results in time-consuming tasks to keep the digital mock-up updated (Graf and al., 2002**).** Ideally, the data should keep information related to the 3D model, metadata (specificity of each piece), kinematics, the process, and documents to make VR a reliable tool for product development. The current difficulties for industrial companies to adopt immersive technologies are the lack of integration with the CAD applications in the product development process (Barbieri et al., 2008). This means that there is a need for skills and knowledge to manually convert the CAD 3D model to be usable in a 3D virtual environment in real-time. These tasks are time-consuming (Figure 3) and can involve monetary investment (Fillatreau et al., 2013); this justifies the fact that the minority of companies manages to implement immersive technologies as a part of their product development process. Figure 3 shows the different paths from the 3D modelling step to the design project review. Time-consuming tasks is the preparation of the model for real-time visualisation and simulation.

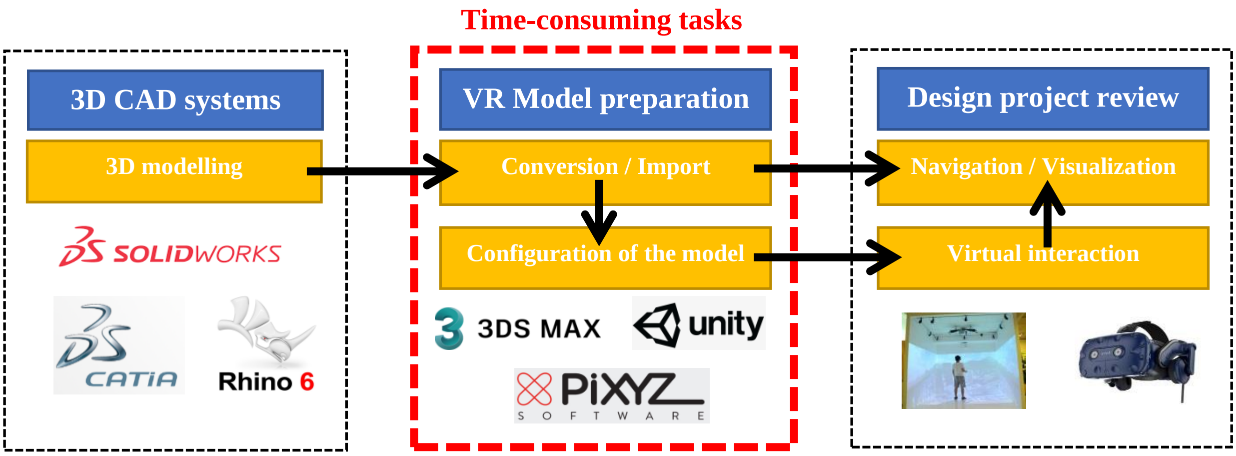


Figure 2: The current workflow of using VR in industry (Source: Own diagram)

Raposo et al. (2006) identified the problems regarding the visualisation of CAD models processed into VR models:

- **Low performance for complex models**. When it comes to loading extensive CAD data, the hardware is critical. This aspect tends to improve with technological advancements. The conversion of the CAD model to the VR model is usually complicated. The choice of algorithms is essential.
- **Lack of realism**. A CAD model does not have material or texture information associated with the object because for the majority of applications it is not necessary for the industry (Tovey, 1989). But it becomes essential when the user wants to visualise the CAD model in the most realistic way as possible. Texturing involves high complexity because a CAD model is not a 3D mesh[6] and not prepared to receive texture due to UV mapping[7].
- **Inadequate treatment of geometry**. During the conversion, the CAD model loses geometry and precision (Berta, 1999). Typical errors occur such as holes in the 3D mesh, inverted or unwanted polygons. In such a case, post-treatment is required.
- **Loss of semantics**. All development history of the creation of the CAD file is lost, and the metadata is not transferred at the conversion from CAD to VR as well.
- **One-way conversion.** It is not possible to reverse the changes after modification are done on the CAD model.

[6] A 3D mesh is the structural build of a 3D model consisting of polygons. 3D meshes use reference points in X, Y and Z axes to define shapes with height, width and depth.
[7] UV mapping is a technique used to ‘wrap’ a 2D image texture onto a 3D mesh. ‘U’ and ‘V’ are the names of the axes of a plane, since ‘X’, ‘Y’ and ‘Z’ are used for the coordinates in the 3D space.

Table 2: Criteria to take into consideration when visualising CAD in VR (Schilling et al., 2006)

Ø not important **+ important** **++ essential**

Criteria	**Importance for the design phase**
Shape accuracy	++
Transfer of physical material properties	+
Keep the CAD model structure	Ø
Transfer of behaviours physical laws	Ø
Texture quality	++
Animations quality	Ø
Real-time modification of the digital Mock-up	++
Collaborative work/virtual team	+
Interactivity with the 3D model	++
The possibility of visualising metadata	Ø
Ability to create annotations, take pictures, export a report	++
Portability	Ø

Today there are applications which offers to manage this important criteria's automatically. These turnkey (without the need for programming) industrial immersive VR CAD solutions make easier the decision-making process by replacing physical prototypes with an interactive digital mock-up allowing the use of large data visualisation. The applications are all available for HMDs such as the HTC VIVE as well as CAVE systems of various brands. Moreover, the applications enable collaborative multi-user sessions. IC.IDO, TechViz, PiXYZ, MeshroomVR, MiddleVR, E0Nreality, VREAD constitutes a selection of turnkey programs made for industrial companies that want to use immersive technologies.

- The application IC.IDO (ESI group, 2019) supports multi-CAD format such as CatiaV5, SolidWorks or Inventor and PDM[8] for quick process integration. The solution provides rebuilding kinematics links tools of the CAD model to simulate them in VR easily. The application is also a tool for analysis ergonomic and human factor when design operators workstations or verify accessibility for a work task (Peruzzini et al., 2017). Interactive project reviews prevent assembly issues from the design stage for Safran nacelles (ESI Group, 2016) by simulating realistic operating conditions in IC.IDO.

[8] Product data management (PDM) in application engineering is known as version control system.

- PiXYZ Review (PiXYZ Application, 2019) is enabling the transformation of this data and developed algorithms to reduce, tessellate and optimise the models without the need for knowledge in 3D modelling. This program is often used in the industry when the 3D CAD data must be prepared. Indeed, the raw CAD model cannot be displayed in VR in real-time. Thus, CAD file is transformed into 3D meshes, which are composed of numerous polygons forming a 3D mesh surface. This 3D mesh can be displayed directly in PiXYZ or exported and rendered in the 3D application or game engine like Unity 3D. Urbas et al. (2019) presented a method in which PiXYZ has been used to transfer product manufacturing information from a 3D model to display graphical presentation using immersive technologies.

All of these programs offer different functions. Some of them exclusively provide the possibility to visualise models. Some other more advanced tools enable the conduct of project reviews with multiple options such as taking measurements, photos, videos, edit a report of all the images and annotations taken at the end of the project review. Some of these options allow recreating mechanical links of the product and interact with the digital mock-up in the virtual environment to simulate different scenarios. This kind of application finds many use cases in the industry. The first case is the evaluation of the arrangement or the modification of a workshop or factory (Gong, 2017). Secondly, the immersive application can be used for the validation of maintenance scenarios when the verification of accessibility of different equipment is possible or dangerous (Gomes de Sá & Zachmann, 1999).
Furthermore, the use of immersive applications allows the verification of ergonomic aspects of workstations (Pontonnier et al., 2014). Moreover, the use of VR applications constitutes a communication channel as well with non-technical actors of a project. This supports and motivates discussions and decisions making for developers and other stakeholders (Galvin & Levac, 2011).

3.2 3D modelling interaction in VR

Modelling techniques can be adapted in VR and offer more intuitive manipulation (Zheng et al., 2001). Conventional modelling applications and CAD applications use complex UI[9] to achieve action to create or modify 3D shapes. This kind of interface cannot be reproduced in VR since 3D UI have to offer an intuitive mechanism for industrial designers to not overload the field of view or being too complicated (Vila et al., 1998). Only essential features can be implemented in a virtual environment, and the way to use them and interact with them must be redesigned. Current publications and studies focus on the technical aspect of interaction in an immersive environment. For instance, the Go-Go Interaction technique allows interaction of

[9] Everything designed into a device with which a person may interact. This can include display, screens, input devices.

the user with the virtual objects by growing the user's hands (Poupyrev et al., 1996) or ray-casting technique (Mine, 1995) with a light ray from the user's virtual hand.

Consequently, the user can select and manipulate the object as if he had it in his hands, it is a reliable technique to use for selecting the object that is not too small but can be subject to error when there are too many objects in a small space or are in movement. Direct manipulation is one of the most intuitive ways of interaction in VR (Tseng, 2018). This technique mimics the way that humans use their hands for interaction and manipulation. These studies conclude that direct manipulation tool for interacting is more accurate when the 3D environment is in movement or with a lot of objects.

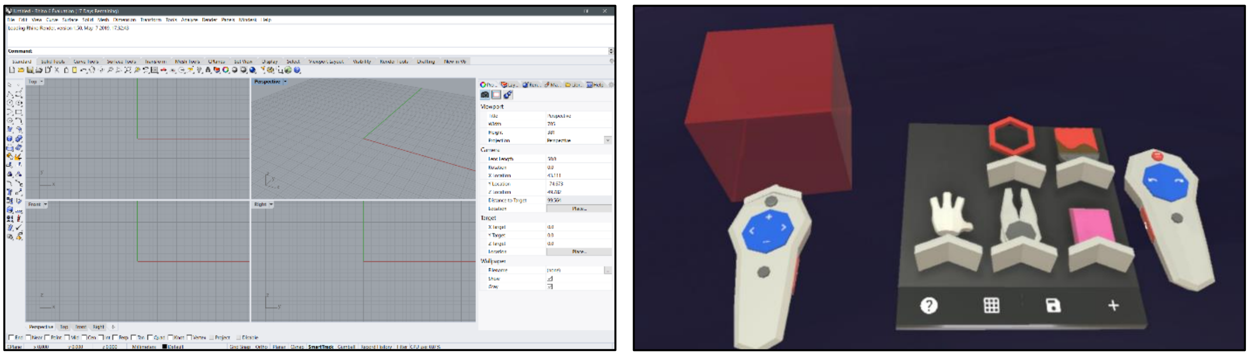


Figure 4: Rhinoceros3D user interface (left) and Google Block VR user interface (right)

3.3 Sketching in a 3D virtual environment

Sketching is a design method to visualise, communicate, prototype, and to tell a story. Today, with the rise of digital applications like photo retouching, 3D modelling or illustration, paper sketching tends to be less and less used (Veisz et al., 2012). New methods using VR open new ways of sketching by taking advantage of the third dimension in an immersive way.

Different sketching methods have been proposed in the literature and investigated by researchers. Arora (2017) present studies to analyse the human ability to draw freely in a virtual environment in 3D with and without a physical surface. Arova (2017) conclude that the lack of physical surface causes inaccuracies in VR drawing. In a second experiment, the researchers used visual guidance to evaluate if this can compensate for the loss of precision while sketching in VR. The result showed improvement in positional accuracy when participants had visual guidance available. Unconstrained by the two-dimensional screen, sketching in VR allows more freedom but only a few VR sketching approaches exist with or without a physical surface and with virtual strokes guidance (Arora et al., 2017). 3D fluid artwork using 3D brush tools constitutes a creative tool for sketching (Eroglu et al., 2018). Sculpting tools can be controlled by a 3D input device that allows the user to add and remove parts of the 3D mesh (Galyean & Hughes, 1991). Sketch-based modelling using reference imagery and freehand sketching can be used to create 3D models in VR (Jackson & Keefe, 2016). Multiplanes

(Barrera Machuca et al., 2017) provide the ability to the user to draw perfect shapes with the flexibility of freehand movement in the 3D environment. Some of the techniques described in literature use interaction by hand like Schkolne (2001) who present a surface drawing tool for designers. The path that is drawn by hand is directly realised as geometry in the application, providing a link between body and shape.

Other applications focus on CAD tools. Fiorentino (2002) developed a solution targeting the car industry to create curves and surface with a tracked glass tablet and a tracked pen. Users appreciate the simplicity of the tool with no need of mathematical skills to create surfaces even if they would like more functionality to finish the design.

The early stage of the design process is mostly dominated by sketching. VR tools allow designers to draw spatial concepts at the same speed as on paper (Zeleznik et al., 2007). The added benefit is the possibility to scale the VR sketches, more natural physical UX[10] patterns and inputs than conventional 2D design applications. Like 3D modelling to create quality models with traditional tools, it requires extensive training with complex user interfaces. A range of research focuses on the use of haptic-aided input techniques. Keefe (2007) simulate the tip touch feedback of a pen in their VR application while drawing with one or two hands in the air in VR. The researchers conclude that the feedback improves the accuracy of the user's 3D drawings.

3.4 Input devices

In industrial design, to physically evaluate the features and shapes of a product, interfaces are needed to interact with it (Zheng et al., 2001). With VR, this interactivity level becomes possible with input devices and a multimodal system, which involve touch, vision, and hearing of the user. Burdea (1996) concludes that adding 3D audio, haptic feedback, force feedback, and tactile feedback increases the realism of the simulation and improves the task completion time with reduced error rates and learning times. By using gesture-based technology for hands recognition like the Leap Motion (2017), selection tasks can be achieved more easily (Zheng et al., 2001).

A range of input devices are available on the market. Depending on the task, the right selection of input device is crucial since it can influence the immersion experience and the way the user interacts with the 3D environment.

[10] User Experience (UX) Design is the process of creating products that provide meaningful and relevant experiences to users.

a) Haptic gloves, b) HTC vive tracker, c) 3D mouse, d) XBOX controller, e) HTC vive controller, f) Haptic arm, g) Flystick, h) Leap Motion

Figure 7: Input devices for VR

Each controller or device offers an own set of advantages and disadvantages. Trackers like VR controllers or CAVE controllers entail high precision thanks to cameras that are placed around the user. This allows free movement within the tracked area.

Haptic feedback gloves have the advantage of tracking all fingers and their positions, and thus, hand positions or movements can be recognised. There are different technologies used for feedback gloves, for instance, the company Haptx offers one of the most advanced solutions allows designers to touch and interact with the virtual prototype throughout the product design process before building the physical prototype. This technology finds use cases in the automotive industry (Nissan, 2019) where the design phase of a car is a long, expensive process that takes years from the first sketch to sitting in the driver’s seat.

3.5 Collaborative design

Projects are often developed in teams. Feedback from colleagues and other parties are essential for the exploration and evaluation of alternative concepts. When doing collaborative design, a common understanding of the proposal is crucial; companies often collaborate with teams located at different places to develop a common product (Smparounis et al., 2008). Mental imagery cannot be shared and hard to communicate verbally, although sketches can help, at least in early design stages. Creating accurate 2D and 3D CAD drawings for accurate communication becomes increasingly more critical as the project develops (Veisz et al., 2012). When a project involves people without a technical background or unfamiliar with the project, 2D and 3D CAD find limitations. This may not be the best way to exchange information between departments inside a company due to the disadvantages seen in Table 1 because people can have difficulties to understand information such as scale, topography, dimension or materials with traditional 2D and 3D supports who require technical skills. However, the use of the VR tools presents a more efficient way to quickly share ideas, although it can be more time consuming to prepare and optimise the CAD model for real-time visualisation in VR.

The use of a PowerWall or a CAVE system presents the advantage of allowing several users to share the same field of view by wearing glasses for 3D stereoscopic render. Usually, one person is in charge of the navigation and the interaction inside the virtual model. A problem in communication arises when watching a scene using an HMD. Only the person wearing the VR headset sees the virtual environment with a 3D immersive rendering. Thus, this person must convey information with others with a simple 2D video feedback and talking.

VR commercial application publishers nowadays offer the possibility to conduct multi-users' collaborative session (Pacheco et al., 2018) between either multiple HMD or HMD with a PowerWall or a CAVE system in long distance. VR has been identified by Smparounis (2008) as an effective way to communicate ideas and collaborate more effectively.

3.6 Conclusion of the literature review

VR is an excellent tool to ideate and design new products. Currently, VR is mainly used by the engineering and design departments of companies as a solution for the evaluation of design choices and the validation of concepts and prototypes (Bordegoni & Rizzi, 2011). VR has the ability as a decision-making tool which allows fast and low-cost modifications in an immersive, real-time and interactive environment for project reviews (Schilling et al., 2006). But VR needs a conversion of data of both native application and middleware.

However, Dorta (2001) points out the negative effects of VR in design:

- **The aesthetic aspect of the project to the detriment of the concept:** the designer can focus only on the design of the product due to the use of the technology and ignore all the other essential aspects in terms of cost, functionality and all the elements that rely on haptic feedback VR.
- **The distance from reality:** since the work is realised in a virtual world, if everything is done with only this tool, the designer can be distanced from the reality of the project and the problems to solve.
- **The designer's dependence on the machine:** the visual render of VR can create a dependency of the designer on the computer in the design process which can affect their comprehension and spatial skills in the analysis or the conception of design ideas.
- **The possibility of altering the reality of the project:** VR can also be used to change and distort the reality of the project and even the opinion of the client or project user.

To summarise, the strengths of VR are the perspective view and notion of scale in addition to simplifying the workflow. The main weaknesses are the lack of accuracy and discomfort can be experienced during a long period of exposures to VR (Boas, 2012). But its open new opportunities concerning the manipulation in a more intuitive way and a user-centred design approach (Peruzzini et al., 2017). The threats despite the expected benefits could be the resistance of designers to change their work methods to this new technology and additional costs involving a VR compatible computer setup. In order to get a better overview of the current market and possibilities offer by current commercial applications, a comparative analysis of chosen commercial VR design applications will be conducted in the next chapter.

4 Comparative analysis of commercial VR design applications

4.1 Categories of applications

There are a range of commercial solutions available on the market to communicate ideas and create design concepts and variants. They can be classified into five categories:

1. Storytelling applications

VR improves immersive entertainments and offers unique opportunities since technology can enable immersive experiences that traditional media devices cannot achieve. The feeling of being there inside the world has not been possible before immersive technologies. It has always been a distance between the viewer and the screen; this is the idea behind a storytelling experience. Disney Imagineering has developed an attraction using VR (Pausch et al., 1996) to study technology as a new medium to tell stories. The researchers conclude that this technology procures the same level of emotion as traditional movies and assume that VR is a satisfactory technology that lets producers or authors focus on authoring. User-controlled viewpoint must use visual and sound tricks to make know where the action is going to happen. Tvori (2016) is a program that lets you create and animate stories and prototype ideas in VR. It has been introduced in 2016 and focus on simplicity and speed of animation created in real-time. According to the company, animators do not need prior knowledge of any 3D application to begin using Tvori.

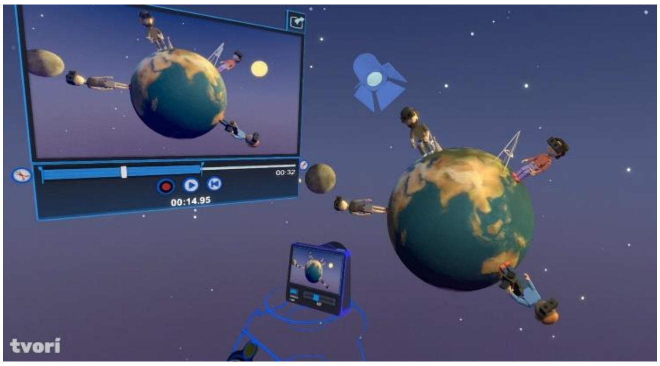


Figure 8: Screenshot of the application Tvori

2. Visualisation applications

The usage of immersive technologies such as VR for 3D visualisation in the design has increased. Autodesk VRED (2019) is often used in the automotive industry to create an interactive 3D presentation of prototypes and design reviews. It is a real-time photorealistic design visualisation application that enables users to prepare and presents 3D designs. Implementation of 3D models and CAD data in VR allows users to see the 3D stereoscopic render of any part in real scale and interact with it in real-time. Technicians, engineers, and operators can test the reachability of equipment, evaluate the feasibility and train complex maintenance operations (Gomes de Sá & Zachmann, 1999). 3D visualisation applications can be used as tools for assessing design concepts and variants. These applications allow designers and engineers to experience products in an environment, close to real-life conditions before physical prototyping or actual mass production. With the improvement of applications and hardware, visualisation applications become more precise in the way that they retransmit the materials, lighting and environments. This increases confidence in decision-making about the design solutions.

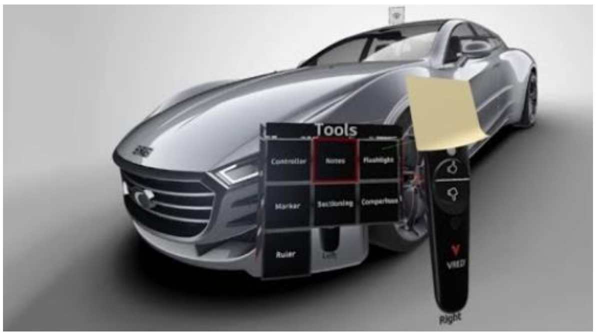


Figure 9: Screenshot of the application VRED

3. Sculpting applications

Tools like Unbound Alpha (2018) present VR sculpting tools. It allows users to modify 3D meshes from a simple 3d primitive by adding and remove 3D pixels called voxels. Usually, the user starts his/her artworks from a simple virtual sphere. These programs use different methods that can also be found in regular 3D computer sculpting applications like ZBrush (1999). There are tools like a colour spray that lets the user spray 3D pixels voxels in space. Models can be smoothened, refined, and details can be added as needed.

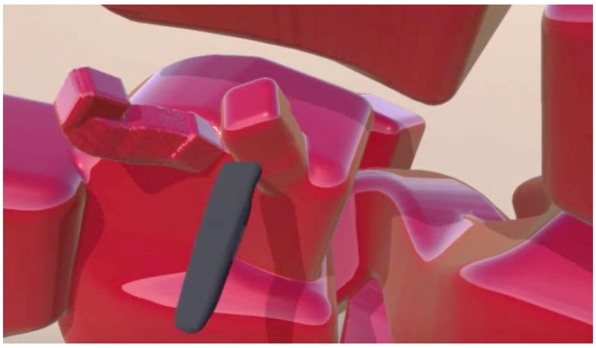


Figure 10: Screenshot of the application Unbound Alpha

4. Painting applications

VR already has a significant impact on the domain of art. Applications like Google Tilt Brush (2016) attracted attention recently (Ekströmer et al., 2018). Painting in VR allows the artist to benefit from all the advantages offered by this technology like the possibility to walk around the artwork and to view its different angles. This kind of application provides a full spectrum of brushes and tool options to change sizes, t shapes, and colours of art pieces. All of this is introducing new possibilities in art-making without being physically constrained or bound to two-dimensional technology.

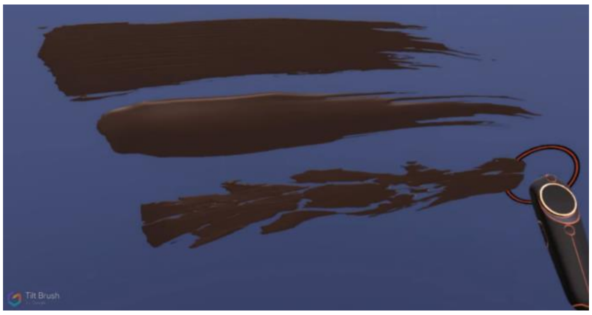


Figure 11: Screenshot of the application Tilt Brush

5. Modelling applications

Similar to the other categories, VR enhances the ability to create models by being able to see it in full-scale. The user has a better idea of what the final product will look like. 3D classic modelling applications are complicated and time is needed to understand the logic of the program. 3D content creation in VR aims to overcome this issue. Tools like Google Blocks (2017) allows everyone to start making 3D models very fast, and the key to achieving that is the interface. Unlike desktop-based CAD applications that give a standardised set of tools and functions to create, VR modelling applications offers an approach that leaves the user more freedom for creating primitives in the virtual space. The main goal of these applications is to democratise 3D modelling regardless of the experience level. This is the interesting category for the experiments in this thesis, the evaluation of four commercial applications of this category is conducted: Google Blocks (2017), Microsoft Maquette (2019), Mindesk (2016) and Gravity Sketch (2017).

Figure 12: Screenshot of the application Google Blocks

4.2 Presentation of selected tools

Google Blocks (2017) and Microsoft Maquette (2019) have been selected for the comparative analysis since both of these applications are freeware. Google created Blocks in 2017 and offers a simple, user-friendly interface that can be learnt quickly. However, Google stopped updating this application but keep fixing inconsistencies and bugs once encountered by the community. Microsoft officially launched its VR design application, called Maquette, in 2019.

On the other hand, two paid solutions have been selected. First, Gravity Sketch (2017) which cost 30 Euros for the basic version. This application is already used in design departments, especially in the automotive sector. Designers from FORD use Gravity Sketch to create more human-centric designs to improve collaborative real-time decision-making when designing new vehicles (FORD, 2019). The solution offers a range of parameters to customise brushes and sketching tools. Different ways for drawing are available such as freehand in 3D or creating curves with control points. Additional features such as a mirror plane and the possibility to add reference images and 3D models are available in this application. Gravity Sketch can be used for both sketching and modelling in VR.

The second commercial VR application is a plugin inside the 3D modelling application Rhinoceros3D, Mindesk (2016), which costs 2000 Euros per year as a commercial licence. Everything that is created in the VR application by the designer is automatically reproduced in real-time in the desktop-based application. It has been developed to answer one of the problems when using VR with desktop-based CAD applications, which is the lack of direct real-time integration of modifying objects in CAD application simultaneously.

Each of the applications mentioned above offers a different approach to create shapes and to sketch. Input mapping on the HTC VIVE controllers differs on each application. One similarity that all of the applications above have in common is the way of moving inside the 3D. In all applications, the grip buttons of both input devices are used to resize, rotate and move inside the 3D scene.

4.3 The development of the VR design application

After getting an extensive insight on commercial VR applications that are available on the market, it has been decided to combine aspects from the following applications: Google Blocks, Microsoft Maquette, Gravity Sketch and Mindesk. After testing each application, a comparison was made. Below, the comparative table 3 shows the chosen VR design applications summary features.

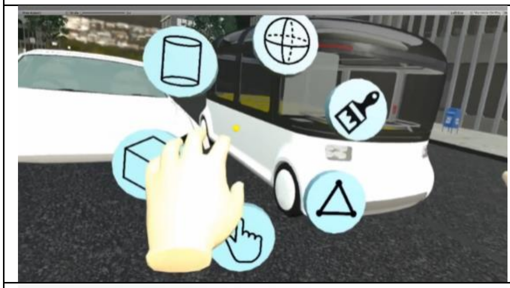
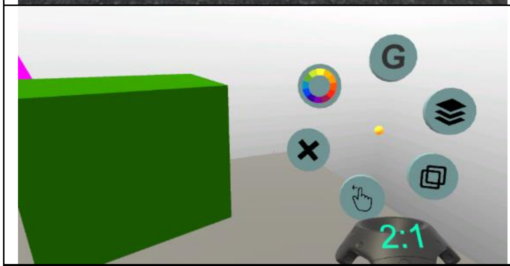
Table 3: Comparative table of chosen VR design applications

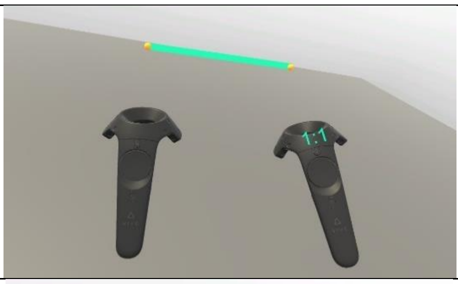
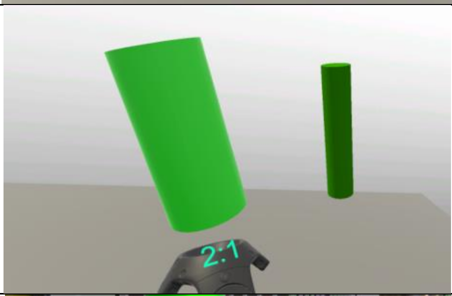
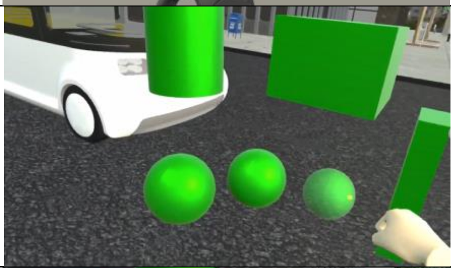
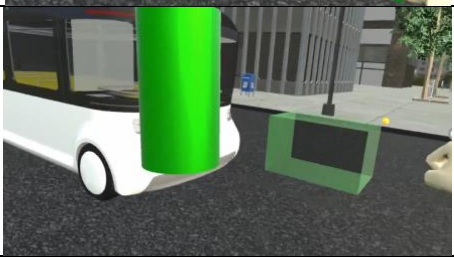
	Google Blocks	Gravity Sketch	Mindesk	Microsoft Maquette
Type of application	Standalone	Standalone	Rhino and SolidWorks Plugin	Standalone
Price	FREE	US$24.99> Limited version US$29.99/month> PRO US$99.99/month> Studio version with import/export to Rhino	US$1,999/year	FREE
Release date	06-juil-17	02-août-17	2016	janv-19
Design Tools				
Surface tools	shape deformation vertices, edges and faces.	Surface creation, Revolve,	Patch, Loft, Revolve,	Brush,
Volumetric tools	Extrude faces, stroke,	free volumetric shape, Offset, ink, curve,	extrude faces, Offset,	
2D tools			Spline creation, Polyline creation, Knots (control points modifier),	
3D Primitives creation	Cone, Sphere, Cube, Cylinder, Torus	Cone, box, cylinder, sphere, torus, pipe	Cone, Cylinder, Box, Sphere	Cone, box, cylinder, sphere, torus, pipe, + 40 shapes
Transform tools	Select, Grab, Scale, Copy, Group selection, reshape, subdivide, eraser, invert,	Select, Grab, Scale, Copy, Group, reshape, subdivide, eraser (object or face).	Scale, Copy, Move, Rotate, Delete,	Scale, Clone, Move, Rotate, Delete, Grouping,
Measurement tools			Distance,	
Visual tools	Paint (object or face)	Paint tools with different texture effect		Paint tools
Other tools			Reference System modifier,	Colouring tool
	Navigation tool			
Method	Grip buttons		Grip buttons	teleportation and with Grip buttons
	Precision Tools			
Geometric Constraints	Snapping objects, edges, vertices, 3D meshes	Snapping tool on points, curve, surface, vertices, 3d grid, 3D mesh Smart tracking mode,	Snapping tools on points, curve, surface, vertices, 3d grid. Smart tracking mode,	snapping tool on the surface
Magnetic Guidelines	on surface, vertex, edges, middle face	X, Y, Z axes, XY, YZ, ZX planes,	X, Y, Z axes, XY, YZ, ZX planes,	on surface
Lock Constraint		onto an axis, a plane, or a surface	onto an axis, a plane, or a surface	rotation
	Import/Export			
Import Options	Import creations from others.	ref picture	Realtime change in rhino Application	import of custom shapes
Export Options	Blocks format	export FBX, Rhinoceros3D	Realtime change in rhino Application	.FBX .GLB. GLTF and to unity3D

Below the good-to-have functions identified after the initial testing.

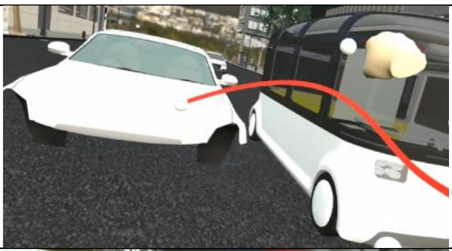
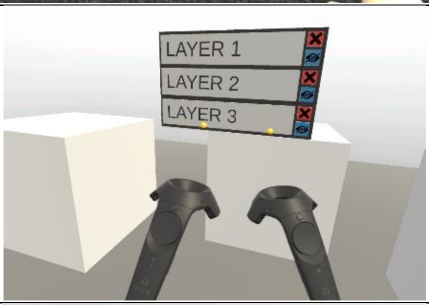
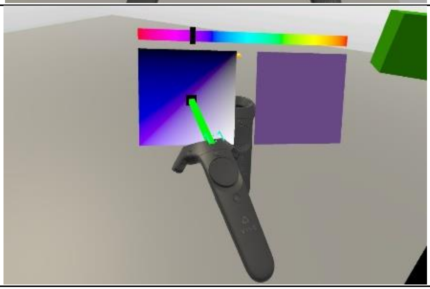
- Primitive creation (box, cylinder, sphere)
- Move object tool (transform tool)
- Historic system
- Copy geometry tool
- Freehand brush
- Line tool
- Curve line tool
- Colour wheel
- Delete tool
- Constrain lock parameters
- Method to modify the geometry
- Export creation method

Table 4: Summary of developed tools for sketching and modelling as well as navigation tools

Screenshot of the tool	Description of the tool
	Circular main menu to access primitive and sketching tools. The menu can be opened with touchpad left.
	Object modification menu where geometries can be grouped or deleted. Furthermore, a colour wheel can be opened, layers can be shown, and geometries can be copied.
	The movement system was chosen to be used via the grip buttons and the touchpad. When the side button is pressed, the user can move around in the virtual space with the touchpad.

	To rescale the scene, both grip buttons have to be pressed and held. When space is resized, the sealing ratio is displayed on the right controller.
	When the user selects a geometry, it is highlighted in dark green. Subsequently, the options menu for modifying the geometry chosen can be open by pressing the touchpad of the right controller.
	When geometry is highlighted, it can be moved by using the 'move' tool. Furthermore, each geometry can be moved by pressing the trigger button of one of both controllers and grabbing the respective geometry.
	The creation of primitives is realised with Rhinoceros3D SDK[11]. Thus, primitives such as cubes, cylinders or spheres can be created.
	The freehand sketching tools are used to create strokes following the movement of the hand. The width of the stroke can be modified.
	The straight-line sketch tool to create a line. When the stroke is finished, a button must be pressed to confirm with the touchpad right.

[11] SDK stands for Software Development Kit. The term software development kit is generally used to refer to a set of resources made available by a platform vendor to enable development on that particular platform.

	A spline with control points can be created. Once created, the curve can be modified via the control points
	Free 3D mesh creation tools can be realised by placing points in the scene.
	The layer windows consist of 3 layers which can be selected. When one specific layer is selected, all the subsequently created geometries will automatically be added to the respective layer.
	The colour picker on the controller left can be used to change the colour of objects in the scene.

4.4 Conclusion of the developed VR design application for the first iteration

This chapter has presented the different categories to communicate and create design in VR, there are five different use cases, storytelling, visualisation, sculpting, painting and modelling. The compaction of the chosen commercial VR design applications has been made in order to identify good to have functions to implement in our developed VR design application. Presentation of implemented functions has been added in the table 4 page 22. Forcing the user to save and export the 3D model every time a modification has been realised can be obtrusive to the design process. The only program found which offers an answer to this problem is Mindesk as tested in our VR design application tests with participants. Mindesk not only synchronises the 3D mesh of the created geometric but also the semantic to create this geometric.

The SDK of Rhinoceros 3D has been used to create the 3D primitive. But this method has been abandoned because it was too time-consuming in iteration 2.

To get more objective feedback on the use of VR design programs, a test session with 16 participants has been organised. The objective was to get comments and observe users while using each one of the four commercial and free applications that are available on the market to gain insights about their usability and use the feedback to improve the newly developed VR design application. Therefore, a functionality questionnaire was prepared together with the developed VR design related to navigation, geometry creation and modification of geometry. Each participant was asked to grade the applications by giving a score each criteria of the functionality questionnaire via a five-point Likert (1932) scale. The goal was to identify which application offered the best usability and the least amount of time to complete a task. In the last phase of the experiments with the help of the user's feedback, the modification of the modules was done to improve them.

5 Test of a commercial application by participants

5.1 Introduction to the sessions

To identify potential improvements for the commercial applications that are available on the market, participants were asked to rate them after experiencing the applications mentioned above. The goal was to get deeper insights into what the users like or dislike. Furthermore, each participant was asked about the general feeling of using VR for sketching and modelling. Finally, open feedback and comments have been collected during each participant's session.

Table 5: Sample of participants

gender	User number	age	Previous VR experience	Previous Video Game experience	Previous CAD/3D modelling application used	Years of experience in CAD/3D
M	User 1	21	high	high	Maya, 3DSMax	1
M	User 2	30	high	high	Rhinoceros3D, Alias, 3DSMAX, SolidWorks	10
F	User 3	26	none	low	Rhinoceros3D	5
M	User 4	28	low	high	Maya, 3DSMax	10
M	User 5	26	none	high	CatiaV5, SolidEdge	2
M	User 6	20	none	high	SolidWorks, AutoCAD	3
F	User 7	31	low	low	SketchUp, Rhinoceros3D	5
M	User 8	25	none	medium	Inventor, CatiaV5	1
M	User 9	28	none	high	AutoCAD, Inventor	1
M	User 10	23	high	high	3DSMax, SolidWorks, CatiaV5	5
F	User 11	23	none	medium	AutoCAD	0.5
M	User 12	26	none	high	SolidWorks, SolidEdge, Inventor	1
M	User 13	31	low	high	Rhinoceros3D	4
M	User 14	30	low	high	Rhinoceros3D, CatiaV5, SolidWorks	3
M	User 15	24	none	medium	AutoCAD	0.5
M	User 16	24	medium	high	Siemens N. X., AutoCAD	2

Specialist in VR   Specialist in design   Specialist in VR and design

16 participants, designers and engineers, with a link of either CAD/3D modelling or design agreed to participate in a 1h30 session (Annexe 1 page 48, Diagram of procedure for the tests with participants). They

were aged between 20 and 31 years old (average 26.3 years old), 3 females and 13 males. Every participant had experience using CAD or 3D modelling applications. The experience with the application for the participants varied from 6 months to 10 years (average 3,375 years). Participants had knowledge mainly in 3DSMax for the 3D modelling application and Rhinoceros3D, SolidWorks, CatiaV5, AutoCAD, or Inventor. All participants had experience in video games, but 50% have not tried VR with an HMD before the session.

Procedures

In the beginning, an introduction for this session was given, and pre-questions about experiences related to VR and video games were asked. The next step was to test each application; each participant was invited to familiarise with each application for 10 minutes. During this period, the experiment's facilitator was present to help the participants and guide them to the basic knowledge they need to use the application. Subsequently, each participant had to create a simple three-dimensional model via the available tools of each respective application.

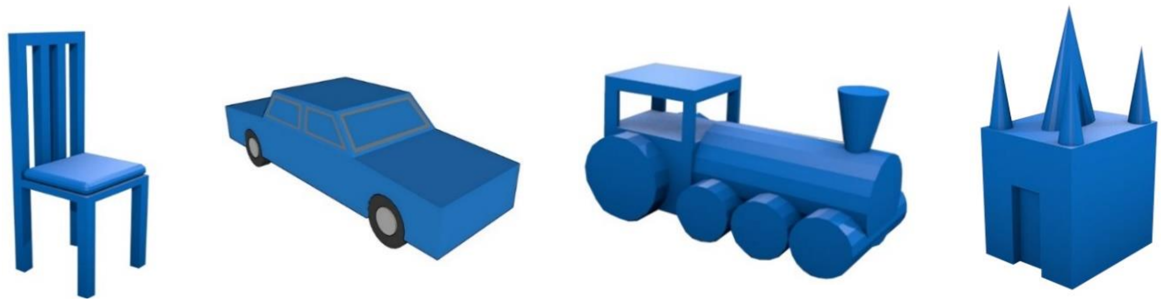


Figure 13: Examples of low complexity models for session 1

This task had to be completed without help from the facilitator. The time to complete the task was recorded by the facilitator. The participants had the option to ask questions when running into problems during task solving. Furthermore, the comments of each participant were recorded for the subsequent analysis.

For Google Blocks, Microsoft Maquette and Mindesk, the users were supposed to use the 3D modelling tools inside each application, but for Gravity Sketch, the users were asked to sketch the model.

After finishing the task, each participant was asked to fill out a functionality questionnaire by rating each question from 1 'strongly disagree' to 5 'strongly agree' (Likert, 1932), that included questions regarding navigation, modification of objects, creation of objects and the usability survey (System Usability Scale) were given for each application.

Functionality questionnaire:

- Q1: Navigation in the menus was not a problem for me.
- Q2: Navigate in the scene was not a problem for me.
- Q3: Change the scale of the scene was not a problem for me.
- Q4: I was able to find the features I am looking for fast.
- Q5: I was able to create a 3D primitive easily.
- Q6: I was able to draw in 3D easily.
- Q7: Deleting an object was not a problem for me.
- Q8: Modify (move and/or resize) an object was not a problem for me.
- Q9: Duplicate an object was not a problem for me.
- Q10: Undo or Redo last action was not a problem for me.

After testing the last application, a general questionnaire regarding the general feeling towards the use of VR for designing concept was filled out by each participant by rating each question from 1 'strongly disagree' to 5 'strongly agree' (Likert, 1932).

General questionnaire:

- I was able to get high level of detail when using VR.
- I found the visual analysis of scale and perspective improved in VR.
- I think VR can reduce the product development time in a company.
- In my opinion VR improve the creativity.

Each reference model that had to be reproduced was always assigned to the same application. That means every participant had to replicate a chair in Google Blocks, a car in Microsoft Maquette, a train in Gravity Sketch and a castle in Mindesk. Additionally, the test order of each application was randomised. This means that four users have begun the test series with Google Blocks as the first application to test. Four for users have done Google Blocks as the second application to test, to minimise the risk of distorted result caused by the test sequence.

The session has been conducted using 6 degrees of freedom (DoF) HTC VIVE and two controllers with a laptop that meets the requirements to run a VR program. Furthermore, the participant was free to stand or sit during the session.

Figure 14: Participants during session 1

Evaluation of the tasks

After the tests, the created 3D models were evaluated. That evaluation in VR had some differences with a traditional evaluation due to the third dimension offered by the virtual environment. This presents new opportunities which should also be evaluated since there is very little research done yet on using VR in the early stage of the design process. Methods used by other researchers to test their VR applications are scarce and not always right for every specific experimentation. Parameters which assure that the VR created model is like the original and the variables which should be evaluated to be able to compare creations of participants from one another must be selected. The planned method chosen for the evaluation of the tasks is based on three criteria which can be applied for each one of the models.

The first criteria were about the number of parts represented. If all the parts were represented by the participant, 5 points are given. For each missing part, the participant was losing 1 point.

The second criteria were proportions of the creation, from the top, front and side views. If the general proportions are respected by the participant, 5 points are given. For each proportion not respected in a certain view, the participant loses 2 points. Since the proportions are evaluated on 3 directions only, the participant loses 2 points instead of only 1.

The last criteria were about the geometries used to realise the task. If all the parts were achieved with the correct geometries by the participant, 5 points were given. For each incorrect geometry used, the participant loses 1 point.

In the end, the average score of the three criteria's is used to compare the similarity of each creation of each participant. Below figure 12 represents a not correct creation which scores a 2.7 out of 5 and figures 13 represents an excellent participant creation which scores 5 out of 5.

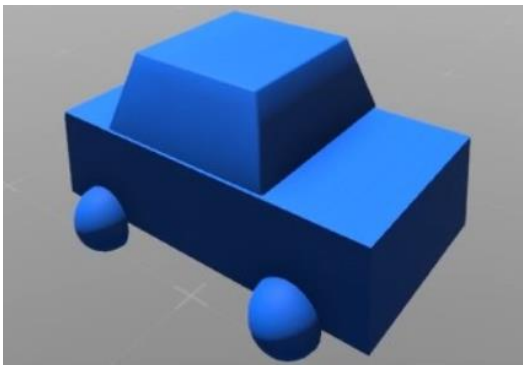


Figure 16: Example of participant creation 1

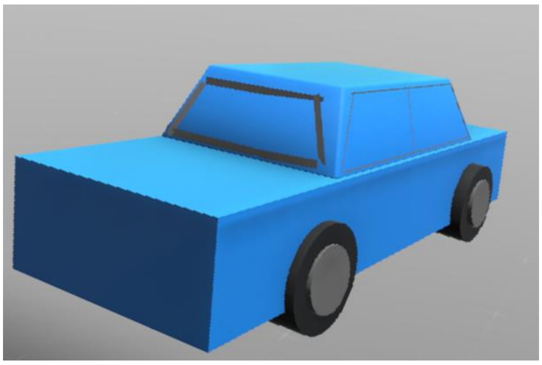


Figure 15: Example of participant creation 2

5.2 Results

The average time of each session varied from 1h 20 min to 2h 10 min depending on the time it took to the participant to reproduce the model.

SUS results

The system usability scale (SUS) has been used for measuring the usability of the applications. According to the SUS, a score above 68 is considered above the average, and anything below 68 is below average. Each item is a statement (positive or negative), and a rating on a five-point Likert scale from 'Strongly Disagree' to 'Strongly Agree' (Likert, 1932).

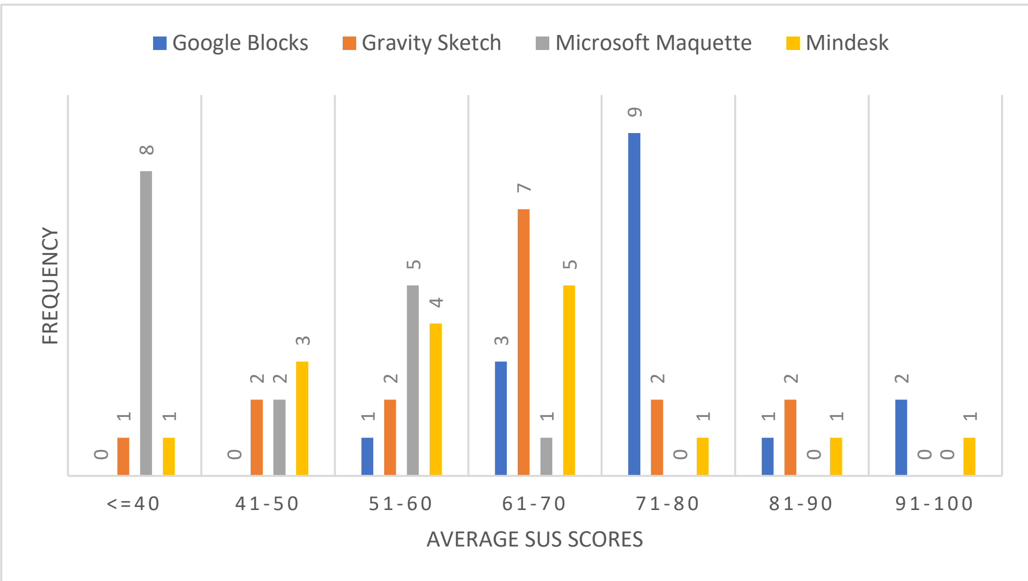


Figure 17: Frequency distribution of SUS score

Raw data is available Annexe 4, page 50.

Without considering the order of the tested application, most of the participants gave the highest score to Google Blocks follow by Gravity Sketch, Mindesk and Microsoft Maquette. For Google Blocks 14 out of 16 participants obtain a SUS score over 68. For Gravity Sketch 6 obtain a score over 68. For Mindesk 4 and Microsoft Maquette 0.

Table 6: Average time to complete the task for each user and each application for session 1

	Google Blocks	**Gravity Sketch**	**Microsoft Maquette**	**Mindesk**
average time (min: sec)	07:10	09:22	13:52	08:44

Raw data is available Annexe 3, page 50.

Participants took more time to complete the task with Microsoft Maquette (13 min 52 s) than the other applications even though the models had the same complexity. When using Google Blocks, the participants could complete the task the fastest (7 min 10 sec).

Table 7: Number of questions asked during the completion of the task for session 1

	Google Blocks	**Gravity Sketch**	**Microsoft Maquette**	**Mindesk**
Number of questions asked	0.75	1.19	2.38	1.38

Raw data is available Annexe 5, page 51.

For the number of questions asked, the mean for Microsoft Maquette was higher (2.38) than all the other (Google Blocks 0,75, Gravity Sketch 1.19 and Mindesk 1.38).

Table 8: Mean of score of the completed task for each application for session 1

	Google Blocks	**Gravity Sketch**	**Microsoft Maquette**	**Mindesk**
Mean scoring of the similarity criteria	4.5	4.6	4.5	4.7

Raw data is available Annexe 6, page 51.

Results of the artworks of participants are available Annexe 7,8,9,10 page 52,53,54,55.

The score does not change between these four applications. Participants get an average of 4.7 with Mindesk, which is the best score, 4,6 for Gravity Sketch and 4,5 for Google Blocks and Microsoft Maquette.

Qualitative evaluation results

The qualitative evaluation was composed of a functionality questionnaire divided into three parts: 1) navigation, 2) creation of objects and 3) modification of objects. They used a rating following the five-point Likert scale (Likert, 1932) from strongly disagree (1) to strongly agree (5). The functionality questionnaire results showed the favourite way to conduct 3D modelling and sketching.

Table 9 : Table of the average score of qualitative evaluation for each application for test session 1

	Google Blocks	Gravity Sketch	Microsoft Maquette	Mindesk
//Navigation:				
Q1 (menu navigation)	4.4	3.6	2.7	4.3
Q2 (scene navigation)	3.9	3.9	3.3	3.8
Q3 (change the scale)	4.1	4.0	3.6	4.1
Q4 (find features)	4.3	3.0	2.9	4.1
//Creation of objects:				
Q5 (3D primitives' creation)	4.6	3.6	3.9	4.3
Q6 (draw in 3D)	3.9	4.6	3.4	3.1
//Modification of objects:				
Q7 (delete object)	4.6	4.0	3.9	4.0
Q8 (modify object)	4.5	4.2	3.3	3.6
Q9 (change colours)	4.3	2.4	4.0	
Q10 (duplicate object)	4.5	3.8	3.9	3.6
Q11 (undo action)	4.3	4.8	4.4	4.6
Overall score per application	4.3	3.8	3.6	4

For table 10, a score of 5 represents the best score and 1 the worst.

Google Blocks obtained the highest score for all questions except Q6 and Q11. Q6 concerns the ability to draw in 3D, for this tool, Gravity Sketch receive the best rating and Q12 concerns the function undo the last object. But all four applications obtain a high score for Q11 with an average of 4.5 out of 5. Mindesk received a good rating for the navigation questions because of its minimalist tool interface; all the tools are available on one panel. The other applications use submenus and shortcut menus.

On the other hand, Microsoft Maquette appeared to be the worst in terms of usability. For example, concerning the menu navigation, Microsoft Maquette achieved a score of 2.7. Google Blocks and Mindesk achieved a score of 4.4 and 4.2, which confirms the comments recorded during the sessions and available page 38 that Microsoft Maquette is not user-friendly compared to the other applications.

Gravity Sketch obtained a good score for the modification of objects except for Q9, which concerns the change of objects colour. Indeed, a lot of people didn't understand how to modify the colour after the geometry was created. For Q6 (i.e. drawing in 3D), Gravity Sketch obtained the highest score for 4.6. Since this application is oriented on sketching in virtual environments, many advanced features are available of sketching and make this application more usable for this specific use case.

5.3 Participant comments and observations

Below are some useful comments that participants stated during the session for the improvement of VR design tools of the developed VR design application.

Google Blocks

- ‘It seems intuitive but offers the fewest features.’
- ‘It is the most user-friendly application.’
- ‘One thing I noticed is that it is easier to walk around the object.’
- ‘This one is the easiest to use.’
- ‘I like that the UI indicates the name of the tool.’
- ‘The tool changes in your hand, this little hand, this clamp, this erase … this is quite cute.’

Microsoft Maquette

- ‘The one big thing I have noticed that the precision is not really there.’
- ‘I always forget if I need this or this button to select things.’
- ‘I guess over time it should work easier.’
- ‘At the start, it would be more intuitive to have the same button (when activating a function and select a function).’
- ‘I noticed that I do not use my left hand.’
- ‘I can see dimensions which I kind of like.’
- ‘This menu has too many things.’
- ‘I think if you get more used to it and if you use this shortcut menu, it is it could be faster than the other applications.’

Gravity Sketch

- ‘I did not use my left hand for this program; I would prefer both hands to manipulate shapes.’
- ‘I really like sketching more than creating shapes.’
- ‘This undo system is really powerful and essential; I’m using it all the time.’
- ‘The selecting tool is annoying.’

Mindesk

- ‘I really like the small icon on the controller that indicates the tool I am using right now.’
- ‘It is quite easy to find things. You just press this button, and everything you need is there.’
- ‘I like the fact that the UI close when you do not need it to compare to the others which have this permanent panel on the left hand that was kind of annoying. You can use your left hand also to use the program.’
- ‘Overall, I find this one more intuitive than the over one in terms of shape creation.’
- ‘The steps are much more standard and consistent. I have to use the trigger button, select the object first and then activate the tool with the trigger again to do the function. With the other tools, it was like I do not know if I should use the trigger button or the button on the side. After a while, I do not have to think about what I must press, and I can just focus on the work.’
- ‘The UI is clear. I want to do this; I select this, and it happens.’
- ‘The other applications were for kids; this one is clearer. And when I create something here, I have the millimetre scale, axis, guidelines. I like it more.’
- ‘The scale function is not very intuitive at all.’

The favourite application of participants was Google blocks because of the simple UI; it was the most user-friendly application. The participants were surprised by the colour’s pallet placement (behind the left controller) on the menu. Participants also liked the simplicity and clarity of the Mindesk menu. Microsoft Maquette is the one that has been the least successful because of the complexity of the UI and the choice of the input control. Gravity Sketch has been appreciated for all the parameters in terms of sketching it offers.

Users used the words ‘fun’ and ‘interesting’ in describing 3D modelling and sketching in VR. Four users expressed criticism towards discomfort due to the weight of the controllers. Moreover, due to unstable tracking in the room setup, the creation flow has been interrupted several times.

Participants became used to navigating inside the environment quickly, but since every application had different controller input mappings, it was confusing to find the right button when changing applications. Five users preferred standing instead of sitting to be able to turn around their creations; all users naturally moved toward the object for closer examinations.

5.4 Conclusion of the first session of test with participants

This user evaluation has identified Google Blocks as the most usable VR design application. It was qualified as user-friendly and the most intuitive and the quickest to learn. The main advantage of Google Blocks is the simplification of the creation process by eliminating the curved surface. All objects rendered in Google Blocks have a low polygon count and therefore easy to modify. Moreover, the simplicity of the UI makes Google Blocks highly approachable. In the Google Block UI, only six tools necessary to start building 3D shapes.

Mindesk workflow is similar to CAD applications. Indeed, the user has to respect specific steps to use the tools, which is selecting, activating, using the tool, and validate the function. To improve the application, it is important to redesign the UI as a more user-friendly. The indication icon of the current function used is important for the user as well as the method used to move the objects.

For the results of the general questionnaire, concerning the ability of users to get a high level of detail participants gave a means of 3.1 out of 5 which means that the responses were neutral. For the improvement of scale and perspective, participants agreed with a mean score of 3.9 out of 5. For the reduction of time and improvement of creativity also received a mean score of 3.6 and 4 respectively.

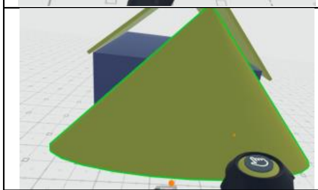
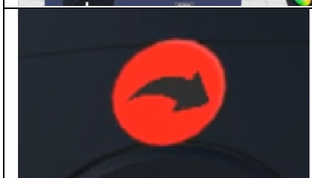
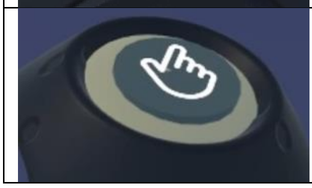
6 Improvement for the developed VR design application

6.1 Modification of the VR design application

After the two first steps which are the comparative analysis of the VR design commercial applications and the first session of user evaluation, second session of user evaluation was conducted by including two desktop-based applications and the developed VR design application. The two desktop-based application is 3DS Max which is a 3D modelling application mainly in game industry and industrial design for realistic rendering. The second one is Rhinoceros3D a CAD application mainly used in jewellery and naval industry.

The developed VR design application was improved with the modification of current function like the UI. Some new tools were added like Redo/Undo function. And some others were completely deleted like the layer management system. Table 10 lists the improvements realised on the developed VR design application.

Table 10: List of improvement realised on our developed VR design application

	The menu has been redesigned. It is now one panel where the user can find ever the creative tools to instantiate simple primitive or draw in 3D. And the edit tools where the user can modify, copy, group, delete and rotate at 90° objects. This was adapted due to the good score of Mindesk with its clear tool UI without sub-categories.
	The colour wheel has been replaced on the touchpad of the controller right. The user can change the colour at any time when he/she creates and modify an object. This was adapted due to feedback of the participant which considered working with only one of the two controllers in the commercial application.
	A selection indicator has been added when the user touches an object. It is highlighted in green. This was adapted from Google Blocks due to the good score with the moving of objects.
	The two cursors represented by the orange sphere on the left and right controllers allow moving and create objects. This was adopted because of the feedback of participants on the un-ability to use both controllers to manipulate objects.
	An undo and redo buttons were added to the controllers to cancel or display objects created. This was adapted because all the commercial application offers these functions and participants used it many times.
	On each controller, an icon has been added to indicate which function is currently used. This was adapted due to the excellent score of Mindesk with a clear workflow.

Other functions like the possibility to lock the aspect ratio of the primitive created have been added, for example, to create a cube with the same height, width and length by pressing the trigger button of the opposite controller used to generate the geometry. During the tests with participants, time was limited, and they were able to use only the simple functions because of the period of training of only 10 minutes. For this reason, more advanced functions like the management of layers or the creation of splines were deleted from the VR design application.

6.2 Tests and feedback of the second user evaluations

For the second session of user evaluation, the developed VR design application was tested, and two desktop-based applications also tested, which are 3DS Max (Autodesk, 1996) and Rhinoceros3D. The same participants in the first session were asked to conduct a second session three weeks after the first one; two of them were not able to join the session. The procedure of the test was the same, 10 min of training followed by a task to complete. Subsequently, the participants were asked again to fill out the SUS and functionality questionnaire.

Participants appreciated the moving tool in Rhinoceros3D. Selecting a geometry in Rhinoceros3D show arrows and lines allowing to move, rotate and change the scale the 3D model. 3DS Max uses another approach since the user needs to click on buttons which are dedicated to move, rotate and scale an object or use shortcuts.

6.3 Results of the tests with participants

Below the results of the second session of test with participants, including the two desktop-based applications and the developed VR design application, a score of 5 represents the best score and 1 the worst.

Table 11: Table of the average score of qualitative evaluation for each application for test session 2

	Developed VR design Application	**Rhinoceros3D**	**3ds Max**
//Navigation:			
Q1 (menu navigation)	4.6	4.3	4.0
Q2 (scene navigation)	4.0	4.1	3.5
Q3 (change the scale)	3.9	4.3	3.9
Q4 (find features)	4.6	3.9	3.4
//Creation of objects:			
Q5 (3D primitives' creation)	4.9	4.7	4.4
Q6 (draw in 3D)	/	/	/
//Modification of objects:			
Q7 (delete object)	4.1	4.7	4.6
Q8 (modify object)	4.4	4.6	4.0
Q9 (change colours)	4.4	/	/
Q10 (duplicate object)	4.3	4.6	3.6
Q11 (undo action)	4.5	4.7	4.8
//Overall score per application	4.4	4.4	4

The question of drawing in 3D (Q6) was not considered of this session since this function is not commonly used when using desktop-based application and only available through the creation of 3D points and splines. For the Q9 on the modification of objects colour, this function was not evaluated in the desktop-based application since it represents a more advanced function.

Table 12: Comparative table of SUS scores for all tested applications

SUS means	
	mean
Google Blocks	75.5
Microsoft Maquette	44.2
Gravity Sketch	63.9
Mindesk	62.5
Developed VR design Application	77.3
Rhinoceros3D	68.4
3DSMAX	55.4

For the comparison of the mean of all SUS score, our developed VR design application obtained the best rating and with 1.8 points more than Google blocks. Rhinoceros3D also has an excellent rating over 68, but Gravity Sketch, Mindesk, 3DS Max and Microsoft Maquette are below.

Table 13: Average time to complete the task for each user and each application for session 2

	Developed VR design Application	**Rhinoceros3D**	**3DS Max**
average time (min: sec)	04:43	07:36	08:28

Raw data is available Annexe 3, page 50.

Participants were fast with desktop-based applications than Microsoft Maquette, Mindesk and Gravity Sketch. Participants complete the tasks in 7min 10s, which is even lower than the desktop-based applications and confirm that Google Blocks were the most efficient application in the first session. Concerning the developed VR design application, the time spent by participants was significantly reduced to complete the tasks (4 min 43s) by apply the feedback of participants and identify implements the right functions.

Table 14: Number of questions asked during the completion of the task for session 2

	Developed VR design Application	**Rhinoceros3D**	**3DS Max**
Number of questions asked	0.14	0.86	0.71

Raw data is available Annexe 5, page 51.

Participants asked 0.14 questions when using our developed VR design application, which is the lowest one. 3DS max 0.71 question, which is lower than Google Blocks (0.75 questions).

Table 15:Mean of score of the completed task for each application for session 2

	Developed VR design Application	Rhinoceros3D	3DS Max
Mean scoring of the similarity criteria	4.5	4.3	4.3

Raw data is available Annexe 6, page 51.

Participants obtained a lower score on the desktop-based applications (4.3 for both of them) and the developed VR design application obtained a similar score than google blocks and Microsoft Maquette (4.5). The mean score of the similarity criteria didn't improve compared to the other VR commercial applications.

This study shows that the application with the highest SUS score (the VR developed application) has been the application in which participants took the least time to complete the tasks (4min 43s). On the opposite, the application with the lowest SUS score (Microsoft Maquette) has been the one on which participants took more time to complete the task (13min 52s). The functionality questionnaire has identified which of the commercial is more suitable for the navigation, the creation of objects and the modifications of objects. Rhinoceros3D, Mindesk and Google Blocks were identified as the best for the navigation. Rhinoceros3D has a movement tool providing an easy way to move the 3D models. Google Blocks is simpler to use and the most accessible. Mindesk also has a clean user interface and easy to understand. For the creation of 3D primitive and the modification of objects, Rhinoceros3D remains the best one follow by Google Blocks and Mindesk. The non-commercial VR design application developed managed to overtake Google Blocks and Rhinoceros3D on specific criteria, for instance, the navigation in the menus and the rapidity to find the function wanted. Moreover, the function to create a 3D primitive was also improved by adding the possibility to lock the three lengths of the primitive and use either right or left hand to create it. The proposed VR design application scored the best SUS score follow closely by Google blocks.

The limitations of this study are the numbers of participants, the training time may have affected the results. The training periods were limited to 10 minutes for each VR design applications. Additional training time may have influenced the result of the similarity criteria and time completion of the tasks.

As a next step, the study of more advanced tools and more functions like the creation of curves or advanced surface and volumetric edit tools would be interesting to explore. A comparison between VR commercial application, the developed VR design application and non-VR methods could be added to the comparative analysis.

7 General conclusions and discussion

This section will discuss how the results with regard to the research questions based on the findings of the comparative analysis of VR commercial applications, the developed VR design application and the tests on participants.

7.1 VR in the design stage

Integrating a VR design solution with traditional CAD tools necessitates an automatic real-time synchronisation between those tools and the VR system. Although the overall effect of VR for the design of concepts was positive in this study, it is not possible to make a general conclusion on whether replacing 3D modelling, sketching or CAD by VR is beneficial for industrial designers. Improvements were observed in terms of task completion duration when using an intuitive application. Current VR technology offers new possibilities to intuitively create 3D content since many restrictions from regular 3D modelling and CAD applications on a desktop computer are gone.

7.2 Advantages of VR design applications

The developed VR design application was globally more appreciated by participants than the commercial applications thanks to the simplicity of use. Participants showed interest in VR and agree on the new perspective it offers in terms of interaction, evaluation of scale and dimensions thanks to the accurate field of view, head tracking and stereoscopic vision. For instance, VR offers the possibility to interact or being inside the 3D model. The evaluation and comparison of VR design applications and desktop-based applications show that with the right functions and tool, desktop-based applications remain better than VR design applications. Participants were faster on the desktop-based application than the VR design commercial application. Moreover, the improvements proposed for the developed VR design application reduce the time to complete the tasks for participants because focus was done on the main functions to complete the task successfully.

Moreover, VR open new perspective for collaborative design to unlock locations limitations of traditional methods for communication design. People can meet in the virtual environment and interact together and with the 3D model by staying at 2 different positions far from each other. Several parameters should be taken into account when developing a multi-user application, the eye contact which means being able to see where the other is looking and the emotion of the other person.

To conclude, the VR strengths are the sense of presence, a better field of view and a notion of scale. VR opens new opportunities in terms of intuitive manipulation and user-centred design.

7.3 Limitations of VR design applications

The weaknesses of VR are the reduced accuracy and discomfort experienced for long exposures. The threats would be the resistance to change in adopting VR for designers and the additional cost of using this technology in terms of hardware, for instance, the computers, the VR system which is very expensive when choosing a CAVE system instead of an HMD system. When a VR application is too complex, it can be discouraging for the industrial designer to adopt this new technology and increase the time need to do a task.

7.4 VR and creativity

Use of VR can lead to more creative ways to create a prototype and variants of design as well improve the design outcomes but as noticed with the tests conducted, using VR is more time-consuming than the desktop-based CAD and 3D modelling methods when the application is complex. VR is more suitable as a supplement and a tool to help to share ideas easily and rapidly. VR cannot replace the traditional methods entirely like 2D and 3D modelling. Wang et al. (2018) created a VR simulated scenario where participants had to solve creativity-demanding problems and conclude that VR enhances creative performance and promote cognitive flexibility and persistence that benefit creative idea generation. Thornhill-Miller and Dupont (2016) outline five ways VR can be used to enhance creativity and problem-solving. First by changing aspects of self-perception. Secondly, by doing collaborative interaction with others. Then by optimising environmental conditions and influences. Next by facilitating gamification of the problem-solving process and finally by integrating other technologies of creativity enhancements.

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9 Table of figures

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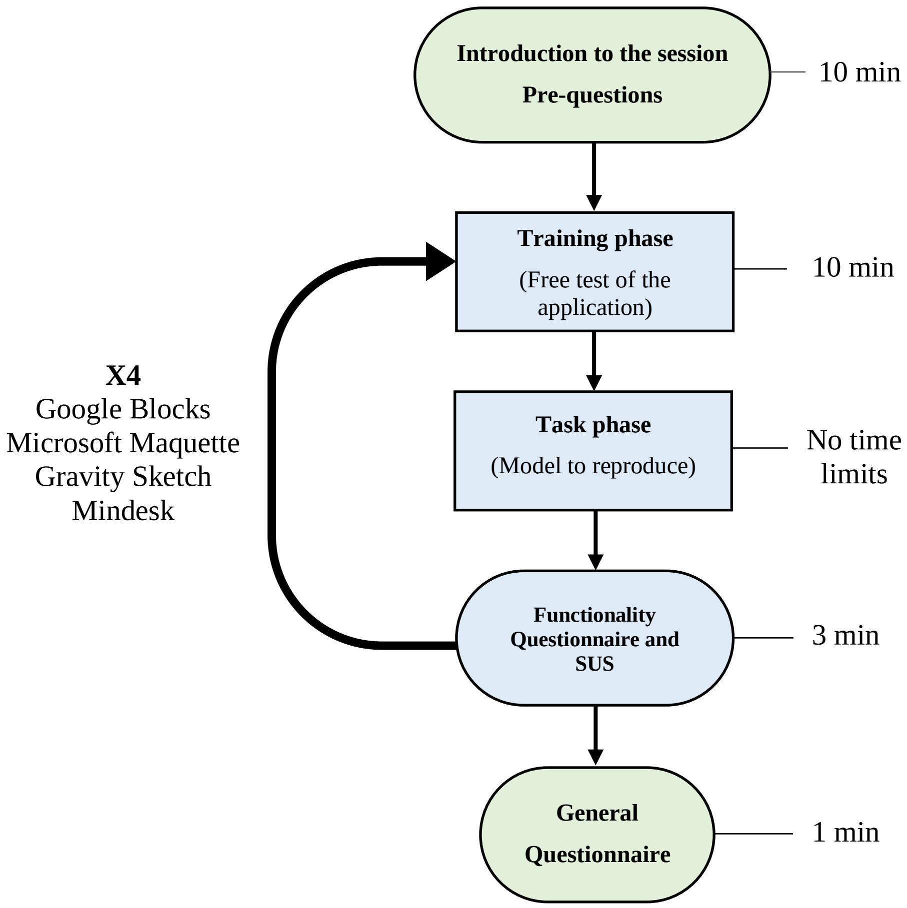
11 Annexes

Annexe 1: Diagram of procedure for the tests with participants



Annexe 2: System Usability Scale (SUS)

System Usability Scale

I think that I would like to use this kind of software frequently.

	1	2	3	4	5	
strongly disagree	○	○	○	○	○	strongly agree

I found this software unnecessarily complex.

	1	2	3	4	5	
strongly disagree	○	○	○	○	○	strongly agree

I thought this software was easy to use.

	1	2	3	4	5	
strongly disagree	○	○	○	○	○	strongly agree

I think that I would need assistance to be able to use this software.

	1	2	3	4	5	
strongly disagree	○	○	○	○	○	strongly agree

I found the various functions in this software were well integrated.

	1	2	3	4	5	
strongly disagree	○	○	○	○	○	strongly agree

I thought there was too much inconsistency in this software.

	1	2	3	4	5	
strongly disagree	○	○	○	○	○	strongly agree

I would imagine that most people would learn to use this software very quickly.

	1	2	3	4	5	
strongly disagree	○	○	○	○	○	strongly agree

I found this software very cumbersome/awkward to use.

	1	2	3	4	5	
strongly disagree	○	○	○	○	○	strongly agree

I felt very confident using this software.

	1	2	3	4	5	
strongly disagree	○	○	○	○	○	strongly agree

I needed to learn a lot of things before I could get going with this software.

	1	2	3	4	5	
strongly disagree	○	○	○	○	○	strongly agree

Annexe 3: Raw data of the time to complete tasks by participant

	Google Blocks	Gravity Sketch	Microsoft Maquette	Mindesk	3DS Max	Rhinoceros 3D	Developed VR App
user 1	228	240	537	192	/	/	/
user 2	232	320	1013	530	319	174	206
user 3	486	233	676	262	495	253	388
user 4	225	516	566	509	250	436	210
user 5	490	692	900	704	422	488	405
user 6	840	945	1206	913	596	483	390
user 7	566	783	1204	1115	/	/	/
user 8	506	789	786	398	702	598	325
user 9	390	524	890	472	582	726	282
user 10	200	478	493	290	226	180	146
user 11	400	510	651	485	709	541	256
user 12	442	361	890	383	576	446	238
user 13	486	763	1318	678	583	534	337
user 14	525	825	1123	743	508	442	213
user 15	433	585	473	477	553	682	287
user 16	431	433	579	236	595	395	284

Annexe 4: Raw SUS score for each application and each participant

	Google Blocks	Microsoft Maquette	Gravity Sketch	Mindesk
User 1	62.5	37.5	70	60
User 2	72.5	45	67.5	52.5
User 3	72.5	55	32.5	65
User 4	72.5	52.5	47.5	47.5
User 5	75	12.5	72.5	95
User 6	57.5	30	57.5	50
User 7	92.5	37.5	87.5	87.5
User 8	92.5	57.5	67.5	40
User 9	72.5	40	52.5	67.5
User 10	77.5	30	65	62.5
User 11	70	37.5	67.5	67.5
User 12	80	37.5	62.5	55
User 13	75	50	70	57.5
User 14	77.5	60	75	70
User 15	70	57.5	45	45
User 16	87.5	67.5	82.5	77.5

Annexe 5: Numbers of question asked the task of each application and each participant

	Google Blocks	Gravity Sketch	Microsoft Maquette	Mindesk	3DS Max	Rhinoceros3D	Developed VR App
user 1	1	0	2	0	/	/	/
user 2	1	1	4	1	0	0	0
user 3	1	1	3	2	1	1	0
user 4	0	3	2	3	0	0	0
user 5	1	2	3	0	1	2	0
user 6	3	3	2	2	1	1	1
user 7	0	2	3	1	/	/	/
user 8	1	0	3	1	0	2	0
user 9	0	1	2	1	1	1	0
user 10	0	0	0	0	0	0	0
user 11	1	1	1	2	1	1	0
user 12	1	1	2	1	2	1	0
user 13	0	1	3	2	1	1	0
user 14	1	1	4	2	1	0	0
user 15	0	2	3	4	1	2	1
user 16	1	0	1	0	0	0	0

Annexe 6: Score of artworks of each participant for each application

	chair	car	castle	train	flower	tree	ice cream
user 1	4.3	3.7	4.7	5	/	/	/
user 2	5	5	5	4	5	4.3	5
user 3	4.3	2.7	4.7	4	3.7	5	5
user 4	4.3	4	4.7	4.7	5	4.3	4.3
user 5	4.3	3.7	4.3	4.7	3.7	5	3.3
user 6	5	4.3	4.3	5	3.3	5	4.0
user 7	5	4.3	4.3	5	/	/	/
user 8	5	5	5	5	4.3	5	5
user 9	3.7	5	4.3	4.3	5	3.7	4.3
user 10	5	5	5	5	5	5	5
user 11	3.7	5	5	5	3.7	3.3	4.3
user 12	3.7	5	5	5	3.7	3.7	4.3
user 13	5	5	5	5	5	5	5
user 14	5	5	5	4.3	5	3.7	5
user 15	3.3	4.3	4.3	3.3	3.7	3.3	4.3
user 16	5	5	5	4.3	3.7	3.7	4.3

Annexe 7: Creations of participants on Google Blocks


user1


user2


user3


user4


user5


user6


user7


user8


user9


user10


user11


user12


user13

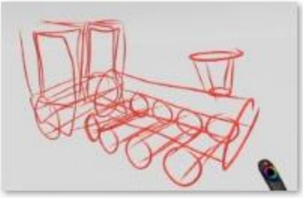

user14


user15


user16

Annexe 8: Creations of participants on Gravity Sketch


user1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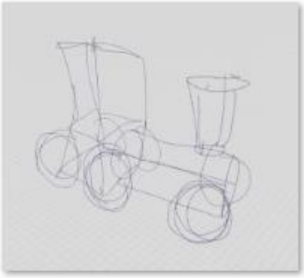
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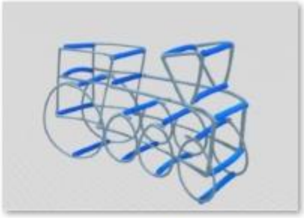
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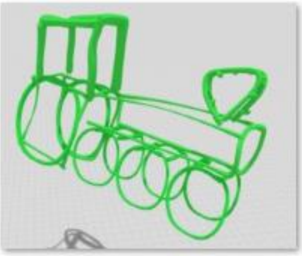
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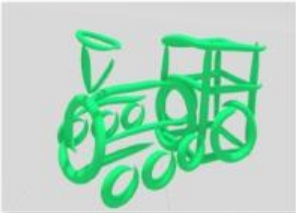
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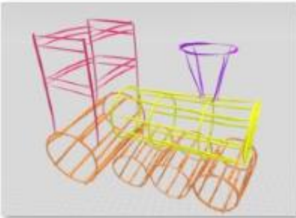
user8


user9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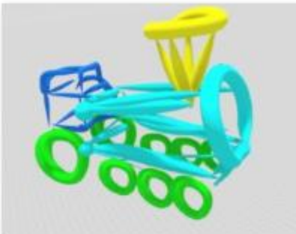
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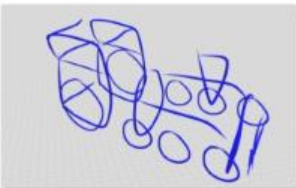
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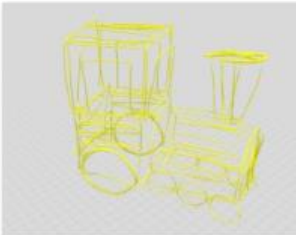
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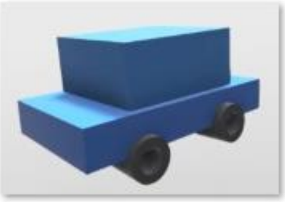
Annexe 9: Creations of participants on Microsoft Maquette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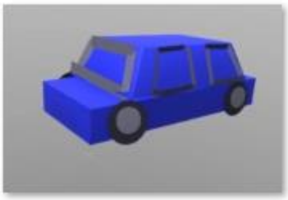
user2


user3


user4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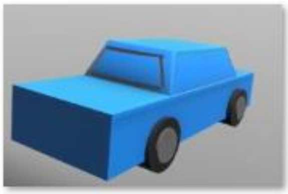
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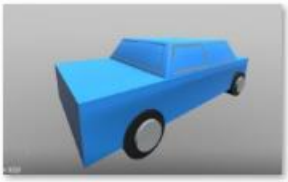
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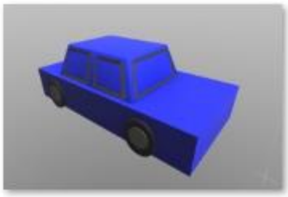
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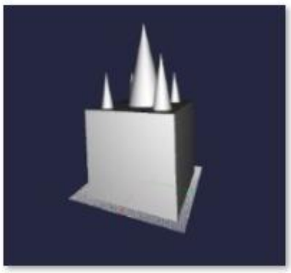
<u>Annexe 10: Creations of participants on Mindesk</u>



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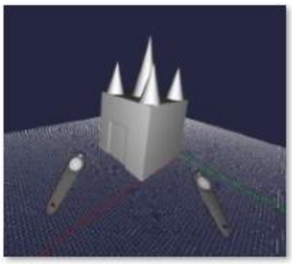

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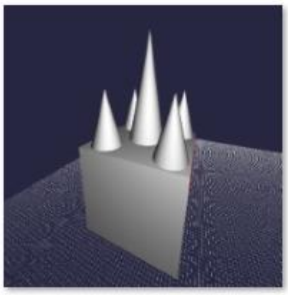

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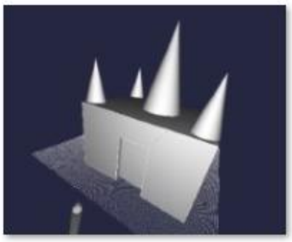

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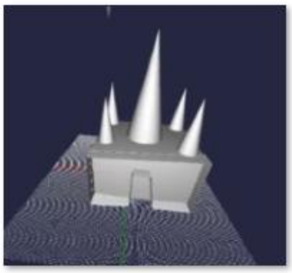

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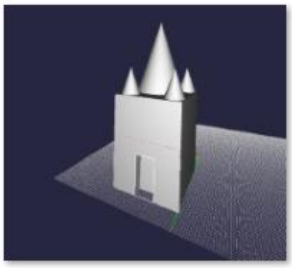

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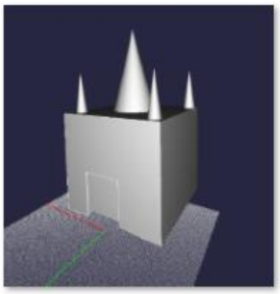

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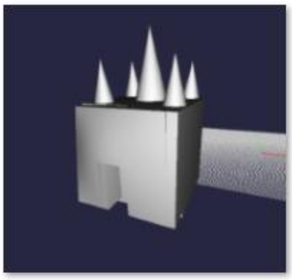

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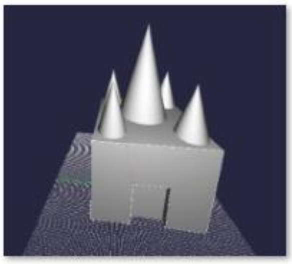

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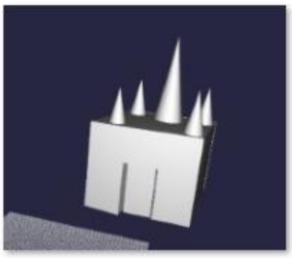

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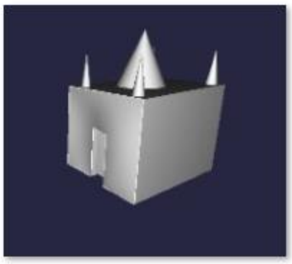

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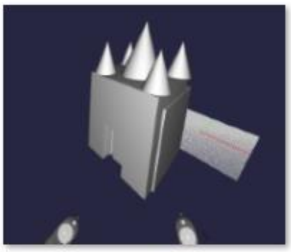

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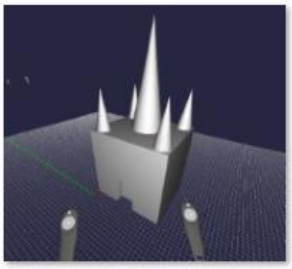

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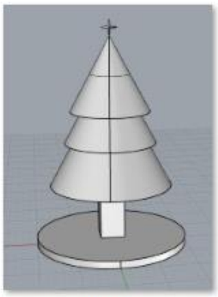
Annexe 11: Creations of participants on Rhinoceros3D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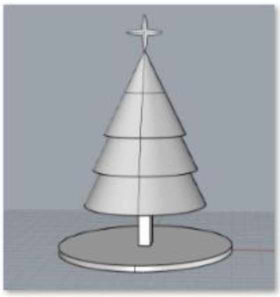
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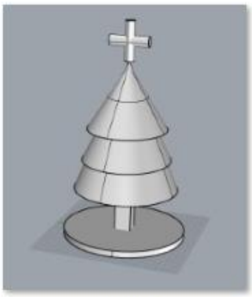
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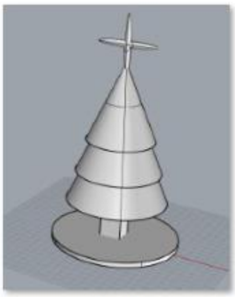
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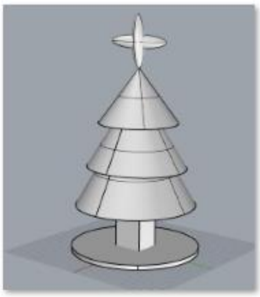
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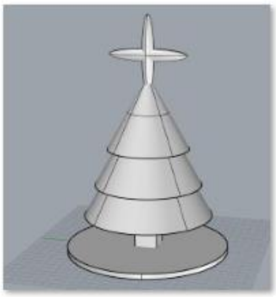
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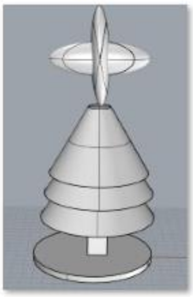
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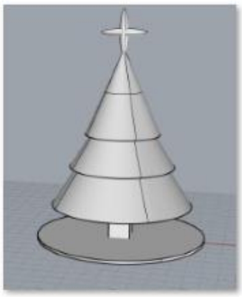
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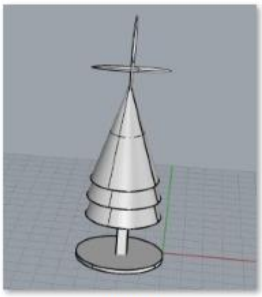
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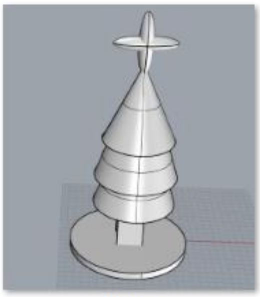
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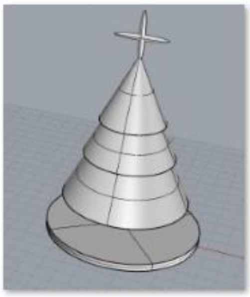
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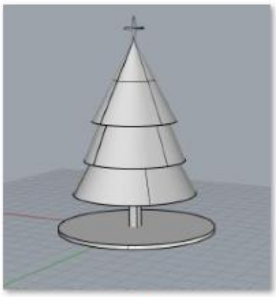
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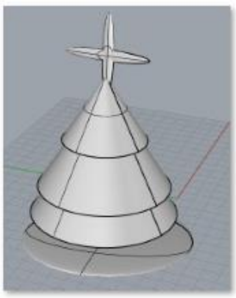
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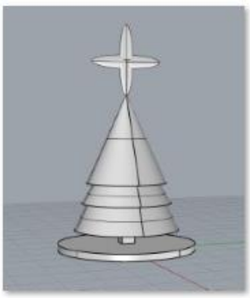
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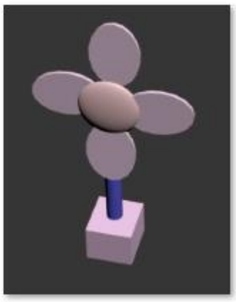
Annexe 12: Creations of participants on 3DS MAX


user2


user3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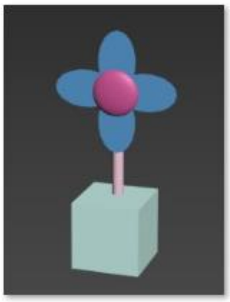
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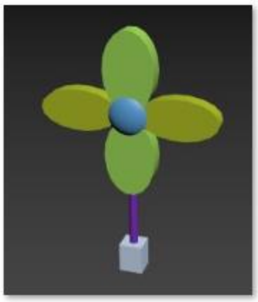
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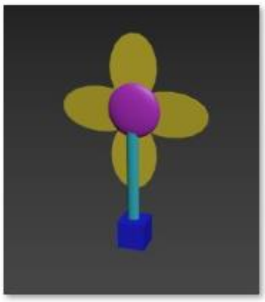
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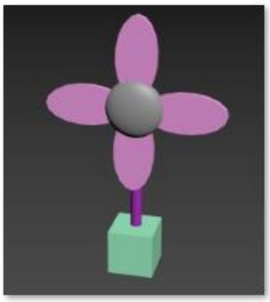
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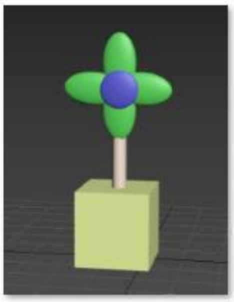
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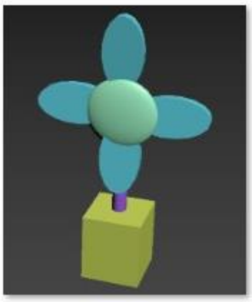
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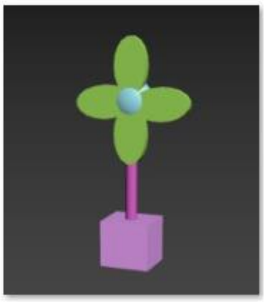
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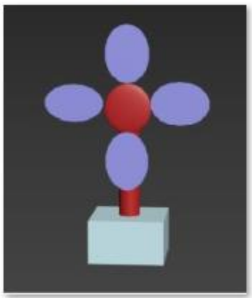
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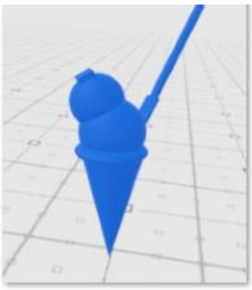
Annexe 13: Creations of participants on the VR developed application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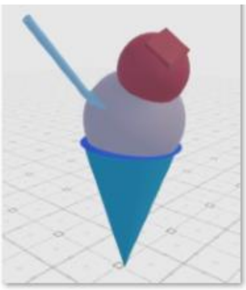
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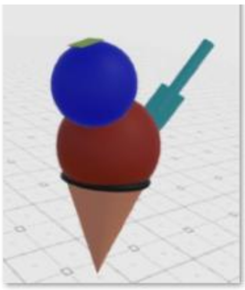
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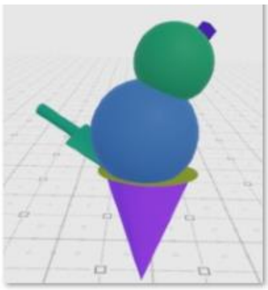
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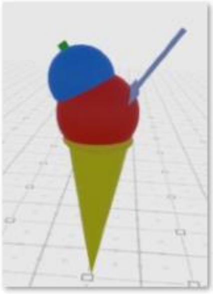
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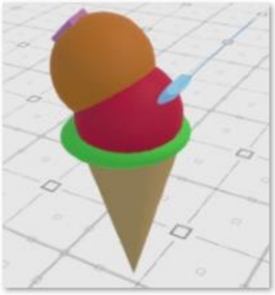
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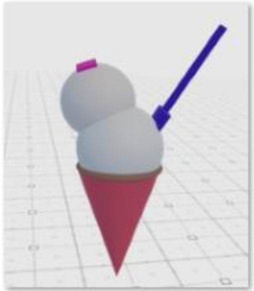
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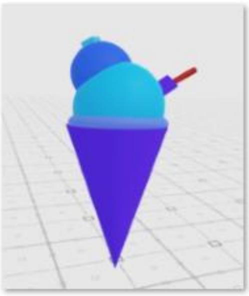
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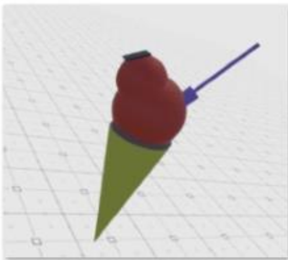
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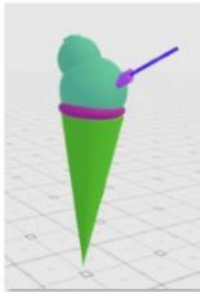
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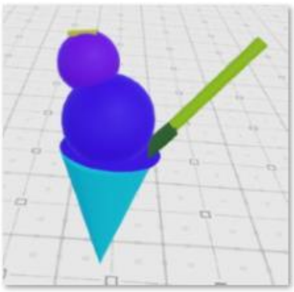
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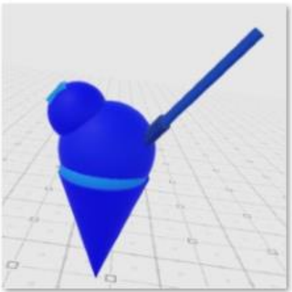
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