Multimodal Technologies and Interaction

Article

Virtual Reality Applied to Design Reviews in Shipbuilding

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Abstract

This article describes a pilot project studying the potential benefits of using virtual reality (VR) in design reviews of cruise ship interiors. The research was conducted as part of a 2020–2022 research project targeting at sustainable shipbuilding methods. It was directly connected to an ongoing cruise ship building project, executed in cooperation with four companies constructing interiors. The goal was to use VR reviews instead of, or in addition to, constructing physical mock-up sections of the ship interiors, with expected improvements in sustainability and stakeholder communication. A number of virtual 3D models were created, imported into a virtual reality environment, and presented to customers. Experiences were collected through interviews and surveys from both the construction companies and customers. The results indicate that VR can be an efficient tool for design reviews. The designs can often be evaluated better in VR than using traditional methods. Material savings are possible by using virtual mock-ups instead of physical ones. However, it was also discovered that the visual rendering capabilities of the used software environment do not provide the realism that would be desired in some reviews. To overcome this limitation, more resources would be needed in preparing the models for VR reviews.

Keywords: virtual reality; design review; shipbuilding; cruise ship; interior design

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1. Introduction

Virtual reality (VR) is gaining popularity in various industrial applications as the technology is advancing, and costs are becoming accessible also for small industries. Numerous potential VR use cases exist in industry, from the planning and engineering stages to visualization for marketing and review purposes.

In this study, the focus is on the visualization needs in design reviews. A research project called Sustainable Shipbuilding Concepts, or SusCon [1] aiming at sustainability improvements in shipbuilding, especially concerning large cruise ships, was run in 2020–22. The virtual reality pilot study, which this paper describes, was one part of the SusCon project and was executed between February 2021 and October 2022. In the Hoffman, Friedman, and Wetherbee categorization of virtual environments in shipbuilding [2], this would fall into “collaboration” and “visualization” categories.

A cruise ship is a complex machine offering a multitude of services. As it is obviously a means of transportation, it also has to produce air conditioning, sustenance, service water and sewerage, and other quality living and working conditions. It has to offer a multitude of entertainment and sensation possibilities such as spas, amusement parks, theaters, and high-quality restaurants for the passengers. This is all controlled by factory-level automation and powered by on-board power generation. Of course, everything must be performed preferably with low emission and waste generation rates. To emphasize, a cruise ship is a modern factory with its own power plant producing life-support, movement, and entertainment.

This article describes research that is first of its kind, as it applies VR to an on-going shipbuilding process. Therefore, unlike being merely theoretical or relying on pre-crafted test settings, the research has been performed while the multi-billion project of Icon of the Seas [3] was being designed and built. This research is focused on the use of VR, following the definition of the Reality-Virtuality Continuum by Milgram et al. [4].

2. Motivation for VR in Design Reviews and Customer Communication

Cruise ships, unlike cars or aircraft, are not serial products. Practically every ship is different, and even sister ships have their unique restaurants and entertainment facilities. Therefore, most of the interiors must be designed and reviewed specifically for the particular ship. A typical cruise ship project has nearly one thousand tier 1 subcontracting companies [5] forming a complex stakeholder hierarchy in building different sections in the ship. During the design and implementation of each section, there is a need for constant communication within the stakeholder network. The motivation for using VR in design reviews comes from this inherent complexity of the project, and making the communication between the customers (the shipping company and its architects and designers) and constructors more fluent.

2.1. The Shipbuilding Process

The design of a large ship begins several years before its delivery. The ship is built in sections so that each large block is assembled separately and then lifted to the pool and welded together. The detailed design of various interior areas is performed parallel to the design and construction of the entire vessel, and the actual construction (also known as outfitting) of the interiors is performed mostly during the last year before the delivery, when all sections of the ship have been joined and the whole ship is in the dock pool.

In this study we are focusing on the design and outfitting stages of the interior sections of the cruise ship, like restaurants, shops and promenades with their stairs, furniture, lighting, etc.

Figure 1 presents a simplified version of the interior design process. It starts with the architectural and engineering design, which are typically performed using computer-aided design (CAD) tools, resulting in virtual 3D models. Then, some parts selected by the customer and supplier are constructed as mock-ups, or physical examples of the interior elements, to be reviewed. After the reviews, some changes may be requested, or the examples are approved as they are, and then the actual construction work begins.

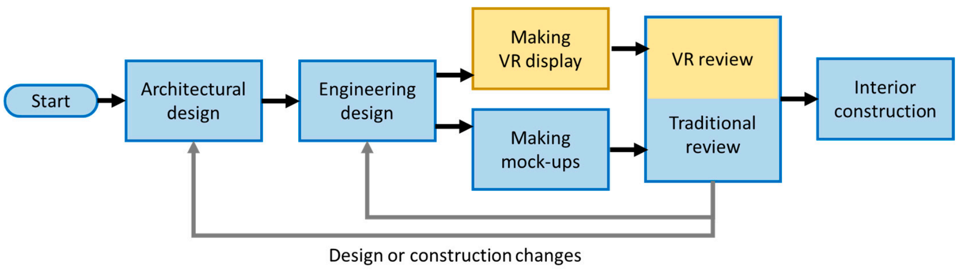

Figure 1. A simplified interior design process flow. The yellow ones are new stages, adding VR reviews. After architectural and engineering design, the resulting 3D models may be used for making VR displays or traditional physical mock-ups. After review, the designs may be returned to design phases for design or engineering changes. When designs are approved, actual construction stage can start.

In the process figure, the yellow sections are the new steps proposed in this study, containing the use of VR in the design reviews.

2.2. Replacing Physical Mock-Ups with Virtual Models

One essential part of the conventional shipbuilding process are the mock-ups mentioned above. They are small constructions of essential elements of the ship's interior, for example, pieces of furniture, wall and ceiling constructions, and decorative objects built to verify the physical and visual properties of ship artifacts. Their purpose is to verify the construction quality as well as appearance and ergonomics of the final products before the actual construction begins thus preventing material loss on re-building larger entities. One such example can be seen in Figure 2.

Figure 2. An example of a physical mock-up. This piece of a staircase was built for verification of the appearance and build quality before beginning the construction of the actual interior.

But since mock-ups are by definition small excerpts of the actual environment, one cannot obtain a complete impression of the environment from those only. Building mock-ups takes time and consumes materials, and they will eventually be destroyed. VR can be an efficient tool for saving resources by replacing some of the physical mock-ups and providing presentations of larger entities than mock-ups (Figure 3), but some physical mock-ups will still be needed.

The customer and interior constructor agree on which elements must be built as mock-ups. In review sessions, the customer can inspect the constructions, and possible modifications can be negotiated. VR solutions bring in the possibility of inspecting larger areas, even the whole ship. It is also possible to conduct VR-based inspection remotely over the Internet, diminishing the need for travel, and remote review meetings can be arranged more often with short notice and even before any construction work has started. The main limiting factors with VR are that it does not provide the opportunity for build quality inspections, and there is no tactile feedback of the materials.

The research focus in this study is on VR visualization of cruise ship sections, and specifically in replacing and supplementing physical mock-ups with virtual objects. The pilot companies' motivation to try VR design reviews is based on a few assumptions of their own derived during project planning:

1. Making virtual 3D models is quicker and cheaper than building actual physical elements.

2. It is easier to perceive the size of the complete product and the relations it has to the other elements in the area when the review is performed in VR, compared to traditional means of presenting 3D models on 2D screens. This advantage has been reported in several studies, e.g., [6,7].
3. It is possible to display much larger entities in VR than in traditional mock-ups, which are by definition only small sections of the entire environment. In fact, the complete surrounding environment can be made visible in virtual reality.
4. Using VR and remote collaboration has the potential to make the communication between customers and construction companies quicker and more efficient, and reduce the need for travel. However, during this pilot, remote collaboration was not tried, as it would have required customers to install VR systems and probably to update them during the pilot period. This could have required too much extra effort within the customer's organization. Therefore, this aspect is not in focus in this study.

Different interaction space options for VR exist. In a collocated setup, all the participants are in the same location, while in a remote setup they are in different locations, interacting with each other via a digital connection. Hybrid setups allow collaboration between collocated remote participants. In this case, only collocated setups were used in practice.

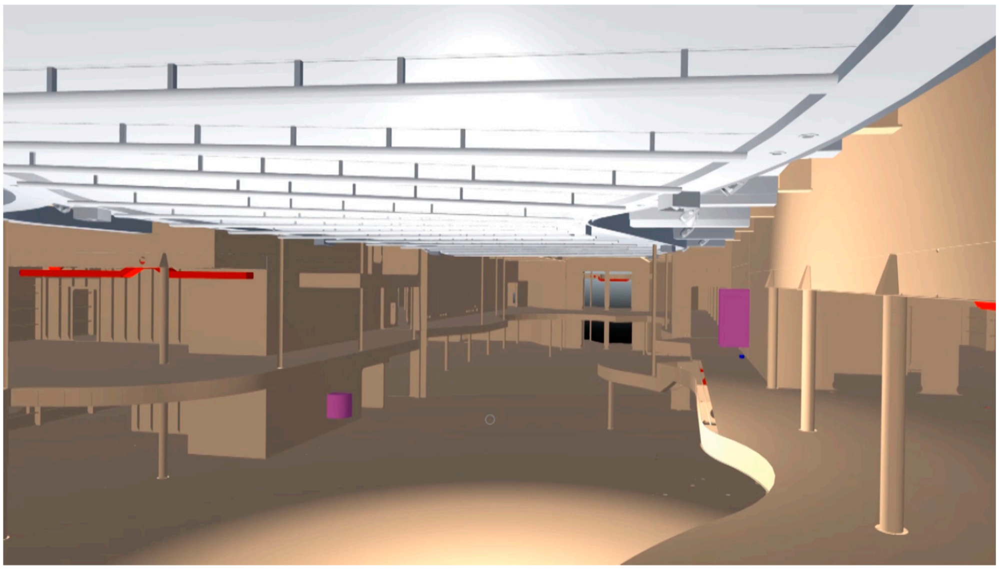

Figure 3. An example of an early phase VR representation. The ceiling construction is the object of review focus, while the other elements help viewers perceive its role in the larger area.

Information security is an essential topic when confidential information is being transferred between companies. In this case, unpublished 3D models must remain confidential. Data security is handled using secure servers and data protocols, but since this issue is out of scope for this study, those subjects are not discussed further here.

2.3. Earlier Work

Gernez et al. [8] discuss various applications of VR in ship design tasks in their paper that is based on two maritime projects. It states that the use of VR for collaborative design has been limited in the maritime industry, compared to, e.g., architecture and construction, even though there are examples of VR application from marketing to design and engineering tasks in maritime industry.

Liu et al. [9] have studied the impact of virtual reality on design review meetings in the field of architecture, which is close to our case: ship interiors can in many cases be considered as architectural environments. The study leads to the conclusion that VR alone does not give better results than traditional media, but it should be used with other visualization media, like drawings, renderings, and maps.

A paper by Fourrier et al. [10] discusses using VR not just for visualization, but also as a data manipulation tool. ("Virtual reality beyond design reviews...") This means enabling data manipulation functions so that the virtual environment would be more interactive and modifiable by the users within the VR space. Obviously, to realize this, some new data interaction techniques and standards would be needed.

Our virtual review concept is similar to the case that Bellalouna presents [11] as a potential VR use case: VR-based product mock-ups for design reviews and requirements analysis. That article describes most industrial VR applications having the character of a prototype. Most companies are in a waiting position towards VR due to reasons like negative experiences with old VR generations and lack of engineering-oriented VR solutions. However, the interest and investments in VR among industry are growing steadily.

In a systematic review article, de Belen et al. [12] report three main factors that are essential for collaboration in mixed reality (MR) environments: annotation techniques (provide non-verbal communication cues to users), cooperative object manipulation techniques, and support of user perception and cognition (to lessen cognitive workload for task understanding and completion, and to increase users' perceptual awareness and presence). All these factors were considered in this study.

A paper by Davila Delgado, Oyedele, Beach et al. [13] lists 21 factors driving MR-adoption in industrial use, as well as 21 limiting ones. The main driving factors are the improvements in project delivery and possibilities of providing better services. The limiting factors are mostly related to the idea that VR and AR technology is expensive and immature. Expert knowledge is required, and there are significant technological issues still to be solved. Also, Fernández-Caramés and Fraga-Lamas [14] contribute to the discussion about AR/VR adaptation of shipbuilding with their insight on improving practices. This research, however, was published too late to be included into this research setting.

Gupta, Ucler, and Bernard [15] have reported about remote virtual customer inspection (VCI) processes, where AR or VR technology is used to remotely inspect an actual product to obtain customer feedback. They also talk about VR inspections of virtual mockups. The study states that using virtual customer inspection the stakeholders can be integrated into the production process from early stages into the end of production realization, and that remote collaboration over such a system can be an efficient and economical solution.

Wolfartsberger [6] describes the VRSmart system in which the functionality is mostly similar with the CTRL Elements [16] software, which was used in this pilot. The study states that users had a good idea of the target object size in VR, and that the VR environment adds value compared to viewing the objects traditionally on a computer screen. Users could also find more faults in a 3D model in a VR design review than in a traditional review using CAD software through computer screens. Similar findings are reported in the article by Horvat et al. [7].

The need for interaction and kinematic functionality of the 3D models depends on the use case. Schäffer, Metzner, Pawlowskij et al. [17] propose a seven-level model of 3D model complexity and functionality, starting from plain 3D shape and going through textured and animated models up to a smart model with physics and logic. In design reviews, the highest levels with animated and physics-based behaviors are typically not required. A level 3 (3D model, including textures) model is usually sufficient, although it would be useful to see, e.g., the behavior and space requirements of opening doors in limited spaces like passenger cabins.

VR has been applied in architecture, engineering and construction (AEC) industry, as described in a systematic review by Wen & Gheisari [18] and others such as [19,20]. In shipbuilding, papers about VR usage for structural engineering purposes do exist, such as [21] and Li et al. [22,23].

As a summary, even though the cruise ship industry is well established and the use of VR in industrial settings is becoming more and more prevalent, to our knowledge, the usage of VR for visualization and reviews of actual cruise ship interior projects has been rather limited [2]. The goal of this pilot project was to introduce VR reviews into the routine building process, verify its applicability, and analyze and rectify detected problems in the VR process.

3. VR Application Pilot

A pilot project studying the applicability of VR in design reviews was executed from February 2021 to October 2022, which was about 14–32 months before the delivery of the ship. This period included the design of interior areas as well as reviews and construction of mock-up sections.

There were four companies participating in this pilot: the local shipyard, two companies that construct ship interiors and furniture, and one company constructing cabins. Previous experience of VR usage in these companies was minimal. Some employees had used VR headsets at home, but the participating organizations had no actual industry-oriented VR applications in use before this project. The persons participating in the pilot were engineers, designers, technical experts, and project managers in the participating companies. They participated in the follow-up interviews during the pilot as well as anonymous surveys in the beginning and end phases of the pilot.

The elements implemented as VR representations for review were agreed with the customer before starting the review process. They included things like staircases and shop cabinets, and they would have been constructed as physical elements if the traditional process had been followed.

3.1. Objectives

The main research objectives in the pilot were as follows:

1. Is VR useful compared to traditional processes of using physical mock-ups and blueprints?
2. Is the visual quality and level of detail in the VR environment sufficient to be used in reviews of cruise ship interiors?
3. How do the experiences from the pilot correlate with the presumptions and prior opinions about the use of VR?

Within the first and second objective, several research aspects needed focus. These include the feasibility of VR, in general, in the customer interface as well as in company internal dialog; the usability of the VR user interface; the ease of transferring the 3D models from CAD to the VR review environment; and the technical functionality of the environment and the realism of the VR view. The third one required analysis of the interviews.

3.2. Hypotheses

Based on the literature and the assumptions the participating companies had made, discussed in Section 2, as well as earlier experiences of the pilot participants, the following research hypotheses of VR-induced benefits were drawn:

1. Reviewing the models in VR is more efficient than using traditional methods.
   In VR, the review participants can move around and observe virtual models much in the same way as they would do with real, physical objects. Object sizes and distances

and be assessed better than from 2D presentations.
As a bonus, digital models can be made modifiable so that the users can remove elements of the models (for example, to see the internal construction), and surface materials and colors can be changed on the fly.

2. Material and human resources can be saved when mock-ups are virtual instead of physical.
An obvious one, since making virtual 3D-models is quicker than making physical constructions, and no physical material is needed. Furthermore, 3D models will be made in any case for the production, and the same models can usually serve for both production and VR presentation, so extra work for VR reviews should be minimal.
Traditionally, physical mock-ups are presented to the customer to verify the appearance and quality of the final product. Using VR, the physically built segments can be smaller than before, while VR offers the possibility of presenting a larger area in the review.
It should be possible to see savings also in travel expenses. It is still necessary to travel to see and try physical mock-ups, but many of the reviews can be virtual.
3. Virtual models can be modified easier and quicker than physical ones.
Different materials, colors, or various alternative construction options can be presented in one meeting instantly, whereas in the traditional process each variation requires duplicating a model, doubling the needed resources and requiring time.
4. With VR reviews, the efficiency of communication would improve.
It is possible to have reviews in earlier phases and potentially more often when performed in VR (and possibly with remote collaboration), as physical constructions are not needed. Meetings in virtual space may prove to be efficient for discussing the designs.
5. The users will be impressed with the easiness and effectiveness of VR.

The pilot participants were aware of certain limitations of the VR solution from the beginning. It was understood that all physical mock-ups could not be replaced with VR, because they will be needed in order to demonstrate the quality of materials and construction of the final product. The lack of haptic interaction with VR objects means also that physical exemplars of furniture like chairs and sofas would be needed to try out how they feel.

4. Materials and Methods

The methodology applied in this study can be categorized as applied action research consisting of qualitative and quantitative research, discussions, and observative analysis of usage within review. As Järvinen explains in [24], a main characteristic of action research is the goal function, an improvement of an existing system thus promoting the iterative and interactive nature of product or process development and research process. An existing VR platform was used in the study, and the collected experiences were taken as input for system improvements. Improvement actions were taken by both the piloting companies (refining their work processes) and in the software providing company, which released several version upgrades of the VR environment during the piloting project.

The pilot project was executed independently in each participating company, with somewhat varying timings during the duration of the pilot, through the following stages:

1. VR process introduction in the participating companies.
This included the purchase of the required equipment, including VR glasses and computers and the VR collaboration software, and taking the system in use in the company.

2. Expert evaluation of the CTRL Elements software environment.
   The software provider arranged introductory training for the users of the VR environment, which was followed by researchers from the university.
3. Following the effects of the VR process on the customer collaboration.
   The progress in the pilot companies was observed through regular interviews, separately with each partner company, from the start to the point where VR presentations had been used a number of times with the customers. The experiences and needs were also discussed jointly with the partner companies and the VR software provider.
4. Surveys about the expectations and achieved results.
   Two rounds of surveys were made in the partner companies: one shortly after taking the VR process in use, and another near the end of the project. At the end of the project, a third survey was made, targeted to the customers that had tried the VR system.

4.1. Software and Hardware

The software platform used in these pilots is CTRL Elements [16], a VR visualization and meeting environment designed for collaboration in virtual reality, enabling virtual meetings over remote connection as well as in collocated settings. There are other software options with comparable features on the market, but we wanted to choose only one environment for this study, in order to avoid additional pressures in the participating companies. Extra effort would have been required if the companies needed to switch environments. If the companies had used different environments, it would have made analysis of the results more complex. An additional benefit in choosing a local software provider was that it allowed quick response times for the improvements requested by the participating companies.

Target use cases for this environment include design reviews and other communication between industry and customers. The software supports typical functions found also in other comparable environments, including avatars, audio connection for discussion, moving freely in the space, and making written notes and 3D drawings into the meeting space.

With this software, 3D models are viewed in a customizable virtual environment. The models are typically made in a CAD system and imported in one of the several supported file formats. Models are essentially static; there is only limited support for moving or animated parts. One of the design principles of this system is that it supports importing 3D models from CAD systems directly, without extra work needed to modify engineering models for VR use. All rendering is performed in real time, again for a simple workflow.

CTRL Elements is a Unity-based [25] application that utilizes the SteamVR platform [26]. Common consumer segment VR headsets from, for example, Meta, HTC, and HP, are supported for the virtual reality experience [27–29].

The software feature set emphasizes virtual meetings and natural communication between users in the virtual space. Three-dimensional objects are imported into the virtual scenes, and end users can scale and position the objects freely using interactive tools. Users are presented as avatars in the virtual space, and they can move freely in the space using handheld controllers of the VR headset systems. Speech communication is supported; speech of another meeting participant can be heard from the direction of the corresponding avatar, and the distance is simulated as well. Using a function menu, avatars can move instantly near a chosen other avatar, or move another avatar near themselves. These functions are helpful in situations where people unintentionally get lost.

Users can also adjust the lighting of the scene to some extent, make 3D drawings in the space using handheld tools, change the surface colors and materials of the models, and take 360-degree photographs in the VR space. During the approximately 18-month period of this VR pilot, several versions of the CTRL Elements software (from 1.2.0 to 1.5.3.1) were used, providing updates to the functionality available to users. (Updates are described in Section 5.4).

For this particular ship, three-dimensional CAD models were created for the production of all the interiors, and an essential goal was to use the same models also for the VR presentations. Only small, preferably automated, modifications to the models should be allowed, to keep the additional costs of the VR process down.

The mathematical CAD models must be converted to mesh models for VR in order to enable real-time use. The cost for creating VR models from CAD models varies from case to case, and import parameters are an important factor of it. As the CAD models are continuously changing during the shipbuilding process, the transfer to VR must be repeatable to minimize the costs of model modifications. In most cases the models could be transferred from CAD to VR with almost no effort, just using suitable import parameters for producing precise enough detail but keeping the model simple enough for real-time rendering.

The computer hardware used in this pilot varied between companies. Both laptop and desktop computers were used for VR presentations, typically with Intel Core i7 class processors, 16 or 32 gigabyte memory capacity. NVIDIA GeForce RTX 2070 Super Max-Q (laptop) and RTX 3080 Ti (desktop) are two examples of used graphics cards.

The VR devices used were the Meta Quest 2 and the HP Reverb G2. Both of the headsets operate with 6 degrees of freedom and use inside-out tracking with built-in cameras. Meta Quest 2 can be used both as a standalone device with its Android-based operating system and processor (Qualcomm Snapdragon XR2) or wired to a pc using a USB-C link cable. The standalone version has a rather low processing power and thus cannot be used for visualizing heavy models, which is why it was not used in this test, but the option gives flexibility to its use cases. The device comes with potential for hand-tracking, which was utilized in a parallel study about gesture-based interaction compared to controller-based option [30]. The results indicated the hand-tracking being still rather unreliable in comparison, albeit more immersive. Gesture interaction was not used in this pilot.

The HP Reverb G2 has no standalone features, but it possesses a slightly higher image resolution per eye compared to the Quest 2. As a PC-linked headset its processing power is entirely tied to the PC it is connected to, with a recommended refresh rate of 90 Hz. Both VR devices were found adequate for the use-cases.

4.2. Usability Requirements for VR Reviews

There are two different target groups for which the usability of the system must be assessed:

1. End users: the review participants for whom the 3D models are presented.
   These participants represent many different roles and professions. There may be both experienced VR users and those who have no previous experience of such systems. Therefore, the interactions must be easy to learn and use, while they should be efficient and extensive enough to satisfy the needs of expert users as well.
2. The hosts: representatives of the ship interior manufacturers, for example, designers and engineers. They need to be able to import the models into the space, define their scale and placement, and adjust the lighting and other properties of the virtual space.

Moving in the space as well as communicating with other participants must be easy for everyone, and users should not experience uncomfortable feelings like nausea and dizziness. Some interaction with the models should be possible for all participants. It should also be possible to make notes in specific locations in the space and take snapshots (360-degree photos) in VR.

From the host users' perspective, it should be effortless to import 3D models into VR, and scale and move them into the desired locations. It should also be easy to adjust the environment for each presentation case. This includes modifying the scene where the models are presented ("the lobby") and the lighting.

5. Results

This chapter begins with user experience discussion of the CTRL Elements environment. Next, the findings from follow-up discussions with the participating companies are summarized. These include feedback from customers on the shipbuilding project. Based on these findings, the VR software environment was developed during the project, and the added features are described next. Finally, the results of anonymous surveys from the pilot companies and customer representatives are analyzed; these were made in order to confirm the results obtained from the discussions.

5.1. User Experience of the CTRL Elements Environment

In CTRL Elements, the user interaction is based on hand controllers of the VR headsets (Figure 4). There is some variation between different VR glasses and controllers, but the basic functionality is similar with all of them.

Figure 4. A user viewing a 3D model of a ship interior, wearing a HP Reverb G2 head-mounted display and hand controllers.

The user can move in the environment using two methods:

1. Teleporting. Pressing a button on a hand controller creates an arc from the controller outwards. Moving the controller, the user directs the arc to a desired point on a horizontal surface, and when the button is released, the user moves instantly to the pointed location.
2. Flying. A joystick in the controller is used to move in any direction in the environment. It is possible to limit the movement in the horizontal plane only thus rendering it walking. The other joystick makes the user turn virtually in the environment and, if vertical movement is enabled, also to move up and down.

Moving by the second method (free flight) may cause uncomfortable feelings to inexperienced users, as the virtual movements contradict with the physical sensations of the user. This was actually observed in some cases in the design review sessions arranged during the project: some users experienced nausea and had to stop using the system. This problem can be mostly avoided by using the teleporting: the user changes place instantly, without continuous movements, so that unwanted sensations in the balance organ are not triggered. Using the continuous movement technique with joystick may give a better feeling of immersion and situational awareness in VR, but the possible VR sickness symptoms can weaken the overall quality of experience so much that teleportation is often considered as the more problem-free movement method [31,32].

The movement methods are similar, like in many other VR environments. Learning them seemed to be effortless in the tutorial sessions arranged for new users in the partner companies. However, the above-mentioned sickness symptoms in some review sessions indicate that a very brief introduction to the movement options for the end users was not enough. Some kind of basic tutorial for moving in VR seems necessary for new users, and some time should be reserved for practicing it.

For settings and various functions in the VR space, CTRL Elements has an end user menu system that is used within the virtual environment. The menu is displayed on a virtual plate on the user's left wrist as seen in Figure 5. Turning the wrist presents the menu for the user, and items are selected from it using the right-hand controller, pointing a ray to the menu item and pressing the trigger key.

Figure 5. An example of the menu interface in the CTRL Elements VR environment. This menu page is used for exchanging the surface materials in the scene. The small white circle near the top edge in the view is the virtual pointer used for selecting the target of the operation.

This menu was found usable and easy to learn in general, although formal usability testing was not performed. Accessing the functions was effortless, and users were satisfied with the interaction design after initial training.

The menu includes the following main functions (all these have been supported during the entire project):

- Three-dimensional models brought into the space can be scaled and moved in the space. The scale, location and orientation values are given numerically through the menu.

- Parts or subsections of the models can be individually made transparent/invisible. Using this tool, the user can point to a component and press the trigger in the hand controller to hide it. Another command makes all hidden elements visible again. Unhiding the last hidden objects (in backward order), was not possible at the project starting time, which was noted as a deficiency by some users.
- Lighting of the virtual space can be adjusted. Originally, the only possible light sources were one ambient light and the sun. The sun's direction (both compass direction and angle of height) as well as intensity could be adjusted.
- Written and drawn notes can be added to the virtual environment. The note objects are called hotspots, and they can be positioned anywhere within the environment. This tool is useful for making notes in a review session.
- Users can take 360-degree images of the VR space at freely chosen locations. The snapshot function is activated from the menu, and the virtual camera is then positioned as desired.
- Distance measurement tool can be activated from the menu, and pointing to locations enables drawing a measuring scale. Distances can be measured between any two points or between planes, perpendicular to a plane.
- IFC model metadata in the 3D models can be inspected. It can contain information about materials and other properties of the construction elements.

5.2. Follow-Up Discussions and Participant Meetings

Regular follow-up interview and discussion sessions were arranged with each participating company. (Due to the COVID-19 situation, these were held as remote meetings.) The total number of meetings was over 20.

Topics related to technical issues were common in the follow-up meetings, but did not dominate the discussions. In the beginning, for example, there were reports of some materials not transferring correctly from CAD systems to VR. Such issues were studied and solved in cooperation with the software provider, and were then left behind.

The topics discussed in the following paragraphs are direct results from the interview sessions. These are considered to be the most relevant ones from the points of view of the research questions.

The initial reaction of the customer (architects and designers of the shipping company) about the use of VR models was found to be negative, as they required all examples as physical mock-ups. When told about the intention to make smaller physical models to ensure quality and larger entities as VR to ensure overall experience, the attitudes changed to positive.

The shipping company was proactive and requested a presentation using VR. Companies also presented the VR system to outsiders like visitors and potential new customers, and the feedback was, in general, positive. Designers were positive about the new addition to the design process as well. A significant difference was observed in the level of interest between technical experts and architects. Technical experts, such as lighting and audio designers, were more interested and positive about VR than architects, who regarded the visual quality of the surfaces as not satisfactory.

Practically all stakeholders spotted shortcomings in the system's original lighting options, but the quality of technical details in the models was seen decent by everyone, customers included. VR presentations obtained positive feedback also for being able to generate useful discussion in general.

A few VR sickness cases were reported from design reviews, which was assumed to be due to low experience and the use of virtual space in "free flight" mode, which could be countered with guidance and using (or forcing) "teleportation" movement. Apart from these cases, the customers found using VR easy and pleasant.

In the VR presentations, there was typically one VR system for the reviewer (customer) and another for the host (representative of the supplier). Therefore, VR's potential for improving the discussion in reviews could not be assertively validated. However, in the follow-up reviews, it was mentioned that VR tends to stimulate discussion about the designs in general.

The cost savings can be seen as notable. Same CAD models made for production had been used in VR presentations. There was not a significant amount of extra work needed to make the VR presentation. One participating company reported saving 2500 kg of materials by using virtual models in reviews, which corresponds to tens of thousands of euros.

Combining the ordered interior with the larger area model of the ship was also experimented. Simplification of the entire ship model (or part of it) was required; parts not visible to the space of interest can be removed to make the model runnable in real time VR.

There were two specific meetings where participating companies discussed together about the experiences and future visions of bringing VR as a standard element into the production process. In the second meeting, a representative of the software provider company was present. In these meetings, the discussion focused on limitations of the current software platform and features that were seen as necessary improvements. (These are discussed in Sections 6.1–6.5).

5.3. Customer Feedback

During the project, the participating companies arranged VR presentations for customer representatives jointly with traditional mock-up reviews as well as in separately arranged VR sessions. The number of customer representatives viewing the VR scenes was altogether around 20. Customer feedback was varied, from persons enthusiastic about the possibility of exploring designs in VR to some that were not very interested.

A found trend was that technically oriented persons (such as lighting designers) were more interested in VR than architects. A plausible explanation for that is that from an engineering point of view, VR enables exploring precise object arrangements in virtual space, whereas the feeling of realism, which the architects may be expecting, remains imperfect due to rendering limitations of certain materials and lighting.

One highly interested recipient was an audio designer, who spent a long time exploring speaker arrangements in a virtual ceiling construction. In a physical mock-up, it is impossible to study the high hanging structures so closely, but in virtual space, one can go near any location. Such cases support the hypothesis that a VR environment is efficient in exploring constructions of which there are no physical examples in existence yet, or which are difficult to inspect as physical structures.

Practically all customer representatives who tried using the VR system noted the lack of photorealistic lighting. Compared to still image renderings of interior designs, which often look like real photographs, the visual appearance of objects in this VR system is simplistic, notably looking artificial. The lack of complex shadows and natural-looking glossy surfaces was seen as the main problem. Such limitations in real-time rendering are due to unrealistic amounts of needed computation in scenes with complex CAD models, numerous light sources and glossy surfaces. This became the most discussed topic in the follow-up meetings with companies. (More of it in Section 6).

5.4. Software Updates During the Pilot

During the project's timespan, the software had three major software updates (from 1.2.0 to 1.5.0) and five small ones, ending to 1.5.3.1. The updates contained new features based on the needs that emerged with the pilot companies, and were also mentioned in the follow-up interviews. The following features were added with these updates:

- Moving objects by dragging, using the hand controllers, was added (only numerical input was originally supported). It is also possible to scale the models by grabbing the model with both hands and stretching/squeezing it.
- Surface materials in the model can be exchanged on the fly by the end users. The menu offers a list of alternative materials, any one of which may be chosen for each surface area in the model. The hand controller is used for selecting the surface patches when working with this tool. An example of the user interface for this function is seen in Figure 5. A further update added the function of changing the material on all surfaces having the same material by a single command.
- Support for adding new surface materials was added. This is not an end user function, but the designer could now define and add a new material into the model and into the list of available materials for end users.
- Point light sources and spotlights can be added to VR scenes by end users. The color and intensity of each light source are adjustable, and the orientation of the spotlights as well. The number of both point lights and spotlights was five in the first update, later raised to ten each.
- Making hidden objects visible one by one, in the reverse order, became supported.
- A viewer-only version of the VR environment was released. It is intended to be used by customers, to allow viewing of models without the participation of the designer/manufacturer. It has limited end user capabilities and allows only pre-made scenes to be used.

The functional updates mentioned above were the result of feedback from the users. During the project, partner companies reported their needs in the regular follow-up interviews, and they had direct contacts with the software provider too.

5.5. Participant Surveys

To verify the results from the interviews, two anonymous online surveys were performed among the participant companies, one at the beginning of the project, and another at the end. The number of respondents to these surveys were small (seven and five, respectively), which limits the possibilities of making statistical conclusions. However, since the total number of active participants in the included companies was about ten, the results seem reasonably truthful.

The first survey contained questions about the respondent's earlier VR experience, tutorial session, opinions about the CTRL Elements software functionality and usability (after some usage), and potential benefits as well as problems expected from the VR process.

The main content of the surveys were eight claims about the usefulness of VR, with which the respondents could either agree or disagree. To find out possible changes in opinions during the pilot, the same claims were presented in both surveys (Table 1). The persons asked to participate were the same for both surveys (those who participated in the project interviews as well), and the surveys were anonymous, so the identities of the actual respondents are not known. The claims were based on the hypotheses and research questions of the pilots, and they include positive, neutral, and negative potential effects of the use of VR.

Table 1. Opinions about the suitability of the VR environment to design, sales, and review use, at the start and end phases of the project. Respondents are the pilot companies' employees.

My Impression About the Suitability of VR Environment to the Intended Purpose According to My Experience So Far	Start Survey: N of Agreed Respondents (out of 7)	End Survey: N of Agreed Respondents (out of 5)
Improves visualization possibilities, affects mainly positively to design and stakeholder/customer communication	7	3
Helps to streamline design and sales work	1	4
Changes the work process, but probably does not streamline it	1	1
Has mostly slowing down effect to work	0	1
Streamlines and eases communication with customers and other stakeholders	3	2
Changes communication with customers and stakeholders, but probably does not streamline it	1	1
Changes the work process, but probably does not streamline it	1	1
Probably causes problems in communication with customers and stakeholders	1	1

The most significant changes in the responses occurred in the two first claims.

Claim 1 "Improves visualization possibilities, affects mainly positively to design and stakeholder/customer communication" received seven (out of seven) agreements in the first survey, and three (out of five) in the second. This can be interpreted to reflect the identified problems with visual quality in the VR environment, which is discussed in Sections 5.3, 6.1 and 6.2.

Claim 2 "Helps to streamline design and sales work" increased from one (out of seven) agreement to four (out of five). A likely explanation for this is that participants had seen the potential of VR in practice when it had been tried in reviews.

Claim 5 "Streamlines and eases communication with customers and other stakeholders" stayed practically the same (3 out of 7 vs. 2 out of 5), whereas all the other claims, that were either neutral or pointing out potential problems with VR, received 0 or 1 agreements in both surveys.

In the starting phase survey, opinions about the introductory training to the CTRL Elements system were asked. It was found to be a smooth experience, four out of seven had no significant problems, and three reported slight problems which were solved in the training. No one felt like needing more introductory training.

In free text answers, the following were mentioned as potential positive effects of VR technology:

- The technology can give better perception of spaces and their functionality.
- It is easier to present the product to people who are not used to traditional 2D/3D design representations.
- Customers can obtain a better understanding of the end product.
- Designing the product and environments will be easier, when it is possible to prove distances in VR space
- Approvals and making the required changes will be more streamlined.

Some potential negative aspects were mentioned as follows:

- The possibility that customers have difficulties in using the system (either usability or performance problems).
- The need for some kind of training for the customers.
- If there are usability problems, some resistance may occur.
- If the VR models require extra work (in addition to the normal engineering workflow) it will consume resources.
- Will the realism of VR models be sufficient? Virtual models cannot fully replace physical mock-ups.

The ending phase survey also contained questions about the user experience with CTRL Elements and reactions of the other stakeholders. Overall impression about the usability of the VR environment was fairly positive—four out of five respondents agreed with the claim "Some usability related problems have been encountered", but three respondents agreed also with claims "Overall easy to use and working well" and "Easy to teach basic use to new users". One user agreed with "Some users have encountered problems within the VR environment", which probably refers to the cases where end users had VR sickness symptoms.

Free text answers about usability in the end phase survey have two distinct problem areas:

One is in the building of the VR scenes. There can be scale differences in models coming from different CAD systems, and it is tedious to scale and move the objects in VR scenes. The adjustments were (in the beginning of the pilot) performed in the VR environment using the menu system and numerical values. The possibility to move and scale models "in an analog way", using the hand controllers, was added in a software update. Still, putting everything in place takes time, especially when several models are imported in a scene. This is discussed more in Section 6.3.

Another significant problem area (not strictly a usability issue) is about rendering quality: the rendered materials are not as natural looking as expected. There are two issues: first, glossy and metallic surfaces do not show reflections, and second, lighting effects such as complex shadows are not rendered naturally. This issue is discussed more in Sections 6.1, 6.2 and 6.5.

Some answers indicate that 3D models made primarily for production purposes do not serve VR reviews perfectly. Although the model geometries are correct, realistic visualization is not achieved.

5.6. End User Survey

A survey containing ten questions about the VR experience was sent to selected persons in the customer companies who had tried the VR system during the pilot. Only two responses were received. Both respondents represented a design or engineering company involved in shipbuilding projects, not an actual shipping company. Their roles were designer and sustainability specialist. Neither of them had any previous experience of VR usage.

Among the questions was the same set of claims (except one) that was presented to project partner companies. The end users' responses are seen in Table 2. Both respondents agreed on claims that VR would improve visualization possibilities and communication, and that it helps to streamline design and sales work.

Table 2. Claims about the suitability of the VR environment to design, sales and review use, response from end users (customers).

My Impression About the Suitability of VR Environment to the Intended Purpose According to My Experience So Far	N of Agreed Respondents (out of 2)
Improves visualization possibilities, affects mainly positively to design and stakeholder/customer communication	2
Helps to streamline design and sales work	2
Changes the work process, but probably does not streamline it	0
Has mostly slowing down effect to work	0
Streamlines and eases communication with customers and other stakeholders	1
Changes communication with customers and stakeholders, but probably does not streamline it	0
Probably causes problems in communication with customers and stakeholders	0

This survey contained a set of claims on the suitability of VR to various purposes (Table 3), where the respondent could choose a number between 1 (not at all suitable) and 5 (very well suitable). For most listed purposes the respondents gave a very positive assessment. The most different opinions were given for reviewing the visual appearance of the objects, where one answer was the highest number and the other the second worst. This may indicate the different expectations that people could have about it.

Table 3. Opinions on suitability of VR for various purposes. Numbers in cells mean the number of respondents choosing that option; columns: 1 = not at all suitable, 5 = very well suitable.

Suitability of VR for These Purposes	1	2	3	4	5
Suitability of VR for these purposes Visualizing design options when no physical models exist yet	0	0	0	0	2
Reviewing large spaces like shops and promenades in a ship	0	0	0	0	2
Reviewing limited spaces like cabins	0	0	1	1	0
Estimating physical dimensions of objects and spaces	0	0	0	1	1
Reviewing the visual appearance of objects like furniture	0	1	0	0	1
As an expansion to physical mock-ups of ship interiors	0	0	0	0	2
Comparing design options, e.g., different dimensions, colors and materials	0	0	0	0	2

Both respondents agreed with the claim that VR helped seeing some things that are not easy to detect by traditional means. Even though both users reported having some VR sickness symptoms, neither thought that being in the virtual space was an uncomfortable experience.

In the last question, four different claims about the future of VR usage in shipbuilding were given as follows:

1. It has high potential, should have high priority.
2. It seems to be promising, should be developed further.
3. I don’t expect it to be very useful at least with current technology, perhaps later.
4. I don’t see any significant benefits in it, would rather try something else.

From these, both respondents chose the second one: VR is a promising technology, should be developed further.

A free text comment from one respondent was as follows:

"Applying VR in traditional building industry example shipbuilding can take a long time before it becomes a natural part of design workflow. So far VR has been used in mock up projects only but it could also be used as a part of final design and drawing approval process. After design phase VR has also potential to be used during area building as a reference and guide for builders. However, we can't replace the traditional manufacturing drawings, but we could achieve better results if VR becomes a shared tool for both design and manufacturing."

This comment includes ideas that are also present with many of the research articles referred to earlier in this paper.

6. Discussion

From the participant interviews, VR presentations and surveys, the results show evident benefits from VR usage. The VR environment enabled efficient viewing of objects to be built into an actual cruise ship, and for some reviewers VR apparently gave added value compared to traditional review methods. In many cases, the quality of the presentation was good enough for review purposes, using moderately capable, but not state-of-the-art hardware. This section discusses the needs that the partner companies expressed during the study (in the interviews, meetings, and some written documents).

A few specific themes especially stand out: 1. rendering quality related to materials, 2. realism of lighting, and 3. building of the virtual scenes. These themes start the discussion, and after them there are subsections discussing technical issues, and the validity of hypotheses are analyzed.

6.1. Rendering Quality Related to Materials

The visual rendering quality of the system became one of the main issues in discussion. For a perfect review experience, the objects in the VR should look real, with realistic shadows and reflections. All rendering in CTRL Elements is performed in real time. In practice, this induces significant limitations to the level of realism that can be achieved especially for shadows and glossy surfaces. In reality, all surfaces reflect light in their characteristic ways, and reflected light hits other surfaces again, giving them additional lighting and causing new reflections, and so on. To faithfully simulate this would require computing-intensive techniques like traditional ray tracing [33], which the environment does not currently support. Only simple first-order shadows are seen in the VR environment, and objects can look somewhat artificial. Figure 6 shows an example of the typical visual quality of the VR environment with different rendering options.

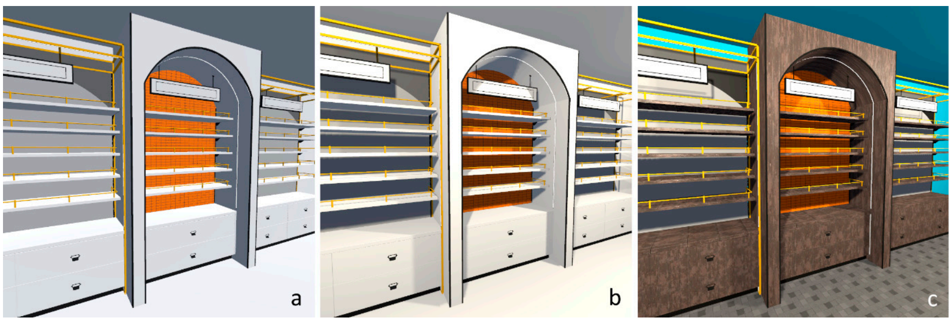

Figure 6. Rendering examples from CTRL Elements environment. (**a**): Model with directional light, no shadows. (**b**): Model with two added spotlights and shadows. (**c**): Model with added textures, two spotlights and shadows.

A different issue is that the textures used in the models' surfaces may be in the wrong scale or orientation. For example, on a wooden surface, the direction of wood grains should be correct. Texture orientations are not modifiable in the used VR environment. Instead, if such errors are found, they must be corrected in the CAD software and the model re-imported into VR.

Another factor in achieving realistic-looking virtual scenes is that engineering models contain only the "hard" elements of constructions. Bedclothes, curtains, and decorative objects are essential for the ambience in cabins, but they are not included in the engineering models. Shop shelves are empty. For a cruise passenger's actual view, such objects should be added to the scenes, and it would increase both the work to construct the review scenes and the computational load in rendering.

The 3D models used in the pilot were often complex as such, with lots of details and in some cases representing large entities. Special attention must be paid to conversions from CAD formats (defined in concise mathematical form) to mesh-based formats (consisting of triangles) that VR requires. Conversion parameters must be set so that the model is simple enough for real-time rendering, but detailed enough to look realistic, even in portable computer setups.

6.2. Realism of Lighting

The software environment (CTRL Elements) initially allowed only two light sources: the sun, the position and intensity of which is adjustable, and ambient light, which gives light to all the objects in the scene from all directions.

Adjusting just the sun's direction and intensity did not satisfy the customer's needs. In reality, there are numerous light sources which give the interior its visual character, but they are missing from the virtual scenes. Adding spotlights and point light sources became possible during the pilot projects, but complex lighting arrangements are still not supported. LED strips are widely used in new ships, but cannot be accurately simulated in VR. Adding numerous light sources in the scene multiplies the amount of computing, and modest computers would not be capable of real time rendering.

6.3. Building of VR Scenes

Reviewed interior scenes consist of potentially large number of objects designed separately, possibly in different CAD systems. The VR scenes in this pilot were constructed in the VR environment, applying the end user interaction capabilities. Some users considered it a tedious way of constructing complex scenes, and requests for a separate scene-building tool were heard in the discussions. In the beginning of the pilot, the adjustments were performed in the VR environment using the menu system and numerical values. The possibility to move and scale models "in an analog way", using the hand controllers, was added in a software update. Still, putting everything in place takes time, especially when several models are imported in a scene. The solution might be a desktop application in which object scaling and placement could be quicker to do than in VR. A similar problem affects adjusting the lighting: each light source is added and adjusted manually from within the VR environment. The environment does not support lights built into the CAD models.

In the scene building process, certain patterns of modifications to the 3D models may occur. Models from a specific CAD system and designer could typically need similar scaling and placement modifications. The VR environment supports defining one default scaling and orientation during the import of models. When contents are coming from several different CAD systems and designers, various modifications may be needed. A possible solution to such issues is to create design guidelines to be used with the CAD system, to make the models fit the scenes without modifications.

6.4. Process-Related Issues

For the participating companies it became obvious that to obtain the best possible outcome for the VR reviews, they must streamline their CAD process, too. It is important to find optimal parameters for exporting 3D models from the CAD system and possibly replacing some complex elements with simpler ones. This ensures that the real-time VR rendering works fluently while offering good visual quality. Secondly, using congruent scaling and orientation in all CAD systems makes importing models into VR scenes easier. All this is important for optimizing the use of work resources in the supplier company. The used VR environment (CTRL Elements) is being actively developed further as well in order to make the process more fluent.

6.5. Options for Graphics Fidelity Improvements

As new processing hardware generations are being developed, the achievable level of visual quality in real-time rendering rises. However, since no order of magnitude improvements are to be expected in the near future, other solutions have to be considered as well.

One new, efficient technique is foveated real-time rendering, where the user's gaze is followed and the scene is rendered in high resolution only where the user is looking at [34]. Another solution is cluster path tracing, where the rendering task is shared between a number of graphics processing units [35]. Such techniques are expensive and not yet commonplace, so they may not be among the top candidates when developing the capabilities of the VR environment.

One potential way of improving the rendering quality is the so-called render baking technique [36], where realistic lighting and shadow effects are calculated using, e.g., ray tracing, and then translated into lighting maps, which are displayed on the surfaces. This technique could be used to solve some of the problems discussed above.

The render baking process is time-consuming, but if the scene is static, it must only be performed once, and the resulting lighting maps can create a very realistic looking view in real-time VR. The technology is widely used in video games, where photorealistic scenes are an essential part of the experience. Larsson's course slides [36] explain the process. However, compared to designing a plain engineering model, there is a significant amount of extra work in defining the textures and reflection characteristics of surface materials, and modeling light sources realistically. A solution to keep the workflow simple should be found. It might be a separate tool to be used when importing models from a CAD system, or it might be added functionality in the VR environment, or something else.

Some of the participating companies experimented using Blender [37] to achieve views with better realism. Blender enables real time lighting effects and use of light-emissive materials, but it is another environment, so it did not seamlessly fit to the process used in the pilot.

An essential factor here is that the CAD models are changing during the building process as the designs change and the multitude of separately designed elements are combined to make the final product. It would probably be feasible to make a single tailored high visual quality VR model for some entity, but updating the model after every change to the design would be too resource intensive to be practical. Overall, it is likely that any resource-intensive tools would only be applied when visual realism is a top priority. In cases where focus is on construction details, the piloted VR environment and process can provide successful results.

6.6. Validation of Results

In Bellalouna's article [11] the claim was that most industrial VR applications are immature, and companies are in a waiting mode. In this case, these companies are taking a step towards routine use of VR. The software environment tried here was proven to be a capable tool for certain review tasks. However, based on customer feedback, some capabilities (especially rendering quality) do need improvement. There are several other comparable software systems available on the market, so the field seems to be developing quickly, and more and more companies are adopting the technology as it becomes more mature.

The list of benefits and challenges found in this research are rather similar compared to those listed by Davila Delgado et al. [13]. In stakeholder engagement, design support and design review, the observations coincide with benefits such as better contextual understanding, real-scale visualization of designs, better understanding of design impacts and efficient decision-making. On Davila Delgado et al.'s list of challenges, there are high investment (space and skilled staff), uncomfortable feelings, need of a chaperone, and feeling of isolation. The investment in this research case did not seem too high. There is indeed a need for skilled staff to prepare the scenes, and VR presentations to customers do require someone to assist, until there is enough experience on the customer side. Uncomfortable feelings did occur, but this problem should be curable by training and use of appropriate movement methods in VR. The isolation problem presumably refers to systems where the user is alone in the VR. The software environment used in this study supports multi-user collaboration, so this problem is not as likely.

Kinematic functions and interaction, as discussed by Schäffer et al. [17], were not considered crucial in the pilot. In some discussions, it was noted that opening doors in, for example, bathrooms and small cabins would be desirable for estimating the practicality of the space and furniture, but it was not seen as a high priority need.

When comparing the VR use of ship interior design reviews presented in this research to the aforementioned research settings by Bellalouna [11], Davila Delgado et al. [13] and Schäffer et al. [17], the results seem to confirm their findings when the quick pace of VR development is taken into account.

6.7. Examination of Hypotheses and Additional Findings

During this pilot some of the research hypotheses were found correct, while some could not be proven. The results reflected in the hypotheses can be summarized as follows:

1. Reviewing the models in VR is more efficient than using traditional methods.
   This turned out to be a partly correct hypothesis. Based on feedback from the VR sessions and the questionnaires, VR viewing was deemed suitable for the kinds of cases where the visual realism is not a top priority. Estimating physical dimensions of objects and spaces was found to be easy in VR, and structural solutions were easy to study. On the other hand, when visual realism is important—when considering the architectural details and atmosphere—the used system did not provide satisfactory results. Thus, for optimal result in these cases, more modeling effort and new software solutions are required.
2. Material and human resources can be saved when mock-ups are virtual instead of physical.
   Using virtual mock-ups, the working resources for construction of physical mock-ups will be saved, as well as all the needed materials and disposal of them. During this pilot, one company made eight virtual mock-ups (parts of seven different interior areas) instead of physical ones, contributing to approximately 2500 kg of savings in materials. The design work was estimated to remain approximately the same. The

number of mockups varies a lot between projects, but an estimate from a participating company was that savings from VR reviews could be in the order of 5–10% of the total cost in a project.

3. Virtual models can be modified easier and quicker than physical ones.
   The possibility of changing materials and colors of surfaces instantly in VR supports this hypothesis. Making different variations of virtual 3D models was not tried during the pilot, but it should have similar effects as replacing physical mock-ups with digital ones (hypothesis 2).
4. With VR reviews, the efficiency of communication would improve.
   The results indicate that some improvement in the efficiency could be detected, as the VR showcases tended to spark discussion among the stakeholders. However, this hypothesis could not be fully verified, as in the VR reviews there was usually just one customer representative with one host, so group discussions in VR did not take place.
5. The users will be impressed with the easiness and effectiveness of VR.
   Most of the users were somewhat impressed with the easiness and effectiveness of VR as a tool in ship interior design review. Some cases of VR sickness, imperfect visual impression, and the need for new work practices should be addressed before the overwhelming majority would deem it as very impressive.

The companies deemed usability, user experience, and the way of use of the pilot more adequate than the visual impression. It seems that the visual impression plays a significant role when evaluating the virtual environment and the realism requirements towards VR systems. However, the virtual environment cannot fully compete with video game industry AAA publications where the pre-renderings, ray tracing, pre-installed reflection cameras, and other advanced technologies are used. As the demanding factor for a digital mock-up seems to be cost savings, multi-million video game projects are hardly a field to compare the end products with. Hence, to achieve an improved acceptance for VR, one should clarify this aspect to the customers early on.

The number of persons involved in surveys was low, which may have affected the robustness of the results. More of the customer feedback from VR reviews was collected through reporting from the constructing companies' personnel, who communicated with the customer representatives. The data came mostly through interview sessions with the participating companies' employees. A balancing factor may be that this pilot was executed as a part of an actual cruise ship construction project. All reported cases were real production-related ones, no artificial test cases and recruited testers were used, so the persons giving feedback about the tools had genuine interest in the interiors being designed.

7. Conclusions

In this pilot study, the applicability of VR to shipbuilding projects was explored. Focus was given to VR as a medium for design reviews in the construction of cruise ship interiors. A shipyard and three subcontracting companies participated in the project. Each company did their own trials using as test material the ship sections they were actually producing. CAD software and VR equipment varied from company to company, but all used the same VR software environment (CTRL Elements). The companies organized review sessions where various ship sections were shown as VR models to the representatives of the customers. The progress of the pilot was followed through regular interviews of the participating persons, and also through formal surveys.

Overall, the participating companies found virtual reality a useful tool. The main findings can be summarized as follows:

1. VR can speed up the interior design and construction process due to several factors: avoiding some mock-up construction, allowing quicker modifications with virtual models than physical ones, and making the reviews more efficient than using traditional methods only.
2. Savings in material and human resources can be achieved, mainly by replacing some mock-up construction work with virtual models and VR viewing.
3. The companies, both the participating supplier companies and customers, plan to continue using VR, and they expect it to become a routine part of the production process in the future.
4. For many purposes within design reviews, the performance and functionality of the used VR environment is sufficient, but in some cases, more visual realism was found wanting in rendering of the scenes.

To improve the visual quality in VR, effort and additional software tools would be needed. This presents a challenge, because the original assumption was that VR should not require substantial new work stages to be added to the production process. In practice, creating visually realistic VR scenes would be a task with some resemblance to video game design. To avoid tedious new work stages, some kind of simple step for specifying lighting and material properties for rendering should be added to the process. At this time, it is open whether it would be a separate tool, added functionality in the VR environment or something else. In any case, the process should not require much effort from human workers; computational resources and time could be traded, as long as the interactive session in VR can be carried out in real time.

Even though the pilot was constructed and tested with a rather limited amount of resources and there are no pre-existing practices of VR use in ship interior design review, the results indicate that the use of VR could have a clear positive impact on the fields of savings and sustainability. As the ship design model process is iterative and under constant change, the possibility of using up-to-date CAD models also for VR visualizations was found essential. When taking into account the quick pace of development in the VR devices and software, usability and user experience of VR, and work practices around VR use in general, these positive impacts can be seen to strengthen even further.

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Abbreviations

The following abbreviations are used in this manuscript:

AEC	Architecture, engineering, and construction
AR	Augmented Reality
CAD	Computer-Aided Design
MR	Mixed Reality
VCI	Virtual Customer Inspection
VR	Virtual Reality

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