

Article

# VR as a 3D Modelling Tool in Engineering Design Applications

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**Abstract:** The study aims to explore the usefulness of existing VR 3D modelling tools for use in mechanical engineering. Previous studies have investigated the use of VR 3D modelling tools in conceptual phases of the product development process. Our objective was to find out if VR tools are useful in creating advanced freeform CAD models that are part of the embodiment design phase in the context of mechanical design science. Two studies were conducted. In the preliminary study, the group of participants modelled a 3D part in a standard desktop CAD application, which provided information about the key characteristics that must be satisfied to obtain a solid model from a surface model. In the research study conducted with a focus group of participants, who were firstly trained in the use of VR, the same part was modelled using a VR headset. The results were analysed and the fulfilment of key characteristics in the use of VR was evaluated. It was found that using VR tools provides a fast way to create complex part geometries, however, it has certain drawbacks. Finally, the ease of use and specific features of the VR technology were discussed.

**Keywords:** virtual reality; engineering design; CAD modelling; surface modelling; product development



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## 1. Introduction

Virtual reality (VR) is a mature technology, which has established itself as an important tool in many engineering applications, such as design review, inspection, and worker training. It was previously determined that VR 3D modelling (VR modelling) is suitable for design purposes [1]. Moreover, some studies report that modelling in VR software is easier to learn, more natural and intuitive to use and enables faster modelling in comparison with traditional computer-aided design (CAD) desktop 3D modelling software [2]. However, research regarding the use of VR in product design has been limited to the conceptualisation phase and design review. Moreover, previous design phase studies expressed doubt that VR tools can be used for mechanical design and engineering work as they lack the required accuracy and the capability to transfer the model into later stages of product development [3].

This study aims to bridge this gap and investigate the usability of the VR tool in the product design stage and to research the possibility of converting and using the VR-created model in later phases such as detailing while ensuring an adequate level of accuracy. The study explores the possibilities the technology offers for the design of complex geometrical models. Given that VR supports easier navigation through the design environment (space), it should be simpler and faster for designers to create designs with complex curved geometries. It was investigated if objects created in VR can satisfy the required model quality and if they can be simply transferred to desktop applications, so that further detailing and editing of the model can be done seamlessly, quickly leading to simulation or manufacture and thus speeding up the development process. The aim was to extract the advantages and disadvantages of desktop CAD modelling and VR modelling in supporting the embodiment design starting from the product concept to its final form.

This work consists of the following parts: (1) Background and objectives introduce the topics and relevant contributions related to CAD modelling, VR technology and its

different applications in engineering design and states the objectives of this research; (2) Methodology includes the description of methods and tools used in the study, which consists of a preliminary study aimed at identifying key steps and evaluation criteria in the 3D modelling process, and an experimental research study which explores the modelling capabilities in VR environment; (3) Results of the study; (4) Discussion of the results, and (5) Conclusion.

### *Background and Objectives*

In recent years, immersive technologies are developing rapidly [4] and are gaining greater recognition in engineering. Augmented reality (AR) and virtual reality (VR) are a part of a wider field of mixed reality (MR), a group of technologies that tend to overlay and anchor virtual objects to the real world so that the users can interact with them [5]. AR is better used in cases where more interaction is required between the users, when the real-world background is important and where the environment or the tasks are not suitable for using headset equipment. For such reasons, in the mechanical engineering domain, AR is e.g., widely used as assistance for maintenance, inspection [6,7], collaborative design [8] and assembly [9]. Eschen et al. [9] suggest that the interaction time between the user and the virtual model can be used as a measure of the utility of a certain MR technology. VR technology is well suited for activities in the earlier stages of the product development process, where the product's form hasn't been finally decided and it is still under development and testing, but also for the design overview and inspection. Delgado et al. [10] defined 6 usage categories for AR and VR in architecture, engineering and construction domains: (a) AR and VR for stakeholder engagement, (b) AR and VR for design, (c) AR and VR for design review, (d) AR and VR for construction, (e) AR and VR for operations, and (f) AR and VR for training. As one of the main challenges of VR technology, they outlined the hardship of archiving AR and VR outputs for later review or to record the experiences that the user had in AR and VR environments. With a focus on VR technology, in the paper by Berg et al. [11], the authors made a survey amongst 25 industrial companies on the use of VR in their processes. They listed different use cases where VR technology was used in practice: visibility/viewability [12,13], ergonomics/reachability [14], packaging, aesthetic quality/craftsmanship (visual inspection), storytelling, abstract data visualization (e.g., airflow simulations) and for communication across disciplines.

In the engineering design domain, several authors have investigated the potential of using VR technology for stakeholder engagement and design review. To measure the influence of VR on the users, the researchers considered different tangible aspects of the review process, e.g., time, the number of identified issues or design faults and analysis of human factors such as spatial perception [15]. Berg and Vance [16] conducted a study with design and manufacturing engineers who participated in design reviews in an immersive VR environment. They found that with the true scale geometry representation in VR participants gained a better understanding of the spatial relationships between product components as well as the interactions required to assemble the product. Also, the environment encouraged engagement and improved the design discussions between the members. Collaboration in dislocated, virtual teams, where team members have never met in person is common in the modern product design process [17]. Novel ICT technologies [18] including VR are proving to be vital in such workflows. Research reveals that people have different spatial cognition capabilities. It was also recognised that these capabilities influence the success in STEM fields, where the inability in mental visualization can have a negative effect on performing tasks involving spatial skills. In a study by Safadel and White [19] it was concluded that VR visualisation had a positive compensating influence on participants with low spatial cognition abilities.

In the work of Wolfartsberger [20] a VR engineering design review approach was compared to a traditional approach using CAD software on a screen. The study showed that a VR-supported design review allowed users to find more faults in a 3D model than in a CAD software-based approach on a PC screen. Another study showed that with using VR

participants could better perceive the fit of user interface elements and estimate the model dimensions with a lower relative error than in desktop interface on PC screen [15]. VR also offers advantages in fields such as programming of industrial robots [21]. By immersing individuals in a virtual world where they may observe and interact with robots in 3D collaborative or distant locations, VR allows for more natural and intuitive interactions. This can improve situational awareness and make interaction simpler [22]. Alongside the improved spatial perception of the objects, virtual environments can enhance the communication between the dislocated participants as they enable speech and gesturing while at the same time viewing the product in true scale 3D environment when compared to the regular video conferencing tools [23]. Gong et al. [24] investigated the application of VR collaboration in a globally distributed manufacturing company. They found that the greatest issue was the transfer of the models from CAD to VR environment. The interaction design of VR systems was highlighted as an important factor for manufacturing companies to widely adopt and benefit from the latest advancements of VR technologies. In addition, VR and AR technologies have high potential and play an important role in education and training of mechanical and design engineers. Researchers have discovered that studying with the support of MR technology can significantly improve the student's abilities in geometric analysis and creativity [25]. However, the learning theories on design are often not considered by developers of VR and AR applications, which makes it difficult to incorporate them in the study process [26,27].

Besides the application of VR for viewing and discussing proposed design solutions, this technology can also support earlier stages of design. According to Ulrich et al. [28] the product development process consists of the following phases: planning and ideation, concept development, embodiment design, detail design, testing and refinement and production ramp-up. Engineers use various tools that can assist them with different tasks during development, with the aim to speed up the process. When the product concept is created, it is commonly represented in the form of sketches. These sketches serve as a starting point for the product embodiment, which can be formed as physical or virtual prototypes [29]. With the rapid development of tools and technologies, virtual prototypes created using 3D modelling in CAD software have become the most common way for design representation [30]. They enable engineers to easily share and modify their designs using dedicated desktop CAD tools. However, CAD on a screen cannot always meet all the requirements regarding the functional and ergonomic validations of complex 3D models [20]. In recent years, CAD modelling tools were developed and adapted to support the use of VR headset technology. Berni and Borgianni [31] classified design functions that can be supported by VR into early phases, co-design, 3D modelling, virtual assembly and prototyping, product evaluation and educational purposes. Balzerkiewitz and Stechert [3] discussed the usability of VR tools and their capabilities for early design phases. They listed several challenges: for the detailed design phase the transfer from 3D VR to a CAD model has to be possible, the VR-created surface models must be automatically converted into solid bodies, collision detection has to be integrated to prevent overlapping of the objects and an automatic alignment of edges and axes must be enabled. In addition, they highlight that the software has to be intuitive and easy to use to enable wider adoption. As one of the main issues that hinder the use of this technology in engineering design, the authors name the reduced quality of imported models and the inability to edit them. The use of VR for creating design concepts was explored in several studies. Ye et al. [2] researched how VR technologies can provide more natural and intuitive interaction between the designer and the CAD system using different sensory channels. It was found that VR can provide better support capabilities for conceptual design through its multiple interface integration and implementation, making the 3D sketching more intuitive and quicker, as there is no need to additionally reproduce the design in the CAD system. Van Goethem et al. [1] tested the VR-supported conceptual design against traditional sketching on paper. The Gravity Sketch VR application with a virtual reality head-mounted display (HMD) was tested by a group of product development students where parameters like efficiency, ease of use and enjoyment

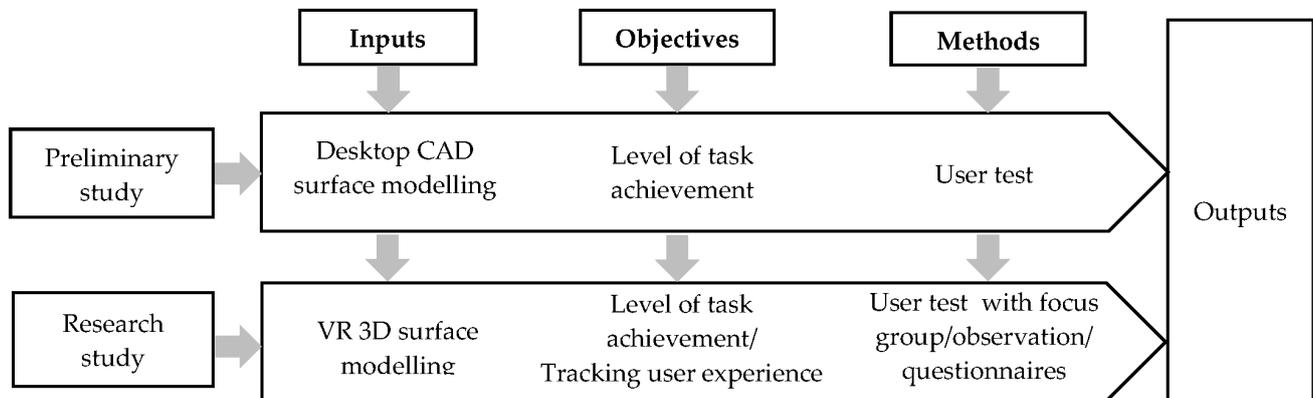
were measured. Results have shown no significant difference between the quality of hand-made and VR-made sketches. A similar study conducted by Joundi et al. [32] showed that the industrial design students find conceptual modelling using VR interesting and a positive experience, however, there are some issues to be considered, e.g., that the lack of surfaces produces inaccuracies in the model and that people draw better on a 2D surface than in 3D space directly. Nonetheless, the users were able to create the desired shapes and models in a rather limited time frame, showing that VR provides good support for quickly generating 3D concept models. Investigating sketching in different environments, Oti and Crilly [33] stated that immersive 3D sketching is a unique tool that simultaneously supports behaviors that are commonly only found in paper-based sketching, CAD modeling and physical model making. In these studies, the VR-created concept models are built from and represented as a set of surfaces, but they lack an explanation of how the models can be used for further product development. In the next step, engineers have to transfer the surface model into a manufacturable model. This means that the geometry has to be fully enclosed (solid CAD model) and the transitions between the surfaces have to be well defined in order to be able to perform simulations and analyses on the models [34], as well as to produce technical documentation and use it as input for manufacturing. The surface model can be transformed into a mesh model so that the VR generated geometry can be further manipulated. Misztal and Ginkel [35] argue that the virtual mesh model can not provide a suitable mathematical surface quality, thus a CAD replica of the shape is also necessary. Zhong et al. [36] took a different approach and proposed a methodology for direct solid modelling in VR. This reduces the need to replicate the design created in VR again in the CAD software. It is based on constraint-based geometry manipulation, which resembles Boolean operations in desktop CAD software. Even though this methodology is suitable for designing simple geometrical objects, it does not provide good support for complex freeform designs. Currently, available VR modelling applications and available features for solid geometry manipulation show that this approach has not gained significant traction.

To address these concerns, our research objective was to determine whether 3D modelling in VR can be used after the conceptual design phase to facilitate the embodiment from a product concept into its final form (3D model) following the engineering design process. If proven successful, this would reduce the need for switching between desktop CAD and VR environments during product development, thus reducing the time and the required designers' efforts. To further explore the main research question, different parameters were considered including the possibility of converting a VR-created model into a solid CAD model and the usability of VR modelling tools in terms of speed, intuitiveness of the tools and the modelling process, as well as the output model quality. The metrics used was the modelling time, degree of task completion, overall usability and the quality of the final 3D model.

## 2. Methodology

The research consists of two user studies, a preliminary study that helped us set the study foundations, and the research study in which the applicability of VR technology was investigated. First, the preliminary study was conducted to define how to evaluate the performance level of the CAD modelling steps since desktop modelling cannot be directly compared with VR 3D modelling. Previous studies determined that conceptualizing using VR is faster compared to using the desktop tools [2,32], therefore, to determine if this also accounts for building the 3D models, the information on the timing and problems encountered was obtained in the studies. After the desktop CAD surface modelling test, where the evaluation criteria were established, the research study was conducted with VR 3D surface modelling, investigating the capabilities of the VR modelling tools using HMDs to support the design process from concept to solid model. Points of interest were: ease of use of tools and controls, geometry generation capabilities, insertion of reference images, combining surfaces, detailing, dimensioning, geometry exploration capabilities, conversion to a solid body.

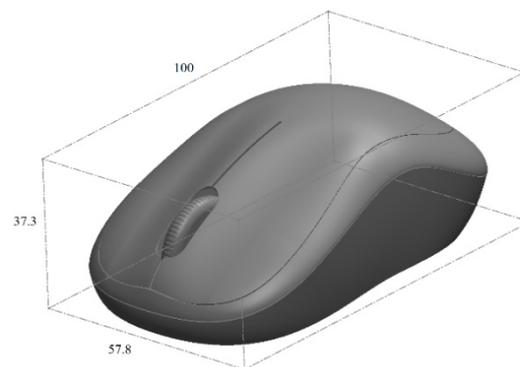
The methodological framework of the studies is explained in Figure 1. A user test was conducted in both studies, while the research study was conducted using a focus group method in order to obtain more detailed information. In addition to the user test in the research study, observations and three questionnaires were made: before, during and after VR 3D modelling.



**Figure 1.** The methodological framework.

The participants in both studies were tasked with capturing the design intent from sketches. This task was chosen as our aim was not to test the user creativity when using the tool but to study whether the VR technology is capable and accurate enough for engineering applications in later product development phases.

The 3D modelling process (the embodiment design) in both studies was tested by using a preselected 3D object. A computer mouse (Figure 2) was chosen to be modelled, due to its suitable level of geometrical complexity. The criteria for object selection were organically (e.g., freeform) shaped surfaces. The features of interest were transitions, fillets, and curvatures that occur between two surfaces. Achieving adequate quality of surfaces and the possibility for the transition from a surface model to a solid model were studied in detail.



**Figure 2.** Isometric image of the reference mouse.

The participants' models in both studies were evaluated based on the criteria defined by researchers in the preliminary study according to known steps in the workflow of capturing the design intent. The key steps for creating a freeform 3D model from a reference image were adopted from [37], based on which criteria and quality indicators of the modelling outputs were established (Table 1).

**Table 1.** Criteria and quality indicators of identified key modelling steps.

Key Steps	Imported Images	Sketches	Surfaces	Geometry Matching	Surface Transitions	Solid Body	Details
<b>Criteria</b>	Importing, scaling, and placing of images. Four images are needed.	Sketches for surfaces.	Surface shape, gaps, errors.	Surfaces match the required shape.	Tangency over the mirror plane.	Solid body creation.	Split surface and mouse wheel.
<b>Quality indicators</b>	Visual indication	Visual indication	Mesh preview. Curvature combs.	Visual indication. Volume and mass data.	Zebra * stripes. Curvature * combs.	Software readout.	Visual indication.

\* Zebra stripes and curvature combs were used as quality indicators for surface transitions and quick full model check-up.

Zebra striping is used in computer graphics to visualize curvatures on smooth surfaces and is thus a diagnostic shading technique [38]. Curvature continuous surfaces show as smooth flowing stripes, whilst broken tangency displays as an abrupt change in the direction of the stripes [39]. Curvature combs are graphical elements associated with 3D modelling software that indicate the degree of curvature at a particular point on an element. They are used to predict problem areas in sketches, especially splines used to create complex surfaces [40].

### 2.1. Preliminary Study

The preliminary participant study aims to benchmark activities in the 3D modelling process using desktop modelling tools. Fourteen undergraduate mechanical engineering students participated in the first study. Prior to the study, the participants attended 7 lectures on surface modelling. The participants all had experience in 3D modelling using Solidworks Premium version 2019, which was used for the purpose of the study. They had the task to create a 3D model of a mouse according to the given sketches (import images, initial sketches, modelling curves, surfaces, 3D model CAD). Steps in the surface 3D modelling were: (1) Importing images, (2) creating sketches, (3) forming surfaces, (4) geometry matching, (5) applying surface transitions, (6) achieving solid body, (7) creating details. The criteria for successful creation of the CAD model were: matching dimensions (object scale), solid body, use of specific surface transitions and detail creation (Table 1). The time limit for completing this task was set to 80 min.

### 2.2. Research Study: VR 3D Modelling Study

Because of the newness of VR technology, the commercially available equipment is high-priced, and exploration of its possible applications is still in progress. There are no established workflows and sources of information and learning materials on different applications are scarce. The possibility of using VR tools for freeform modelling was firstly studied by the researchers and the steps were determined as explained in detail in Section 2.2.1. It is important to note that it takes a certain amount of time to get comfortable with the headset and controllers' manipulation and to learn the functionality of the VR tools. For this reason, the study was conducted with a focus group. The focus group methodology enables the researchers to obtain more in-depth insights and information by employing open-ended questions and encouraging the participants to speak openly [41]. The VR study consisted of the preparation activities, where participants (Section 2.2.2) were given instructions (Section 2.2.3), and later participated in a focus group test (described in Section 2.2.4), where they modelled the assigned 3D part.

#### 2.2.1. VR 3D Freeform Modelling Steps

VR 3D freeform modelling can currently be achieved with NURBS surfaces or subdivision surfaces. However, good surface transitions and merging of surfaces in VR modelling can currently only be achieved with subdivision surfaces. Therefore, they were used as they preserve the curvature continuity across the entire shape.

The process of modelling using VR tools can be split into distinct phases, similar to desktop modelling. Considering that the goal was to create a model according to the images, some precision is required. Sketching of the rough outline could be omitted in VR; however, it is often useful to capture the geometry as best as possible. One of the critical points is to achieve a solid body. As the VR tools enable only the export of meshes, it needs to be later converted. The detailing can also be done after the conversion.

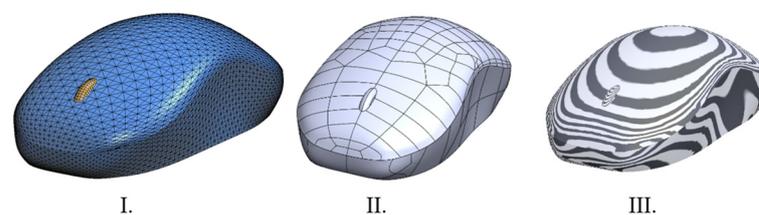
One of the important key features identified in the participant study was the ability to capture the desired shape. To achieve this, the reference images need to be placed on appropriate planes and scaled to a suitable size. The VR tools achieve this by snapping the images to the planes and by incorporating accurate measuring tools to scale the images. Some tools enable the snapping of images to the middle point of the image. If the images are prepared with care, this can enable very accurate positioning and alignment. A 3D view with a bounding box can be included to depict the shape more accurately.

The modelling can then be continued by directly creating the surfaces. However, sketching a rough outline can sometimes be useful. The sketch also includes control vertices (CVs), to which the surface CVs can be easily snapped to later. Firstly, a sketch is created, then the users can position themselves to a certain projection and move the CVs in an XYZ direction to accurately match the reference images. This ensures that the desired shape is achieved.

The most important key feature identified in the participant study is creating the surfaces. Design guidelines need to be considered when creating the surfaces. These include: the fewer control curves and control vertices the better; be mindful of the transitions between the surfaces; when translating the mesh to CAD, be mindful of the mesh accuracy; when aligning surfaces, they need to have an equal number of CVs; create surfaces where the angle of the corners is as close to 90°; and try to create four-sided surfaces. It is possible to create only half the model and mirror it over the mirror plane. This ensures a tangent transition over the mirror plane.

The detailing can be executed in the VR or desktop environment. However, when creating a model for design review in VR, it is faster to create it directly in VR tools.

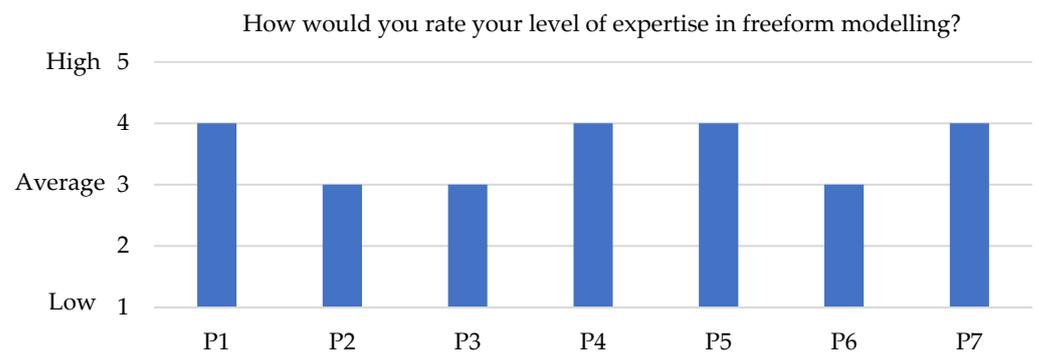
One of the key features of modelling in desktop applications is to achieve a solid body, which is later used in downstream processes. Current VR modelling tools do not enable the export in formats for solid body modelling. If this would be ensured, the VR modelling would be even more compelling to engineers. However, the design can be exported in a mesh file (Figure 3I), which can be converted to a solid body with many tools. Figure 3II shows the creation of a solid body with surface patches on which zebra stripes can be applied (Figure 3III).



**Figure 3.** Solid body conversion. (I) Exported mesh file. (II) Solid body created from surface patches. (III) Applied zebra stripes.

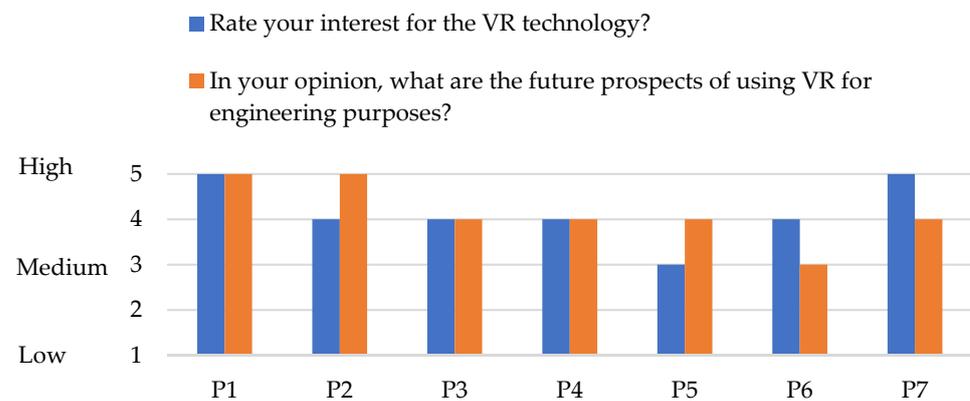
### 2.2.2. Participants

As VR technology requires a lot of training the study was conducted with a focus group. It included seven participants, six male and one female, who were all students of mechanical engineering and had previous knowledge of 3D modelling in desktop modellers. All participants had experience and were familiar with the creation of 3D models using freeform (surface) modelling (Figure 4), for which they used either SolidWorks or NX software.



**Figure 4.** Participant freeform modelling knowledge: self-evaluation.

Three out of seven students have tried using VR equipment before, but only once and it was for videogames. None of the participants owns a VR headset, nor did any of them tried using VR for 3D modelling before this study. Figure 5 shows participants' interest in VR technology and their opinion on the perspective of using this technology in engineering.

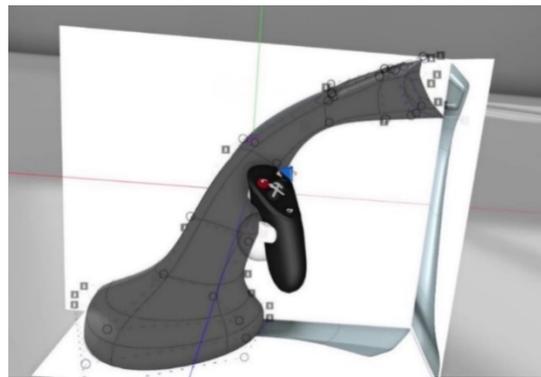


**Figure 5.** Participants beforehand opinion and interest in VR technology.

### 2.2.3. Study Preparation

Three researchers who led this study are considered experienced users (experts) based on their experience in both desktop CAD surface modelling and using VR technology for 3D modelling. They also participated in the study to test the features and prepare the user study. Multiple design software were tested before performing the study. Simple design tools such as Google Blocks and Microsoft Maquette enable designing with primitives and export of FBX format of results, however, they do not enable complex modelling with surfaces. The considered surface modellers were Autodesk Alias Create VR, Gravity Sketch, and Flyingshapes. At the time of the study, Gravity Sketch had the best capabilities of surface modelling, geometry manipulation, and subdivision surfaces, so further experiments were performed using this software.

Prior to the research study, the participants attended a presentation of modelling in VR and were given videos of modelling example models (shown in Figure 6) in the VR environment. They were then also given a chance to create the model shown in the videos (Figure 6). Throughout the workshop, the participants were encouraged to adhere to guidelines for creating the surfaces (explained in Section 2.2.1).



**Figure 6.** Still from a video showing the creation of an example model in a VR environment.

#### 2.2.4. Focus Group Study

The participants in the focus group study were tasked with creating the model from reference images of the computer mouse (Figure 2). The study took place in a classroom and was prepared according to a practical guide for focus groups by Krueger et al. [42]. An individual user's modelling time was limited to 60 min. Three experts were present during the test and had the role of the observers during the study. Before the test, each participant was given an individual introduction to the task and was asked to answer a questionnaire about their background. During the test, the observers helped the participants if they had problems finding the correct controls in the VR modelling software. The design steps and flow were not influenced by the observers. The participants were systematically questioned during the test. Each individual test with a participant was recorded by capturing the video stream and sound from the VR headset and one of the observers recorded the user's comments. In the end, they were given a questionnaire about their experience.

The study was performed with an Oculus Rift S headset. The headset includes inside out tracking and, therefore, does not require any external sensors. All of the tested software offer support and are compatible with the mentioned headset. The software and VR were run on a laptop with an NVIDIA GeForce RTX 2070 with Max-Q Design, 16 GB of Memory, and Intel Core i7-10750H @ 2.60 GHz.

### 3. Results

This section consists of (1) the results from the desktop modelling participant study and the observations; (2) the VR 3D modelling participant study, which includes the evaluated level of participants' task achievement, observations, and questionnaire results.

#### 3.1. Preliminary Study: Desktop Modelling

The results of the tasks indicate that most participants chose a similar approach of importing the drawings, creating sketches and projected curves, creating surfaces, and then creating a solid body with details. All of them used the strategy of creating half of the model and then mirroring it. However, correct surface transitions need to be used between the mirrored surfaces because the joined union need to be blended without any visible edges.

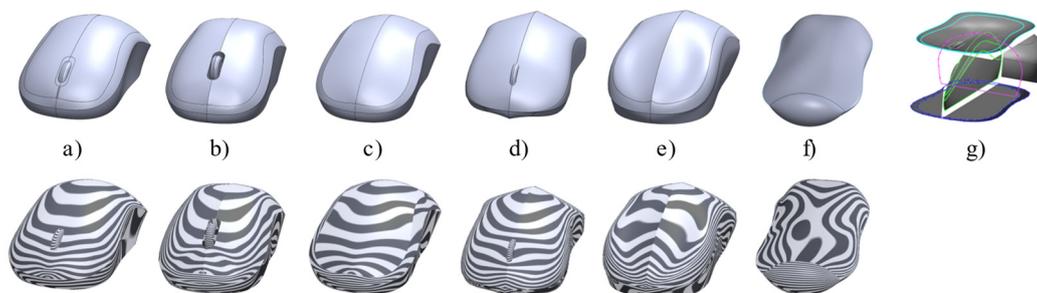
The average total time of task completion was 75 min, with eight of 14 participants reaching the time limit. The fastest one took 63 min. All except one participant managed to import and set the drawings and it took them an average of 15 min. All but two participants managed to create sketches and projected sketches that would later be used for creating the surfaces. It took them an average of 19 min for this step. All but two participants managed to create the base surfaces. It took them an average of 25 min for this step. The geometry matching and surface transitions are included in the time for creating surfaces. Only six participants managed to create a solid body. This step took them an average of 4 min. Seven participants managed to detail the body. This step took an average of 20 min. Values displayed in Table 2 specify the percentage of participants completing each task. A

single task is divided into three levels of achievement which are: achieved, not achieved and partially achieved.

**Table 2.** Desktop modelling participant study—level of task achievement.

Level of Achievement [%]	Imported Images	Sketches/Projected Sketches	Surfaces	Geometry Matching	Surface Transitions	Solid Body	Details
achieved	93	57	36	36	29	43	21
not achieved	7	14	14	50	57	57	43
partly achieved	0	29	50	14	14	0	36
Average time [min]:	15	19	25	/	/	4	20

Most participants managed to import the images. There were only 7% of participants that did not import images into the CAD software. Figure 7 shows participants' models of diverse levels of achievement.



**Figure 7.** Crated models. (a) reference mouse (b) good shape and details, unsatisfactory surf. transitions (c) good shape and surf. transitions, no details (d) no solid body, bad surf. transitions, bad shape (e) bad surf. transitions (f) bad shape, only surfaces (g) didn't reach surface phase.

Commonly the difficulties started when they had to project and scale sketches in the layout of the software. Only 57% of participants arranged the sketches in the correct order. Next, half (50%) of participants have partially achieved creating the surface model. This means that the quality of the surface was not sufficient and would probably result in a zero-thickness geometry in the next steps (Figure 7d,e). Still, 36% managed to create a surface model. In the geometry matching, visual similarity between the picture of a mouse and the surface model was observed. This task was successfully achieved by 36% of participants (Figure 7b,c). The quality of a surface is essential for creating a smooth surface transition. If continuity is not established at a merging point between two surface models, an edge or hole will appear at the joining end. Again, only 29% of participants achieved a satisfactory surface transition. If every step in a process of CAD modelling was made at a sufficient level so far, this would lead to a solid body. A solid body with varying surface quality was achieved by 43% of participants. Furthermore, a high number (43%) of participants didn't create details on a solid body. The participants which faced difficulties during CAD modelling dedicated too much time to steps trying to complete a particular task and lost the motivation to make details or didn't know how to achieve it (lack of knowledge).

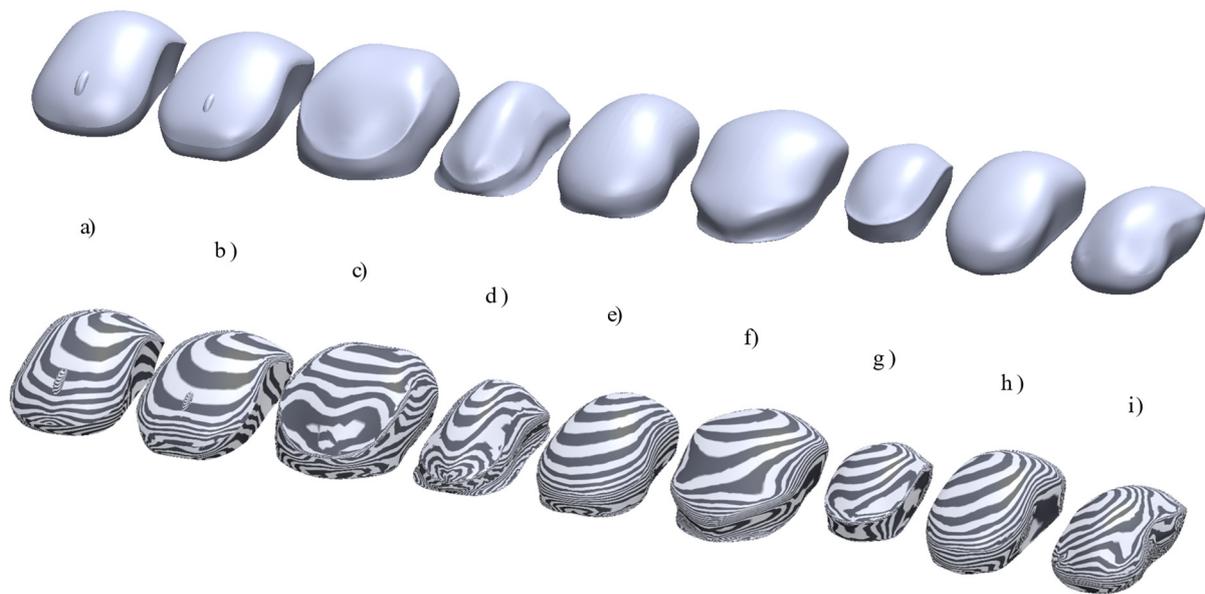
### Findings

Seven participants managed to capture the geometry accurately. Others did not create the model according to the sketches. Only six participants included the right transitions between the surfaces. Only six managed to create a solid body, others had problems because of incorrectly modelled surfaces, having gaps and incorrect transitions. When

creating the top surface, the participants rarely used the correct transition over the mirror plane, which would be the tangent transition.

### 3.2. Research Study: VR 3D Modelling Results

The participants in the VR 3D modelling study all managed to create 3D models with varying success. Their efforts are shown in Figure 8. Case (a) is a reference mouse made in Solidworks. Case (b) is a mouse made by a Gravity Sketch expert user (mouse modelled in Gravity Sketch with SubD surfaces). Cases from (c) to (i) show the participants' results in order of their try. The average times of individual phases were as follows: image placement and scaling—5 min 30 s; sketching the rough outline—12 min 17 s, creation of surfaces—17 min 7 s.



**Figure 8.** VR 3D modelling participants results: solid geometry models (**above**) and zebra stripes models (**below**). Case (a) reference mouse made in Solidworks; (b) mouse made by a Gravity Sketch expert user; (c–i) the participants' results.

Table 3 shows the volume of the models in  $\text{cm}^3$ . The participant (e) visually achieved the shape, which best resembles the design intent. This is also evident from the volume, which is close to the reference volume. The participant (g) failed to scale the images correctly and consequently created an inadequately sized mouse. All other participants managed to adequately import, scale and place the images.

**Table 3.** The volume of models in [ $\text{cm}^3$ ].

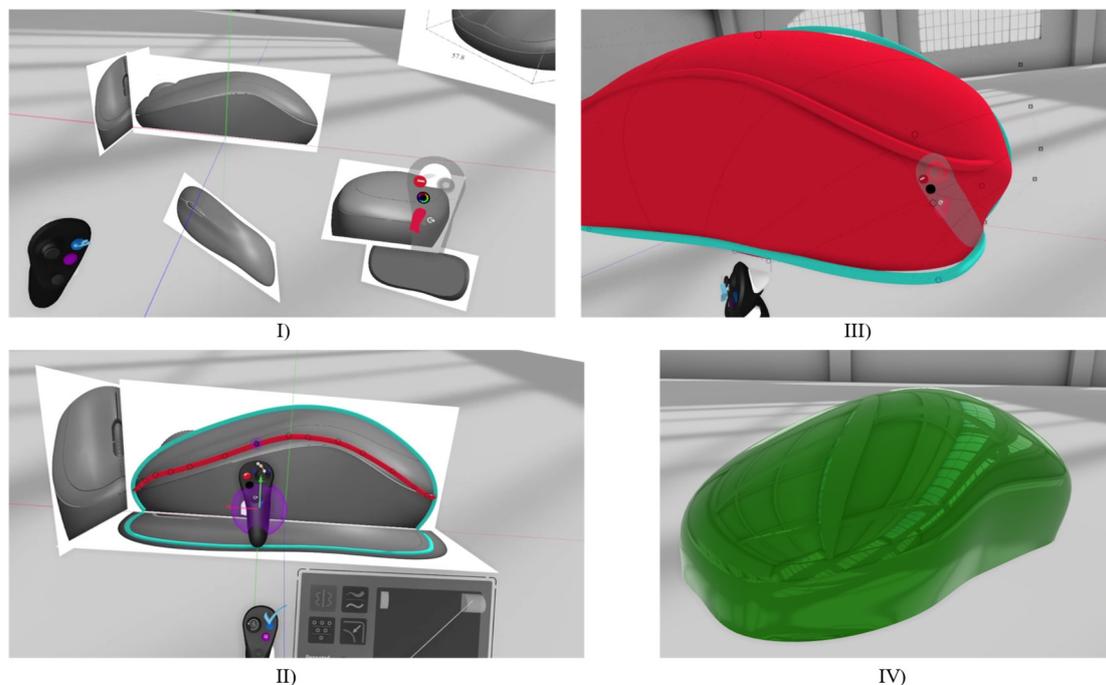
Case	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
Volume [ $\text{cm}^3$ ]	130.5	144.0	183.7	80.9	119.3	165.0	64.4	118.3	93.4

The level of individual task achievement in percentages is shown in Table 4 and individual phases in VR 3D modelling are illustrated in Figure 9. The images are captured stills from the workflow of participant e. Phase (I) includes importing the images, scaling, and accurate placement. The average time for this stage was 5:30 min. Phase (II) includes the creation of the rough outline, which consists of two planar sketches and one 3D sketch, created by accurately moving the CVs in an individual axis. Four out of seven participants achieved a sufficient level of sketching the rough outline with the other three reaching a partly achieved level. The main mistake was not outlining the correct edge. The average time for this stage was 12:17 min. Phase (III) represents the creation of the surfaces. Five out of seven achieved good surface transitions and the other two reached a partly achieved

level. The average time for this stage was 17:07 min. Geometry matching and surface transitions are also included in this time. Only two achieved good geometry matching, three partly achieved, and two didn't achieve good geometry matching. This can be attributed to not scaling the images correctly (case g) and not sketching the rough line accurately. Phase (IV) includes mirroring and merging of the model and exporting. All the models could be converted into a solid body. The time for the conversion was not measured since it was performed by the researchers after the participants finished the study.

**Table 4.** VR modelling participant study—level of task achievement.

Level of Achievement [%]	Imported Images	Sketches/Projected Sketches	Surfaces	Geometry Matching	Surface Transitions	Solid Body
achieved	86	57	86	29	71	100
not achieved	0	0	0	29	0	0
partly achieved	14	43	14	42	29	0
Average time [min]:	5:30	12:17	17:07	/	/	/



**Figure 9.** Phases in VR part modelling. (I) Image placement; (II) Sketching the rough outline; (III) Surface creation; (IV) Final model.

### 3.2.1. Observations

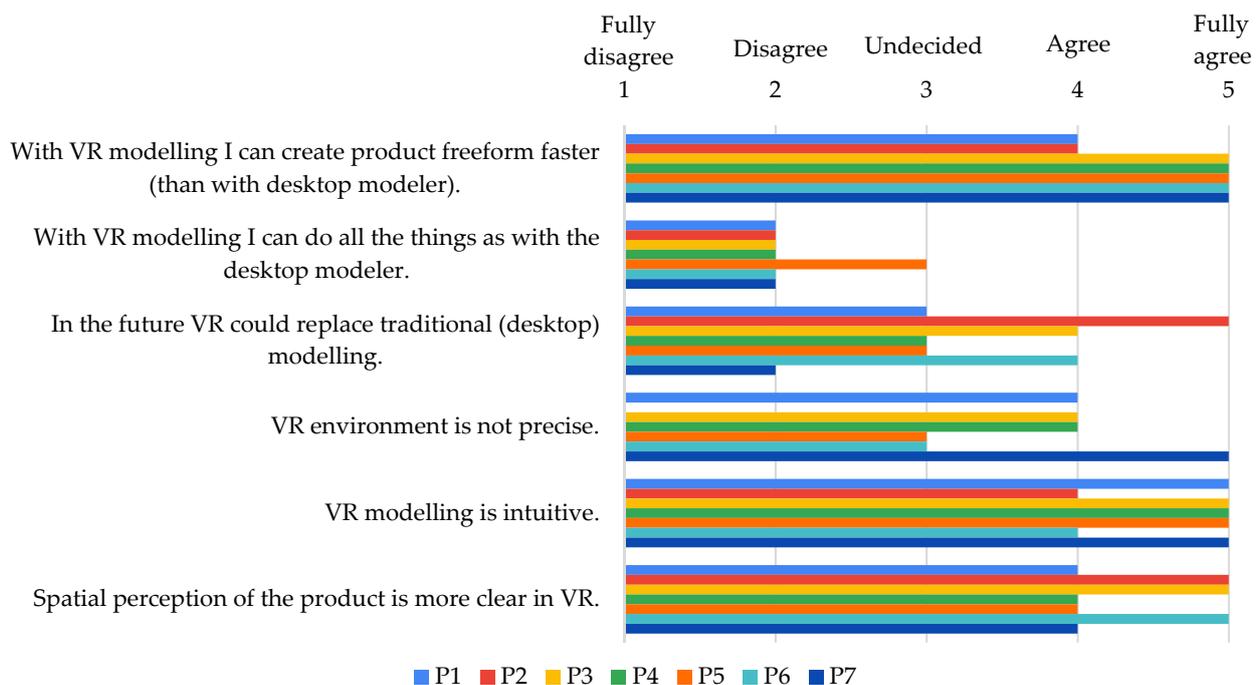
During the user testing with a focus group, the researchers recorded the modelling process and documented their observations related to different VR modelling phases (Table 5). In general, the user test records show that the participants had initial difficulties with the use of controllers but later managed to get a hold of the controllers to create the surface model. Their comments during the user test show the need for tools that would ensure higher accuracy in the VR 3D modelling environment. The most difficulties occurred when trying to mirror and merge the surfaces using the appropriate features in the VR modelling software. In cases when the participants got stuck with the appropriate selection of the tools and clearly expressed their intention, the instructors helped them.

**Table 5.** Researchers’ observations during the modelling steps.

VR Modelling Phases	Researchers’ Observations
Imported images	Importing alone was easy and none of the participants complained about it. They all said it was intuitive.
Sketches/projected sketches	Placing the sketches in the coordinate system was reasonably quick, but scaling the images caused problems for the participants.
Surfaces	Creating the surface patch was quick but fitting the surface to the curves was time consuming and required some extra work.
Geometry matching	The VR process does not allow for exact positioning on planar views (e.g., top view, side view), therefore, the alignment of the geometry must be done from a 3D perspective, which caused issues with geometry fitting to the reference images.
Surface transition	At this point, participants have prepared half of the surface model for mirroring on the right plane. They had difficulties creating a suitable surface model with an appropriate amount of vertices to achieve symmetry and frequently needed help with the controls.
Solid body	All participants succeeded in creating a fully enclosed surface model, which enabled the conversion of the model into a solid body. This step requires some additional work for model conversion in desktop tools. However, some participants did not succeed in creating the model with the right geometry and proportions.

3.2.2. Questionnaire after Modelling

After the user testing of 3D modelling in VR, participants were given a questionnaire consisting of 5-scale rating questions and open questions. First, they were asked to respond to questions about how much they agreed with statements about the use of VR technology. As can be seen in Figure 10, they largely agree that a freeform model can be created faster with VR modelling than with a desktop modeller. All but one participant disagreed with the statement that VR enables the same modelling options as a desktop modeller. They had difficulties deciding whether the VR is accurate or not, but in general, they feel that it is more of an inaccurate tool. They agree that VR modelling is intuitive and that the spatial perception of the product in VR is clearer.



**Figure 10.** Participants’ opinions on modelling using VR technology after the study.

In the questionnaire, participants were also asked to describe their experience in VR regarding 3D modelling, to state and argument their opinion if they would rather use VR than traditional (desktop) modelling and if they find one to be easier than the other (Table 6). The answers in the table below are given in their original form.

**Table 6.** Participants' statements about 3D freeform modelling using VR technology.

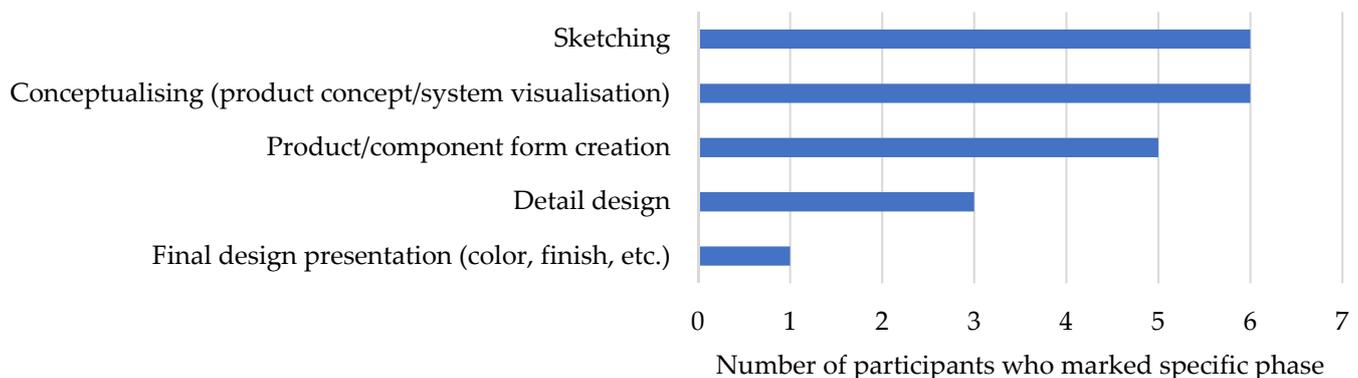
1. For freeform modelling I would rather use VR than traditional modelling.		
P1	I don't know	Certain things are easier in VR, even though I have more experience with classical (desktop) modelling. With more experience it would be easier to precisely model the surfaces.
P2	I don't know	It is useful, but it very much depends on the purpose. VR does not have the functionalities for numerical simulations etc. and for more detailed analyses I would rather decide for traditional modelling(desktop). For designing it is nicer to work in a VR modeller.
P3	Yes	Faster and simpler.
P4	I don't know	It might be faster to use for visualizing some rough ideas, which could later be edited and finalized in a traditional modeller (desktop).
P5	Yes	Faster and more fun.
P6	Yes	Easier editing of the freeform shapes.
P7	I don't know	Depends on the application: For reverse engineering of the object, I would rather use classical tools because it seems to me that they enable for more control. For designing from scratch, I would rather use VR because it enables more freedom, better perception of the details, it is more intuitive...
2. Is freeform modelling easier for you in the VR environment than in a desktop modeller?		
P1	I don't know	The same answer as before, current experience in desktop modeller.
P2	Yes	Because the vertices are more simply positioned and enable easier control of the movement in the 3D space.
P3	Yes	VR modeler(interface) enables interaction with the model directly in three dimensions.
P4	Yes	Creating and forming the surface is faster, it is easier to move around the model-turning of the model and moving the control points.
P5	Yes	VR is more intuitive.
P6	Yes	Because it is easier to edit the freeform surfaces.
P7	Yes	There are fewer problems/errors that there would be in the desktop modeller, everything somehow 'works out by itself.

When describing their 3D modelling experience in VR, few participants compared it to the modelling using the desktop tools. They argue that the freeform surface modelling is easier in VR: "VR enables very fast and intuitive surface modelling." (P3) and "Modelling is similar to Solidworks, more free forming (better ability to create free forms), maybe some control points are missing. It's easier to move around the model." (P4). Participant P6 gave a more detailed description highlighting specific modelling activities which are better in one tool than in the other: "VR modelling is pretty simple, maybe some functions are missing (closing the surfaces, extrude, ...). Certain functions, e.g., freeform modelling was easier in the VR environment than in SolidWorks because it is easier to move the points in 3D space. Positioning is easier in SolidWorks because we can choose the view which we want, in VR we have to position it manually. In SolidWorks modeller scaling of the images is also easier, because we can perform it in a way that we 'drag' the point and mark the dimensions of the model. In VR the spatial perception of the model is easier because of the more 'realistic' view of the model."

At the end of the questionnaire, the participants were asked in which stages of the design process related to 3D modelling they find the VR technology the most useful (Figure 11). Most participants think that VR is best to be used for sketching and conceptualising, more than half think it is suitable for product/component form creation, while only a few of them think it can be useful for detail and final design. Participants P1 and P2 reflected on the 'more realistic' perception of the model in VR: "In VR environment it is

easier to match the contour of the imported image and to do the detailing of the surface, because you see it ‘more realistic’” (P1) and “I think that in 3D modelling creating the rough shape of products is better in the desktop modellers, on the computer. For sketching, conceptualising and design (industrial) it is better if we can see the product model in the ‘realistic’ form.” (P2). Three participants mentioned that VR enables faster modelling but recognize this advantage mostly in the phase of sketching, conceptualisation, and rough form creation: “For more rough initial ideas it is definitely better to use VR because it enables fast, even though not very precise, modelling.” (P3), “Build-up of the model is pretty fast, but there is not enough control over the details (curvature comb, normal to the surface, elements’ relations...)” (P4), “Sketching, i.e., creating rough forms is faster in VR than in a desktop modeller. In remaining two (design) phases there are not enough functions available for appropriate phase completion.” (P6). Participant P5 stated “Application for (industrial) design is definitely better with VR”, where he referred to the usability of VR for earlier design phases and more complex freeform geometry creation. Participant P7 added that “Detailing is the only thing that doesn’t seem sensible to do in VR because there is less control over specific functions/parameters”.

In which of the following phases is the use of VR most useful? Multiple answers are allowed.



**Figure 11.** Participants’ opinions on the use of VR technology in different design phases.

#### 4. Discussion

Considering that VR is still a new technology and only a small amount of the general public has had the chance to experience it, introducing specific tools in VR requires a great deal of user training. Due to this, the study was conducted with a focus group and included both a qualitative and a quantitative study.

The results of the study show that modelling approaches in VR and desktop tools are comparable. Based on the participants’ comments recorded during the focus group study and statements expressed afterwards in the questionnaire, they describe the process of modelling in VR as intuitive and fast but rather imprecise. The reader should note that the participants were given a task to create a 3D model in VR based on the reference images. All participants had previous experience with surface modelling and were familiar with a similar procedure from using desktop 3D modelling tools. Hence, they had an idea of the main phases (steps) comprising the modelling process: insertion of images, creating reference curves, creating surfaces, and finalizing the model. The participants quickly got a hold of using the controllers and the features of the software tool and several times they mentioned that VR enables better and more realistic spatial perception than desktop tools, making it intuitive to use.

Considering the measured time for different phases (steps) of modelling, it is evident that the creation of a freeform model in VR is faster than using a desktop interface. However, comparing deviations of the output models from the VR and the desktop modelling studies, it can be seen that VR modelling lacks precision. During the focus group test and in the questionnaire after the modelling, several participants commented on the lack of tools in VR

that could provide more accuracy. Moreover, even though the VR environment is preferred for viewing the final model, aligning the geometry in VR according to the reference images seems to cause issues, as the images are viewed from a 3D perspective instead of the planar viewpoints as in desktop interfaces. In the current state, VR modelling software has some important features missing, such as missing zebra stripes or other surface quality evaluation tools. Therefore, if an error is identified in later stages, the user is required to go back to the VR environment to adjust it. Essential information about the model, such as dimensions and the enclosed surface volume are also missing. Therefore, it requires more post-editing of the form to achieve a solid model of acceptable quality. Nonetheless, our study showed that the transformation of the surface model into a solid body is possible using the appropriate tools, even if the quality of the model is not the finest.

Solid body exporting options are missing in the current tools, however, the model can be exported as a mesh file, which can then be transformed into a solid body using a variety of programs. Furthermore, these tools require a quality mesh to achieve a good result and entail additional know-how. Design review in VR has many reported advantages over the traditional process. There, the conversion from a solid body to a model appropriate to be used in VR is also a time and resource-consuming process. However, if the model would be initially created in VR, it would already be ready for the design review, which would shorten the time for the preparation of the review. The model could then be quickly edited in the same environment and afterwards converted to a solid body, when the final shape is decided.

Additionally, an important feature missing that would allow the users to create more technical models consisting of basic geometric shapes are the Boolean features. In this respect, a new feature would also be necessary for the application in mechanical engineering, which would enable the inclusion of multiple assembly components in the VR environment.

Participants of this study included only mechanical engineering students. It would be beneficial to conduct the study with industrial specialists and collect responses from their perspectives to identify additional potential issues that may be relevant for the engineering practice. The expert users managed to create a model of acceptable quality, nevertheless, it is evident from the participants' models that capturing the exact design intent with VR technology is challenging. The participants recognize the potential of VR technology for modelling and some even think this will replace conventional desktop modelling, however, they agree that with the current VR tools they cannot perform all the things as in desktop tools. This is also backed up by their observations, indicating that the VR technology is more useful in earlier stages of the product development process (e.g., sketching and conceptual design) and for the design review.

## 5. Conclusions

The research objective of this work was to investigate whether VR 3D modelling can be used after the conceptual design phase to bridge the gap between the concept and product's final form (model) in the engineering product development process. Currently, desktop CAD modelling is being used for this purpose, but it is a time-consuming process, where multiple issues arise, especially if the product has a complex geometry. VR technology enables the users to be immersed in the design environment and offers more liberate geometry manipulation, therefore it shows great prospects for modelling purposes. To further explore the main research question, different parameters were considered including the possibility of converting a VR-created model into a sold CAD model and the usability of VR modelling tools in terms of speed, intuitiveness of the tools and the modelling process, as well as the output model quality.

It was found that VR modelling is intuitive, fast, and offers better spatial perception/visualisation for users and enables the transition from concepts to detail design. However, when compared to the desktop modelling tools, VR lacks precision which leads to increased inaccuracy in the created 3D models. Also, it was found that current VR tools

do not provide suitable features for creating technical objects with simple, elementary geometrical shapes, and that they can be created faster and with greater precision in desktop modelling applications. Another important missing feature in VR is the inability to define relations between the elements (e.g., parallelism, distance, etc.). Based on these findings, it was concluded that VR 3D modelling in the current state is not yet a suitable technology to provide adequate support for mechanical engineering design applications. However, VR modelling proved to provide a quicker alternative for creating freeform models, which have more complex, organic forms. An advantage of modelling in VR is that the control vertices of the surfaces are more easily distinguished from one another because of the added depth of the VR environment. This has a significant impact when dealing with more geometrically complex models. Along with the fast-learning capabilities and intuitiveness of the use, this feature also indicates that the tool has potential for teaching purposes as it leverages the 3D visualisation to improve the spatial perception and the understanding of the structure of the surface (control vertices and curves) more clearly.

In further research, the technology could be tested in different stages of the product development process, and for different activities in product design, such as ideation and conceptualisation without a predefined design, for which the tools offer more advantages. Several advantages in the field of education were identified. To properly evaluate the educational prospects of VR 3D modelling different metrics should be considered to e.g., measure interestingness, fun, engagement, and knowledge transfer efficiency. Finally, the VR 3D modelling process could be tested by engineering professionals from the industry to obtain feedback from the real industrial use cases.

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