Collaborative Virtual Reality as an Adaptable Boundary Object in the Design Phase of Facility Life Cycle

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Abstract: Although the large majority of costs of buildings incur in the later operation and maintenance phase, major decisions affecting these costs are made in the early design and construction phases. Virtual Reality (VR) and Collaborative Virtual Reality (CVR) have been noticed to have significant potential in involving the expertise and needs of various stakeholders into the early design phases, increasing the quality of building designs and reducing related costs. Boundary Object Theory has been noticed useful in better understanding and improving the knowledge transfer of actors with different backgrounds and expertise. VR and CVR remain yet little studied as boundary objects. We will address this research gap in this study by aiming to understand how CVR can act as an adaptable boundary object in the building design phase of the facility life cycle. We have made use of a qualitative approach, consisting of a multiple case study approach and semi-structured interviews in Finnish AEC industry companies and organisations. We contribute to academic research by providing a deeper understanding of how CVR functions as a boundary object, which enhances the transfer of knowledge in new ways between various stakeholders in the building design phase.

1 INTRODUCTION

The architecture, engineering and construction (AEC) industry faces a problem which is related to the fact that although the large majority of the costs of a building incur in the later operation and maintenance phase of buildings, major decisions affecting these costs are made in the early design and construction phases (Bullinger et al., 2010; Goulding et al., 2014). Collaborative Virtual Reality (CVR) has been noticed to have significant potential in involving various stakeholders, especially the customers and end customers into early phases of design, thus making earlier, faster and better design decisions, and significantly reducing building and building redesign costs, and increasing the quality of building designs. With the help of CVR the users can understand the proposed designs better than with other existing methods and give more accurate feedback to the designers. This is becoming increasingly possible due to the recent advances in digitalization in the AEC industry. More specifically, the increased adoption and use of Building Information Modeling (BIM) has significantly expanded the possibilities for digital collaboration between different stakeholders (Miettinen and Paavola, 2014).

Reviewing the existing Virtual Reality (VR) literature, the research gap of this study is related to the relatively little studied field of VR enabled collaboration, especially in the context of the AEC industry, which has specific collaboration related challenges. Furthermore, we want more specifically here to understand how CVR can be used as a boundary object, which are seen as vehicles for enabling efficient knowledge transfer between various collaborating stakeholders with different backgrounds and expertise.

The purpose of the study is to better understand how CVR can act as an adaptable boundary object in the building design phase of the facility life cycle and enable enhanced knowledge transfer between

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stakeholders. To answer this, we divide this into three research questions:

1. How is CVR used in technical building design?
2. Which type of fundamental stakeholder collaboration and knowledge transfer-supporting mechanisms related to CVR are important in the technical design of buildings, and why were these important and beneficial in building design?
3. How does CVR function as a boundary object, enabling knowledge transfer between the stakeholders of building design?

To answer the research questions, we made use of a qualitative approach, consisting of a multiple case study approach and semi-structured interviews (Yin, 2009; Ghauri et al., 2020). This was chosen to understand in sufficient depth the application of CVR in studied organizations of the building industry. The building industry in general was selected because they can benefit significantly from VR use in building design, are generally seen as early adopters of VR in design related collaboration and are actively innovating and developing new VR solutions for this purpose. Among such companies, pioneering companies from the industry were selected as case companies.

This paper is structured as follows: we first review existing research concerning VR, VR-related collaboration and boundary object theory related to knowledge transfer between stakeholders, and the research gap in more detail. Second, we introduce the methodology of the paper, describing the case selection and case companies. Third, we present the results, and finally, present the main conclusions and managerial implications.

2 THEORETICAL BACKGROUND

2.1 Virtual Reality and CVR

The concept of virtual reality (VR) has been known for decades (Sutherland, 1965), but only recently the wider commercial adoption of VR technology has been witnessed (Slater, 2018). The use of VR in organizations has been mainly focused on different simulations, education, or training (Slater and Sanchez-Vives, 2016).

VR can be used in many ways. The prevalent use of VR is still largely concentrated on its non-collaborative use, e.g. in non-social games or as non-social learning environments. Earlier remote collaboration experiments with desktop-based virtual worlds (VWs) (i.e., 3D worlds that are used via computer screen) have mostly failed to attract participation and engagement. Increasing sensory immersion was seen necessary when mitigating these problems in the future. (Kohler et al., 2011). Therefore, head-mounted displays (HMD)s and the use of VR are a significant step forward in different remote collaboration practices. Accordingly, the collaborative and social use of VR has recently gained in importance in both consumer and business use (Perry, 2015). This is due to the development of VR software and related collaboration-supporting technologies, as well as the increased performance of VR gear in the fluent handling e.g. several persons' simultaneous activities in the same virtual space. Thus, along with this development, it has been increasingly noticed that collaboration in and through VR means has produced significant benefits for companies and individuals in the enabling of better collaboration and knowledge transfer (e.g. (Slater and Sanchez-Vives, 2016; Steffen et al., 2019). Due to this novelty, there is yet a limited amount of research on the collaborative and social use of VR in the working context, in their use in the transfer of knowledge between different actors, and the use of CVR as a boundary object, especially in the AEC industry, as in our case. In this study, we will concentrate on the collaborative and social use of VR and will use the concept 'Collaborative VR' or CVR in a broad sense, as described above.

Information and knowledge sharing are central to collaborative work (e.g. Churchill & Snowdon, 1998). VR can be used in supporting inter-personal or even inter-organizational collaboration in many ways. VR-supported collaboration can be co-located or distributed. Furthermore, it can take place either fully in VR, or partially in VR and in the real world. Collaboration can involve spoken, written, or pictorial communication, and can happen in 2D or 3D. Communication and collaboration can be supported by manipulation of and interaction with digital objects and with other users directly, or through means of digital objects in various ways in the VR context. Figure 1 depicts the dimensions of interaction in the real world, in VR, or partially in both, and defines the collaboration dimensions between users and digital objects.

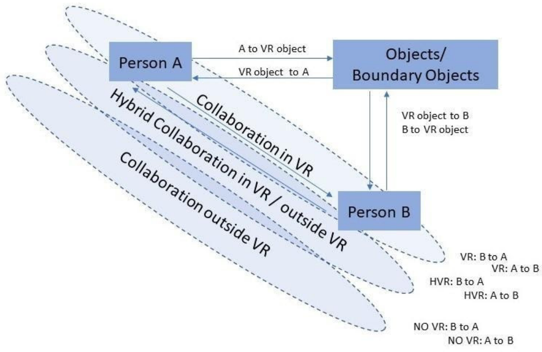

Figure 1: Dimensions of interaction in VR.

The whole digital environment can often be flexibly adapted to different users (see e.g. Affendy & Wanis, 2019). The above characteristics are closely related to the concept of boundary objects (BO), which can be defined as "objects flexible enough to adapt to individual needs of the actors using them, yet specific enough to maintain a common meaning across different actors" (Star and Griesemer, 1989). We will discuss the concept of BO in more detail below in section 2.3.

2.2 Role and Significance of CVR in Building Design

The utilization of CVR as a boundary object requires easy access to digital building models. In this regard, the increased adoption of BIM is expanding the possibilities for collaboration in the AEC industry, although the industry's fragmented and project-focused nature is hindering the full utilization of BIM and has largely limited its use to the earlier design and construction phases of the AEC value-chain (Miettinen and Paavola, 2014). Although around 80 percent of the costs of a building are incurred in the operation and maintenance phase, crucial and long-lasting decisions affecting these costs are made in the design and construction phases (Bullinger et al., 2010; Goulding et al., 2014). Thus, there is significant potential to address these issues with more user-centric design and in ensuring the building better matches user needs by enabling more effective knowledge transfer with CVR in the building design phase. Until recently, immersive virtual environments, such as CVR, have mainly been used in marketing and not in collecting user feedback from the end-users with the intent to change the building design (Bullinger et al., 2010). However, this is becoming increasingly possible due to the recent developments in BIM adoption and use.

The aforementioned fragmentation of the AEC industry accentuates the importance of communication between different stakeholders in order to successfully complete projects (Goulding et al., 2014). Possibilities for enhancing knowledge transfer are especially prominent in the building design phase. With VR it is possible to precisely measure how the users behave (e.g., movement and gaze) in the proposed design of the building (Kuliga et al., 2015) and to quickly compare user behavior in different design options (Heydarian et al., 2015). The digital design can also be easily manipulated in the VR space unlike with physical scale models (Kuliga et al., 2015). The use of immersive VR also promotes a better spatial understanding of the proposed design (Portman et al., 2015), especially among professionals and those with higher educational levels (Paes et al. 2017), and aids in creating mutual understanding between different stakeholders (Du et al., 2018). Thus, with the aid of CVR the users can understand the proposed design better than with other available methods and give more accurate feedback to the designers. In addition, the content can be easily tailored for different user groups by showing them only content that is relevant to them. For example, end-users can view a more visually polished version of the design whereas various technical structures can be shown for structural designers. VR also makes it possible to reduce travel by making it easier to participate remotely (Perry, 2015). This also makes it possible for experts to participate in design sessions more often, thus, increasing design iterations. Furthermore, immersive VR also increases users' focus on the task since the use of HMDs reduces external stimuli (Hilfert & König, 2016). These characteristics of CVR make it a potential tool to be utilized as a boundary object in the building design phase of the AEC value-chain.

2.3 Boundary Objects and Knowledge Transfer

Star and Griesemer (1989), introduced the concept of 'boundary objects' and defined it as "objects flexible enough to adapt to individual needs of the actors using them, yet specific enough to maintain a common meaning across different actors". Thus, boundary objects can be understood as artifacts, or some kind of arrangements, that enable communication and collaboration between members within and between different communities of practice.

According to Wenger (2000), boundary objects can be categorized into three groups: artifacts, discourses, and processes. Artifacts can include tools, documents, models, or virtual places that stand out by having meaning across boundaries. Discourses, again, represent a common language that collaboration process participants use to communicate across boundaries (Wenger 2000), and include negotiated terms and language constructions that have the same meaning for all the participants. Processes include negotiated routines and procedures (e.g. rules and agreements) that allow coordination across boundaries (Wenger 2000; Fominykh et al., 2016).

The interesting and important role of VR as a boundary object has been noted, in overall, in recent literature: An and Powe (2015) found that visualizations, and more specifically VR, seemed to provide a reasonable fit to the boundary object conception, and more specifically, provided a focus for better translation of for instance expert findings, improving communication and understanding between the various groups, and helping e.g. the process of negotiation on controversial aspects. Furthermore, Fominykh et al. (2016) explored how boundary objects facilitated, in more general, group work and learning across different boundaries in a cross-disciplinary educational context. Olechnowicz (2018) found that immersive imagery or VR had a substantial potential as an effective boundary spanning object that seemed, especially, to increase participant's perceptions of credibility and saliency towards VR and wildland fire management. More specifically, in the context of building design, Building Information Modeling (BIM), which is made use of in CVR, it was noted as important "to view BIM artefacts as boundary objects and explore how they contribute to collaboration and support management of projects" by Papadonikolaki et al. (2019).

To summarize the recent literature, VR has been noted as a useful and interesting boundary object in general, and it has been further studied as a boundary object in a few contexts. However, VR and CVR more specifically, has not been studied empirically as a boundary object in any useful detail in the context of building design. Since BO's can be very different and can be used in different ways in different contexts, understanding CVR as BO is important in this specific building design context to better enable knowledge transfer in building design.

Due to different knowledge and experience systems of stakeholders, and lack of a mutual design environment, knowledge transfer is considered generally as challenging in cross-disciplinary settings in the facility life cycle. Boundary objects are thus critical since they provide bridges across boundaries allowing different knowledge systems and communities to interact by providing a shared reference that is meaningful within all parts (Star and Griesemer, 1989; Wenger, 2000). The role of CVR as a boundary object is presented in Figure 2, defining how collaboration between focal stakeholders can be supported in a shared virtual environment in building design of facility life cycle.

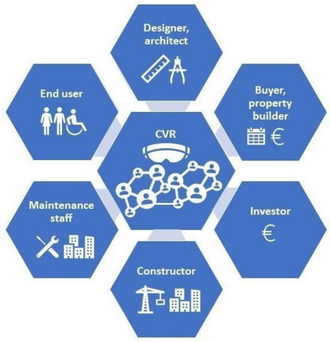

Figure 2: CVR as boundary object in facility life cycle.

3 METHODOLOGY

The aim of this study was to map and understand how CVR functions as a boundary object in the building design phase of the facility life cycle and how VR enables interaction and enhanced knowledge transfer between multidisciplinary stakeholders. The focus of the study was on novel and enhanced collaboration in VR, which can be perceived to be better than in current practices.

The study has a qualitative approach. A multiple case study approach was chosen to understand the level of implementation and usage of CVR in organizations that are seen as early adopters and pioneers in innovating and developing emerging virtual solutions for the AEC industry (Yin, 2009). Three Finnish FM companies participated in the study. The focus was on companies that were seen as early adopters in the use of VR, and also benefiting clearly from solutions that improve the quality of building processes and reduce costs. The interviewees were experts and pioneers in innovating and developing virtual solutions for the different phases of facility life cycle. The list of the interviews is presented in Table 1.

Table 1: List of the interviews.

Interviewed company	Persons	Role of the interviewee/s
Company A	one	XR Technology Manager
Company B	two	VR Technology Manager R&D Manager
Company C	one	VDC Manager
AEC expert organization	one	AEC Industry Expert

The study used purposeful sampling to gather data that was pertinent for our research (Patton, 2002). Finland is a remote and big country with long distances and low population density, thereby the organization of cross-disciplinary design meetings is found challenging. Thus, pioneering AEC companies in Finland have a clear interest to invest and develop novel solutions for virtual modes of operations and hence enhance the efficiency of cross-disciplinary building design meetings.

Semi-structured interviews were used as a data collection method. This is seen as a useful method for exploring novel research areas, such as CVR is, where limited research is available (Ghauri et al., 2020). The aim of the interviews was to find out how CVR was utilized in the building design use scenarios and what benefits it can bring to the companies. A list of questions and themes were used in the interviews. All together four interviews were carried out in September - October 2019. The interviews lasted from 60 to 90 minutes. The interviewer and the interviewees were Finnish. The interviews were audio-recorded and transcribed in Word documents. The transcribed interviews were analysed and grouped according to the interview themes: mechanism and characteristics, as well as consequent benefits, how VR can be utilized in collaborative context in building design scenarios.

4 RESULTS

Three building planning and design phases of the real estate life cycle were identified in the interviews: land acquisition and building area planning, project planning, and technical planning. Largely due to recent developments in BIM adoption and use, which have enabled easy access to digital building models, CVR was seen by all the interviewees as a potential and useful means to enhance interaction and collaboration in the multifaceted phases of building planning and design processes. According to the interviews CVR was utilized mostly in the technical design processes, and secondarily in the project planning activities. CVR was seen to have a considerable potential both in project planning as well as in the preceding phases of the real estate life cycle. However practical implementations utilizing collaborative VR in the phases preceding project and technical building design processes were still seen as very scarce. The use cases identified in the interviews were related to complex technical design building activities. The use cases are listed in Table 2.

Table 2: CVR use cases in technical building design.

Case Company	Use Case	Definition of use case context
Company A	case 1	technical maintenance building design
Company A	case 2	technical building design
Company B	case 3	technical building design of ducts
Company C	case 4	technical building design
Company B	case 5	erection procedure sequence of structural steel design

4.1 Fundamental Collaboration-Supporting Mechanisms in CVR

Three main fundamental collaboration-supporting mechanisms were identified in literature, which were found as useful particularly in VR supported collaboration in multi-faceted building design use cases: Adaptability, Agile trials, and High level of focus (Steffen et al., 2019). The interviewees were able to identify all these three fundamental mechanisms: Adaptability mechanism in 6 different use cases, Agile trials in 8 use cases and High level of focus in 6 different use cases. The use cases of the fundamental collaboration-enabling mechanisms of CVR are presented in Table 3.

First mechanism identified by the interviewees was Adaptability. The ability of CVR to adapt itself according to the tasks and situations where it was used, as well as according to the expertise and knowhow level of the users, was seen as a big advantage by all the interviewees. Moreover, the knowledge within CVR was seen as intuitive for various different stakeholders. The visualization levels of virtual building designs were adapted according to the expertise and professional level of the participants. According to the interviewees the building design professionals, architects and designers, preferred working with basic and simple 2D models, whereas the non-professional users, e.g. end users, needed more fine-tuned 3D models in order to be able to comprehend the building designs. Colour codes were used in professional virtual models to clarify visually the functionality and interoperability of different structural parts (e.g. purple for supporting parts, blue for stiffener parts etc.) and hence accelerate the comprehension of the technical designs at a glance. The virtual building designs enabled the designers to scale themselves to different end user roles, e.g. child or wheelchair users, and thereby more authentic experience-based perspectives of the building designs were able to be acquired.

Second, and by the interviewees the most often mentioned mechanism was Agile trials. CVR was seen to enable agile, low threshold sprints, simulations and experimentations to test ideas and customer needs and thereby further the acquisition of fast and immediate feedback to building designs. In fast simulations the used VR models were often simple, rough and easy-to-build block models. Participants visited the virtual models quickly, instant feedback was received on the spot, discussions about observations and perceived problem areas held along the way, solutions co-created and functionality and effects of suggested changes were able to be tested and analysed immediately in the VR model, even with several variations during one design session. Agile customer and end user surveys were able to be implemented with virtual simulation models already in the very early phases of the technical building design process, e.g. to test if potential parking hall users would be willing to pay higher parking fees for more spacious use of space. The acquired fast feedback was seen to accumulate the decision-making process of investors and other partners. Spontaneous idea discussions and tests were able to be organized by agreeing a quick visit to the virtual design model instead of numerous email interactions and telephone conversations.

The third mechanism identified by all the interviewees was High level of focus. CVR was seen to enable focused observation level and better attention span of the participants since they were isolated from the outside world during the design sessions. Thereby distractions were eliminated, and the attention of the participants better directed on desired targets. Parallel usage of mobile phones and laptops was seen complicated, if possible, at all. In general, the virtual design meetings were seen efficient to manage: the virtual models were able to be structured beforehand to guide the participant what to observe, where to focus, and what to discuss. The virtual models ensured automatically that all the necessary spots of the design plans were systematically checked. Some interviewees found the parallel working possibilities in multidisciplinary design meetings in VR as useful, since they cannot be allowed in the real site meetings where free movement in the building sites is prohibited. If the issue at hand was not relevant for all the participants, the observations outside the actual agenda were possible without disturbing the actual meeting.

CVR was seen to enable monitoring and registration of non-verbal participant reactions, e.g. direction of glance, gestures, motions, expressions, and reactions. However, as emphasized by the interviewees, this possibility has not been utilized on a larger scale because of the undefined privacy protection regulations restraining the utilization of individual non-verbal communication in VR.

An interesting new fundamental mechanism supporting collaboration in VR was identified by all the interviewees: Sense-augmented examination of data. This new mechanism was found to enable sensing, experiencing and visualizing objects with new dimensions, also with rather strong immersions: visualization of data for sight, visualization of sight with hearing, as well as experiencing various effects like wind, light and e.g. falling effect with sense of balance. The knowledge within these virtual sessions were identified, acquired, transferred and stored automatically. The Sense-augmented examination of data mechanism was seen by all the interviewees to have a huge potential in the usage of VR implementations in a co-creation and design context. According to the interviewees there is a scarce technological knowledge about the usage of this new mechanism, as one interviewee mentioned: *“Currently only the peak of the iceberg is identified*”. Due to limited user experiences in the case companies this new mechanism was not analysed in detail in this study. However, when the technology evolves the sense-augmented examination of data mechanism was seen to provide significant possibilities to integrate totally new reality dimensions in virtual design models, which are not possible to implement in the real world. This would significantly transform the possibilities of VR to identify, acquire and utilize data in building design processes.

4.2 Benefits of Fundamental Collaboration-supporting Mechanisms

From the perspective of enhancing collaboration, two focal and important benefits caused by the fundamental collaboration-supporting mechanisms were identified in the studied cases: better quality and resource efficiency of the technical building design sessions. Better quality presented itself as better quality of building design outcomes and more qualified processes, risk reductions and better risk management. Resource efficiency presented itself as time and cost savings, contributing to higher work efficiency.

All the three main fundamental collaboration-supporting mechanisms identified in the literature, Adaptability, Agile iterations and High level of focus, were recognized by all the interviewees to impact both benefits - better quality and resource efficiency, as summarized in Table 3. The Adaptability mechanism was primarily seen to affect better quality, however it was seen also to streamline the processes and hence enhance the process efficiency. Agile iterations and High level of focus mechanisms were seen to affect both better quality, mentioned as BQ in the Table 3 and resource efficiency, mentioned as RE in the Table 3.

Table 3: Fundamental collaboration supporting mechanisms in CVR and their benefits in CVR use cases.

Case company	Mechanism	Use case	BQ	RE
Company A Company B Company C	Adaptability	Variable visualization levels	x x x	x x x
Company C	Adaptability	Easy-to-movemodels	x	x
Company B	Adaptability	Colour codes	x	x
Company B	Adaptability	Scaling to user roles	x	
Company A Company B	Agile trials	Fast tests of ideas and customer needs	x x	x x
Company A Company B	Agile trials	Rough easy-to-build, fast-to-visit block models	x x	x x
Company B	Agile trials	Low threshold sprints and iterations	x	x
Company B	Agile trials	Visualizations for investors	x	x
Company B	Agile trials	End user and customer surveys	x	x
Company C	Agile trials	Spontaneous idea tests and discussions	x	x
Company A	High level of focus	Automatic meeting structuring	x	x
Company A Company B Company C	High level of focus	Isolation from outside world distractions	x x x	x x x
Company B	High level of focus	Parallel observations outside agenda	x	x
Company C	High level of focus	Automated registration of nonverbal reactions	x	x

The Adaptability mechanism of CVR was found fundamentally important in stakeholder collaboration by all of the interviewees to enable easier and better comprehension of technical building designs, which in turn enabled the engagement of a wider variety of stakeholders, e.g. end users and investors, into the technical building design processes. This was seen to further the possibilities of cross-disciplinary collaboration activities, and thereby to streamline the building design as well as decision-making processes significantly. The versatile and qualitative feedback enabled the co-creation of more accurate building designs, and thus generated better customer satisfaction. This all was seen by the interviewees as a big advantage since it was not seen easily realizable by traditional means, such as caves.

The interviewees considered the Agile trials mechanism fundamentally important in stakeholder collaboration since it lowered the threshold of tests and experimentations in general, especially in the early phases of facility life cycle. Thus, the acquisition of fast feedback already in the very early phases of building design processes was able to be acquired, early recognition of mistakes and co-creation of novel solutions enabled and thereby the accuracy and functionality of the building design outcomes improved. Consequent early recognition of errors and mistakes enabled the minimization and avoidance of risks, which final economic impact in the facility life cycle was seen by all the interviewees to be enormous.

High level of focus mechanism was found fundamentally important in stakeholder collaboration while enabling the better concentration of the participants on the issues at hand during the design meeting and "*allowing them to be immersed in the VR model*", as one interviewee defined. Because of the good attention span and immersed experience of the space, possible problem areas, mistakes and interesting observations were seen to be perceived better. Hence the feedback and the acquired outcomes were found to be more functional and accurate than with traditional means. Some of the interviewees assessed the discussions and course of the meetings in VR to be even more focused and efficient than in real life. Parallel observations enabled within the virtual site meetings outside the actual agenda were seen to enrich the feedback, enhance the retention of the interest of the meeting participants as well as the efficiency of time management in the multidisciplinary design meetings.

4.3 CVR as Boundary Object in Building Design

CVR was found to function as a boundary object in the five identified building design use cases, which are listed in Table 2, enhancing transfer of knowledge between design stakeholders. Actors being involved in the building design processes were mainly designers from different building design functions. In one use case also the end users of the property, service maintenance personnel, were attending the building design session. In the studied use cases boundary objects of CVR were studied regarding three different characteristic boundary object types: processes, artefacts and discourses (Fominykh et al., 2016; Wenger, 2000).

The collaboration in the studied design use cases was currently seen to exploit VR mainly in the hybrid process models. Process type of boundary objects supporting knowledge transfer between different stakeholders have been identified in several kinds: characteristics is that processes include diverse rules and agreements on discussions and procedures enabling coordination across boundaries (Wenger 2000; Fominykh et al., 2016).

The dimensions of interaction presented in Figure 1 are utilized in this analysis. In the studied use cases three different dimensions of interaction were identified: 1) collaboration fully in VR, 2) hybrid collaboration partially in VR and in real world, and 3) collaboration only in real world. Also, an interesting new dimension of interaction was identified in the studied hybrid use cases; indirect, observer-based collaboration realized outside VR, while one person at a time was visiting the VR model. Table 4 presents the dimensions of interaction in hybrid processes describing the context of collaboration between different environments: in VR and in the real world, or partially in both. The collaboration dimensions between VR objects and actors participating in the design sessions are also illustrated in the table. The legends 'x' and '-' describe whether interaction between objects and actors took place.

Table 4: Dimension of interaction in hybrid processes.

	A to VR object /VR object to A	VR object to B /B to VR object	In VR B to A/A to B	Outside VR B to A / A to B	Hybrid VR + no VR
Case 1	x/x	x/x	-	x/x	x/x
Case 2	x/x	-	-	x/x	x/x
Case 3	x/x	-	-	x/x	x/x
Case 4	x/x	x/x	x/x	x/x	x/x
Case 5	x/x	x/x	x/x	x/x	x/x

In the hybrid design meeting the participants were moving from real world meetings to VR, even several times in one meeting. The collaboration among participants occurred either inside or outside VR, or in both environments. In most of the cases the discussions about the observations and solutions took place in the meetings outside the VR model. In two of the studies cases the building design session participants observed and communicated with the VR objects as well as with each other both in the VR model and outside the VR model. In one use case the design session was organized completely within the animated virtual model.

Interestingly in three of the studied cases the communication with the VR objects took place indirectly through one person at a time visiting the VR model, while the others observed and monitored the session outside the VR model. As one interviewee pointed out, the possibility to utilize all dimensions of interaction in the hybrid processes were seen to have positive aspects: *"The actual discussions and co-creation activities are often organized outside VR, either in physical or online meetings. This is often seen as a relief since the participants do not usually want to wear the VR glasses all the time. The VR glasses disturb some of the participants and they might even cause physical symptoms."*

The participants in the building design session were seen to perform actively in two different roles; as a VR model visitor and an observer outside the VR model. As one interviewee pointed out: "*Observer role, also felt like an indirect VR model visit, seemed to ease the tension and nervousness towards the new technology and thus enhanced the readiness to give feedback. This enabled more versatile observation and comprehension, as well as more spontaneous feedback."* One interviewee explained how "a *quinea pig setup*" generated a real storm of observations and insights among all the participants, which in turn inspired and stimulated the discussion, advanced the level of observation and thus inspired and enhanced discussions and co-creation of solutions.

According to the interviewees the reasons for the frequency of hybrid implementations were seen in the general habit and common practice in the AEC industry to meet in physical design and site meetings. This was considered to be caused mainly by the limited adoption and knowhow of CVR technology, and virtual technology in general, in the AEC industry. Thereby the willingness to invest and readiness to utilize VR technology and equipment in different functions in the building design is still in its infancy.

The hybrid case implementations were found to be a functional way to utilize VR technology under the current circumstances. One interviewee prognosed that the actual building design activities will most likely never be transferred fully to virtual reality environments since the building design programs and tools are tightly linked to specialized computer systems: *"Designers from different building design functions prefer to use their own design programs so that the strengths of different design systems can be utilized more efficiently."*

VR models per se were seen to function as an artefact type of a boundary object in all use cases. The capability of VR models to adapt according to the expertise level of the actors participating in the design session was seen as useful in order to provide meaning across boundaries. Certain artefact types of VR model boundary objects were identified, e.g. technical building design of ducts and erection procedure sequence of structural steel designs. In some of the hybrid use case processes VR models were utilized as an additional tool or function to the actual building design programs.

VR model artefacts were seen by all the interviewees to ease the ability to comprehend the building designs and enhance the observations and perception skills of the participants. Thus, the integration of new stakeholders was enabled and collaboration between technical building design actors was enhanced, and thereby novel knowledge and perspectives were able to be integrated into the technical building designs. Relevant problems and errors were seen to be detected more accurately. Visual format and animations were seen to enable more unambiguous perception of the building design. As mentioned by one interviewee: "*Experiencing and observing the building design in the right scale, while actually being in the VR model yourself, enhanced and eased the capability to understand the building design and thereby detect relevant problematics.*" One interviewee pointed out: "*If the design plans are presented with traditional text documents, and five people will read the text, there will be five different perceptions and interpretations of the plan. Virtual design are comprehend more uniformly*" One interviewee explained: "*Staying in the visual animation yourself enables better overview and understanding of the designed property, eases and accelerates to realization of possible problematics and errors, enables communication and finding solutions on the spot and thus enables to prevent the risks more efficiently*."

Other identified artefacts performing as boundary objects were agendas and memos utilized in the design sessions. The roles of the agendas were found to structure and guide the building design sessions, whereas the memos were used for documentation of observations and correction proposals, and to transfer the knowledge further to other instances and stakeholders. The technical building design viewing sessions were structured with predefined agendas. In some use cases the order of the spots to be reviewed were integrated in the VR model, whereas the participants were guided step-by-step by the model itself in the virtual viewing process. These procedures were found to function as useful boundary objects ensuring that all the relevant parts of the virtual building design model were inspected in the right order, and no relevant spots were not missed. The observations and comments made in the VR model or in the design meetings were in most of the use cases documented in separate memos. Some interviewees had been testing examples of VR model solutions where self-supporting tools immersed in the VR model have enabled direct integration of the observations and comments directly in the model. One interviewee pointed out that future scenarios of fully automated virtual solutions have been discussed and tested by major players. In these solutions the sessions can be structured, managed and documented without any human input.

The main discourses identified in the studied user cases were discussions about observations and perceptions made in the VR model as well as co-creation of solutions for the identified problematics. The utilization of CVR in the building design processes was seen by most of the interviewees to enable beneficial exchange and integration of knowledge and perspectives of cross-disciplinary experts. It was emphasized by the interviewees that CVR has been found to enable the instant discussions, co-creation of solutions and decision making on the spot during the design meetings. With the usage of a VR model together with other building design tools, the changes to the building designs were able to be updated and transferred to the VR model immediately, changes analysed and the functionality tested and evaluated, and hence necessary decisions made immediately. One interviewee explained: "*When inspecting and observing the VR model together with experts from different building design functions, participants had possibilities to learn from each other and thus achieve more comprehensive understanding of the complex building designs, e.g. the technical building system of ducts, as well as evaluate the economy aspects of the solutions created*."

5 DISCUSSION AND CONCLUSIONS

The purpose of this study was to better understand how CVR can act as an adaptable boundary object in the building design phase of the facility life cycle and enable enhanced knowledge transfer between stakeholders. Regarding our research questions, how CVR is used in building design and which type of collaboration-supporting fundamental mechanisms were found important, we were able to identify four different types of fundamental mechanisms, which were used in the early phases of building design, especially in the technical design, in the studied case companies. The first three mechanisms, also identified in VR literature (Steffen et al., 2019) were named as Adaptability, Agile trials, and High level of focus, and the fourth a newly identified one named as Sense-augmented examination of data. Three first ones were actively used in all studied companies, and the fourth one was found as very promising in technical design, bringing very unique and important possibilities and benefits compared to earlier design approaches and technologies in building design. All these mechanisms made use of CVR possibilities in a way which provided novel possibilities and benefits, not essentially provided by other traditional design approaches, making fundamentally in-depth use of unique CVR possibilities in building design.

These fundamental mechanisms were quintessential in enhancing the efficient design collaboration in new ways, as well as in enhancing the related knowledge transfer between design stakeholders and enabling the co-creation of new knowledge by three major ways:

- Enabling fast and agile design experiments.
- Eliminating distractions and focusing efficiently the attention of design participants on desired focal design characteristics and focal area.
- Adapting the design environment flexibly to the varying needs and expertise levels of design participants.

The above mentioned three ways, and the ability to combine them in various design tasks, can be seen largely responsible for providing the unique opportunities and benefits from CVR in building design.

In relation to our second research question, why the mechanisms were beneficial and important in collaborative building design, all the identified collaboration-supporting fundamental mechanisms of CVR were found to enhance better technical building design outcomes, more qualified processes and enhanced resource efficiency. The mechanisms were seen to contribute to the more qualified and efficient acquisition and transfer of knowledge, especially tacit and experiential knowledge, in the building design phase of the facility life cycle.

In particular, the mechanisms were found to enable the participation of new stakeholders in the design processes. Due to the fragmentation of the AEC industry it has been challenging to engage different stakeholders in the technical building design processes (Miettinen and Paavola, 2014). In accordance with previous studies (Goulding et al., 2014), the collaboration and communication between different stakeholders in technical building design processes were noted to impact on higher quality of design processes as well as enhanced resource efficiency. The identified mechanisms of CVR were found to enable much wider participation of different stakeholders, e.g. best experts, end-users, other decision makers, and thus enable the more qualitative and effective knowledge transfer.

Possibilities for enhancing knowledge transfer are especially prominent in the technical building design phase, as crucial and long-lasting decisions affecting the major part of the costs of a building are made especially in the building phase of the facility life cycle (Bullinger et al., 2010; Goulding et al., 2014). CVR and the fundamental mechanisms were found to enable the acquisition of fast feedback from end users and other stakeholders already in the very early phases of the facility life cycle. This enabled early identification of mistakes, thus affecting more qualified building design and better risk management.

Regarding our third research question, how does CVR function as a boundary object enabling knowledge transfer between the stakeholders building design actors, CVR was found to meet the general criteria and be aligned with the definition and main functions of a boundary object in the way Star and Griesemer (1989) described it in the literature, and CRV was seen to utilize the certain characteristic of boundary objects; processes, artefacts and discourses (Fominykh et al., 2016; Wenger 2000). Our study revealed that VR models were performing as an artefact type of boundary objects in the way Papadonikolaki et al. (2019) described them to contribute to collaboration and managing the projects. The identified boundary objects were seen to have an important role in how CVR functions as a boundary in the technical building design processes facilitating communication, collaboration, and in particular knowledge transfer between cross-disciplinary facility life cycle stakeholder groups.

Interestingly, the collaborative VR and related knowledge transfer was currently carried out in technical design through 'hybrid VR processes'. The hybrid processes are defined in the Result section. The main reasons mentioned for the extent of hybrid processes were established practices in the industry, the limited maturity and knowhow of the usage of VR technology in the AEC industry in general, limitations in VR technology and software in the companies as well as the unwillingness of some stakeholders to utilize VR, or possibility of experiencing cybersickness. However, the potential and benefits of VR technology has been recognized and there is a noticeable interest experimenting with it. The utilization of hybrid VR processes in building design might at least partly change in the future, the exact direction of development being still open.

The identified fundamental collaboration-supporting mechanisms of CVR, Adaptability, Agile trials, High level of focus and Sense-augmented examination of data, were found to significantly support the functionality of the identified CVR related boundary objects, artefacts, processes and discourses, and hence enhance collaboration in technical building design. This is in accordance with previous studies (e.g. An and Powe, 2015) on how the adaptability of VR provided focus for better translation of expert and end user findings, improving mutual understanding and collaboration between various stakeholder groups.

All the fundamental mechanisms were found to be connected closely to the identified boundary objects: Adaptability mechanism was found to support the flexible adaptation of the information in VR design model (artefact boundary object) to particular use case and expertise level of the actors in the design process, and hence support the better comprehensibility of the technical building designs to be inspected. Thus, the centralized problem solving and achievement of common meaning across different stakeholders were supported. High level of focus mechanism was seen to enhance the quality of discourses (boundary object) by focusing the attention of participants better on desired targets, and thus also the process (boundary object) flow within the VR model sessions was streamlined. Agile trials mechanism was found to enable fast experimentations in VR, even with multiple iterations, which significantly supported the usability of the design processes (boundary objects).

The newly identified mechanism, the Sense-augmented examination of data, was seen to provide totally new reality dimensions to the processes and discourses of the CVR supported design sessions. Provided that the related VR technologies and software are further evolving in this respect, this was seen to significantly transform the possibilities of VR to better identify, acquire and utilize data in building design processes which are not realizable in the real world and with current design means.

5.1 Academic Contribution

The study contributes to academic research by providing a deeper understanding of the role of CVR as an adaptable boundary object, and how CVR functions as boundary object. The aim of the study was to examine what type of boundary objects (processes, artefacts and discourses) are manifested in CVR specifically in the technical building design processes, while the role of boundary objects have not been earlier, to our knowledge, been more specifically researched and understood in construction industry and technical building design. To this purpose, we also explained how relevant and beneficial CVR and related BO's are in this context.

The study also improved the understanding of four fundamental mechanisms of CVR, which contribute to identified boundary objects, as well as the better quality and resource efficiency of technical building design processes. The findings indicate that CVR, as characteristic to boundary objects, enhances knowledge transfer in the technical building design processes.

5.2 Managerial Contribution

This study contributes managerially to the practices of building design actors, especially in the technical building design phase. AEC stakeholders can use these findings to acquire better quality feedback faster from current and new stakeholders already in the very early phases of the facility life cycle. The study helps to understand how four fundamental mechanisms of collaborative VR enable better collaboration and co-creation activities in building design than current methods used. The achieved benefits are significant. CVR enables better quality building design outcomes and more qualified processes with less risks, cost and time resources in technical building design processes. The utilization of CVR in building design processes does not necessarily mean that all the design activities will be implemented in the VR environment. The hybrid model implementations provide versatile possibilities to utilize specific aspects of virtual and real-life collaboration modes from different actors.

5.3 Limitations and Future Research

There are certain limitations which limit the usage and generalizability of this study. The main limitation is that the study was based on interviews with five persons from three companies. A larger number of interviews would improve the confidence in the conclusion on CVR and boundary objects. However, this sampling strategy was deemed to be necessary to collect relevant data on CVR as it is currently only in limited use in pioneering companies. The interviewees are focusing on R&D and innovation activities in the technical building design phases of the facility life cycle. Generalizing of the findings to the building design as a whole cannot be directly done. The functionality of CVR as a boundary object can be applied to the other phases of the facility life cycle, but cannot be evaluated in detail how, based on this study.

Further research should be conducted in other phases of the facility life cycle. The utilization of collaborative VR as a boundary object will be in those phases in a different form. The innovative approach could be to further study CVR as a boundary object, how it benefits new stakeholders and improves building designs. Moreover, VR hardware and software are evolving rapidly. There will be more opportunities available for CVR: the usage of virtual environments will become more popular, competencies and readiness to utilize virtual tools will evolve, and new collaborative characteristics and features in collaborative VR will increase. When the adoption has increased and generalized, further studies will be needed on what kind of effect this will have on the exploitability of the results.

REFERENCES

An, K. and Powe, N. (2015). Enhancing 'Boundary Work' Through the Use of Virtual Reality: Exploring the Potential within Landscape and Visual Impact Assessment, Journal of Environmental Policy & Planning, 17:5, 673-690.

Affendy, N. and Wanis, I. (2019). A Review on Collaborative Learning Environment across Virtual and Augmented Reality Technology. Joint Conference on Green Engineering Technology & Applied Computing 2019, IOP Publishing IOP Conf. Series: Materials Science and Engineering 551.

Bullinger, H. J., Bauer, W., Wenzel, G., & Blach, R. (2010). Towards user centred design (UCD) in architecture based on immersive virtual environments. Computers in Industry, 61(4), 372–379. https://doi.org/10.1016/j.compind.2009.12.003

Churchill, E. F., & Snowdon, D. (1998). Collaborative virtual environments: an introductory review of issues and systems. virtual reality, 3(1), 3-15.

Du, J., Zou, Z., Shi, Y., & Zhao, D. (2018). Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making. Automation in Construction, 85(August 2016), 51–64. https://doi.org/10.1016/j.autcon.2017.10.009

Fominykh, M., Prasolova-Førland, Y., Divitini, M. & Petersen, A. (2016). Boundary objects in collaborative work and learning, S. Inf Syst Front, 18, 85–102.

Ghauri, P., Grønhaug, K., & Strange, R. (2020). Research Methods in Business Studies (5th ed.). Dorchester, UK: Cambridge University Press.

Goulding, J. S., Rahimian, F. P., & Wang, X. (2014). Virtual reality-based cloud BIM platform for integrated AEC projects. Journal of Information Technology in Construction, 19, 308–325.

Heydarian, A., Carneiro, J. P., Gerber, D., Becerik-Gerber, B., Hayes, T., & Wood, W. (2015). Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations. Automation in Construction, 54, 116–126. https://doi.org/10.1016/j.autcon.2015.03.020

Hilfert, T., & König, M. (2016). Low-cost virtual reality environment for engineering and construction. Visualization in Engineering, 4(1), 2. https://doi.org/10.1186/s40327-015-0031-5

Kuliga, S. F., Thrash, T., Dalton, R. C., & Hölscher, C. (2015). Virtual reality as an empirical research tool - Exploring user experience in a real building and a corresponding virtual model. Computers, Environment and Urban Systems, 54, 363–375. https://doi.org/10.1016/j.compenvurbsys.2015.09.006

Miettinen, R., & Paavola, S. (2014). Beyond the BIM utopia: Approaches to the development and implementation of building information modeling. Automation in Construction, 43, 84–91. https://doi.org/10.1016/j.autcon.2014.03.009

Mäenpää. A., Suominen, A. H., & Breite, R. (2016). Boundary Objects as Part of Knowledge Integration for Networked Innovation. Technology Innovation Management Review, 6(10): 25–36. http://timreview.ca/article/1025

Olechnowicz, C. (2018). Immersed in Fire: The Use of Virtual Reality as an Attitude Assessor and Boundary Object in Wildland Fire Management. Electronic Theses and Dissertations, 2837. Retrieved from https://digitalcommons.library.umaine.edu/etd/2837.

Paes, D., Arantes, E., & Irizarry, J. (2017). Immersive environment for improving the understanding of architectural 3D models: Comparing user spatial perception between immersive and traditional virtual reality systems. Automation in Construction, 84(August 2016), 292–303. https://doi.org/10.1016/j.autcon.2017.09.016

Papadonikolaki, E., van Oel, C., and Kagioglou, M. (2019). Organising and Managing boundaries: A structurational view of collaboration with Building Information

Modelling (BIM) International Journal of Project Management 37, 378–394.
Patton. M. Q. (2002). Qualitative research and evaluation methods. 3rd Edition. Thousand Oaks, CA: Sage Publications.
Perry, T. S. (2015). Virtual reality goes social. IEEE Spectrum, 53(1), 56–57. https://doi.org/10.1109/mspec.2016.7367470
Portman, M. E., Natapov, A., & Fisher-Gewirtzman, D. (2015). To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning. Computers, Environment and Urban Systems, 54, 376–384. https://doi.org/10.1016/j.compenvurbsys.2015.05.001
Sutherland, I. E. (1965). The ultimate display. Multimedia: From Wagner to virtual reality, 506-508.
Slater, M. (2018). Immersion and the illusion of presence in virtual reality. British Journal of Psychology, 109(3), 431-433.
Slater, M., & Sanchez-Vives, M. V. (2016). Enhancing our lives with immersive virtual reality. Frontiers in Robotics and AI, 3, 74.
Star, S., & Griesemer, J. (1989). Institutional ecology, 'translations' and boundary objects: amateurs and professionals in Berkeley's museum of vertebrate zoology, 1907–39. Social Studies of Science, 19(3), 387–420.
Steffen, J. H., Gaskin, J. E., Meservy, T. O., Jenkins, J. L., & Wolman, I. (2019). Framework of Affordances for Virtual Reality and Augmented Reality. Journal of Management Information Systems, 36(3), 683–729. https://doi.org/10.1080/07421222.2019.1628877
Wenger, E. (2000). Communities of practice and social learning systems. Organization, 7(2), 225–246.
Yin, R. K. (2009). Case study research: Design and methods. 4th Edition. Thousand Oaks, CA: Sage.