Thesis for the degree of licentiate of engineering

Virtual Collaborative Design Environment: Information structure and interfaces

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Department of Architecture and Civil Engineering

Chalmers university of Technology

Gothenburg, Sweden 2023

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Abstract

The failure to identify design issues in early phases of construction projects has been identified as a significant cause of costly rework, as these issues can impact the building occupants' abilities to efficiently perform their daily work tasks. Therefore, it is crucial to consider their feedback when design reviewing. To date, efforts have been made to involve building occupants via a variety of user-interfaces that provide different understandings of the project. One such example is Virtual Reality (VR), which increases building occupants' spatial understanding. Another, is use of design guidelines, intended to support both end-users such as building occupants and also the design team in basing their decision-making on best-practice and ensuring compliance with design requirements. When used together, these different user-interfaces can complement each other by enabling, for instance, visualization of the furniture layout depicted in design guideline documents. However, few studies have identified what is required of a design tool capable of supporting both visualization of design and design-compliance via different user-interfaces. Therefore, the aim of this thesis is to advance the understanding of end-users' involvement in virtual collaborative environments in the building design process. Accordingly, Design Science Research was applied with a two-fold purpose. First, to identify different stakeholders' challenges that are faced in the design process and specifically how building occupants' daily work tasks are considered in the design process. Secondly, the research methods such as workshops, semi-structured interviews and documentation analysis helped identify the requirements of a design tool that would enable this knowledge to be transferred and accessible at a cross-project level. The results show that the information structure and user-interface of design guidelines determine to a large degree how effectively compliance with requirements can be validated. An example is the absence of user-interfaces in design guidelines which prevents building occupants from gaining sufficient spatial understanding. This lack of spatial understanding results in them to being reliant on other project members, such as architects and facility planners, for providing input on the design. Moreover, the results show how cross-project knowledge is difficult to facilitate due to how design guidelines have not been created in relation to today's digital design process. Therefore, this thesis bridges the concepts of integrating design guidelines and VR in the same design tool.

Keywords: Virtual Reality (VR), Head-mounted display (HMD), Design Guidelines, User involvement, Collaborative Virtual Environment (CVE), Cross-project learning, Decision-making

List of appended papers

Paper 1: ***From informative to Co-design: the role of Virtual Reality for user-involvement in healthcare design***

Sateei, S., Roupé, M. and Johansson, M. (2023)
Work in progress

Paper 2: ***Collaborative design review sessions in VR: multi-scale and multi-use***

Sateei, S., Roupé, M. and Johansson, M. (2022)
This paper was included in the Proceedings of the 27th International Conference of the Association for ComputerAided Architectural Design Research in Asia (CAADRIA) 2022. Vol. 1, p.29-38

Paper 3: ***An ontological approach for a recommendation system of a requirement tool: the case of a national standard framework for hospital design***

Sateei, S., Roupé, M. and Johansson, M. (2022)
This paper was included in the proceedings of the European Conference on Computing in Construction (EC3) 2022

Paper 4: ***Knowledge integration through resource combining: the case of a national standard framework for hospital design***

Sateei, S. and Sundquist, V. (2022)
This paper was included in the Proceedings of the 38th Annual ARCOM Conference

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Shahin Sateei
Göteborg, 2023, May

Terminology

Action space – The space in which users use various types of technologies to work together and complete tasks, including both a physical space as well as virtual environment

Allocentric frame of reference – Perceiving space based on external cues in the environment such as relationship between objects

Best-practice – The collection of relevant and experience-based knowledge available in design guidelines

Building Information Modeling (BIM) – A digital representation of the building that allows for designing and managing information connected to the building project

Collaborative Virtual Environment (CVE) – A shared virtual environment from which multiple users can interact and collaborate

Collaborative design system – CVE systems that support use of multiple user-interfaces for collaborative work on the design

Collaborative practice – Processes where both the design team and end-users collaborate to achieve a design outcome, allowing end-users to both evaluate as well as develop design proposals together with the design team.

Cross-project learning – Applying knowledge and experience gained from previous construction projects to inform and improve decision-making in different construction projects

Daily working tasks - Building occupants' routine activities that they engage in within the building

Design guidelines – Instructions intended to support a consistent understanding of the building design across projects

Design reviewing – Process of evaluating design proposals to ensure they meet specified requirements

Design team – Involved project members that include architects, interior architect, BIM coordinator, design manager

Egocentric frame of reference– Perceiving space based on an individual's own body position and movement

End-user – Involved project members that include building occupants, client representatives, facility planners and project managers

Generative design – Use of computer programs to generate multiple design proposals based on certain requirements

Head-Mounted Display (HMD) Virtual Reality (VR) – VR technology that uses a headset to display the virtual environment, allowing users to feel fully immersed in the 3D model

Industry Foundation Class (IFC) file – A file format used for exchanging data between different software programs

Information structure – The way information is organized and managed within a construction project

Levels of involvement – Refers to the different degrees end-users are involved in the design process, ranging from low levels where feedback is given by commenting to high levels of involvement where end-users help the design team develop the design

Object manipulation – Ability to control objects in the virtual environment by moving and rotating them

Project members – Refers to any type of user involved in the project, either design team members or end-users

Reflective space – Space where collaborative activities are reflected upon and discussed

Rule-language – A computer-interpretable language that uses geometry concepts and logical operations, with the purpose of automating decision-making related to design layout

Task-based scenarios – Scenarios in the virtual environment where building occupants evaluate how their routine tasks are influenced by the building design

User-interface – The visual representation of the design that allows user to interact and review when providing feedback

Visual and information mediums – How information is presented and communicated to the viewer, such as use of 2D drawings and 3D models.

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1 Chapter One: Introduction

The construction industry is continuously challenged by cost overruns and delays. For example, many projects experience rework, costing 5% to 20% of the total contract value (Forcada et al., 2017; Love et al., 2019; Safapour & Kermanshachi, 2019). One major cause for this costly rework is the failure to recognize design issues in early design phases which can lead to as much as 50% of the rework that occurs (Barber et al., 2000; Love & Edwards, 2004). Furthermore, studies have shown that the design influences building occupants' efficiency in performing their daily work tasks (Bjørn et al., 2021; Mitterberger et al., 2023). One such example is healthcare facilities where the quality of patient service is influenced by the healthcare staffs' ability to efficiently work together when performing their tasks (J. Carthey, 2021; Reiling, 2006; Støre-Valen, 2021). Another is where student performance and teaching methods are linked to and affected by design choices and the physical layout of a school (Byers et al., 2018; Frelin & Grannäs, 2021, 2022).

As a response, design guidelines have been developed as a common base and best-practice across different projects and to avoid reinventing the wheel in every new project (J. Carthey, 2020; Cruickshank et al., 2013; Phiri & Chen, 2014b; Tétreault & Passini, 2003). An example of a building type where design guidelines are commonly used is hospital projects. In this thesis, design guidelines consist of both mandatory and legally regulated building codes together with design recommendations intended to guide decision-making processes related to the design. Mandatory and legally regulated building codes describe safety standards of a building such as structure, fire safety, ventilation, daylight requirement, and accessibility etc. In contrast, design recommendations for hospitals describes layout of standard rooms, room sizes and functions etc. These design recommendations and legally binding policies consist of both national as well as regional level. Applying these on a project level creates a "*complex mix of statutory and guidance documents, which creates a confusing regulatory environment*" (Mills et al., 2015). In practice, this means supporting project specific requirements whilst at the same time complying with mandatory requirements in legally binding policies. During this process the healthcare staff usually have an input on the design via their representatives (e.g., facility planner, health and safety representatives), although studies have shown that healthcare staff often experience challenges when starting to use the facilities (J. Carthey, 2021; Lindahl et al., 2010).

A particular challenge when users (e.g., building occupants, facility planners) start occupying the space is experienced in countries such as Sweden where the healthcare is regionalized, as is the planning and building of healthcare facilities. This on the one hand allows flexibility in design work, but at the same time makes national knowledge coordination difficult. As a result, knowledge-transfer between new healthcare projects is not only difficult to facilitate but it would also require a strong national coordination. Also, with no efficient national coordination in place, it becomes difficult to validate how up-to-date the design recommendations are and specifically, how these reflect the healthcare staffs' actual wants and needs in regard to their daily work. An example of this are the requirements connected to different standard rooms (e.g., ICU unit, operating theater), made up by both quantitative requirements (i.e., what the rooms consist of such as number and type of medical equipment and furniture etc.) and requirements describing how these rooms should be furnished. Specifically, both these type of requirements are perceived as difficult to apply due to insufficient description in the quantitative requirements of what the rooms should consist of (e.g., only listing room size, ventilation) as well as abstract formulation of the requirements describing furnishment (e.g., using words such as “good” and “close enough”). As a result, healthcare staffs’ representatives who mainly interpret these two different type of requirements, experience difficulties with understanding how design recommendations can support the healthcare staffs’ daily work. Moreover, these limitations mean that healthcare projects can be designed differently and not based on the experience and knowledge from existing projects. Beyond this cross-project transfer of knowledge and experience, understanding for how the building design affects the healthcare staffs’ daily work is another challenge experienced within separate projects. Specifically, design processes that do not incorporate direct involvement of healthcare staff can make it difficult to understand on what premise their representatives interpret their daily work when interpretating design recommendations.

In light of these issues, research in recent years has explored how involvement of end-users such as building occupants (e.g., healthcare staff) can be facilitated through various collaborative practices such as Participatory Design and Co-design (Caixeta et al., 2019). However, the visual and information mediums used in these collaborative practices do not always support a mutual understanding of the design. Specifically, visual and information mediums such as 2D drawings and 3D models have been shown to be ineffective in providing sufficient spatial understanding for end-users (Okada et al., 2017). One explanation for a lack of spatial understanding is that end-users do not always possess the appropriate knowledge and experience to accurately interpret 2D drawings (Lin et al., 2018; Okada et al., 2017). Additionally, end-users may experience difficulties perceiving the depth of the design, which is especially difficult when viewing 3D models on a flat screen or 2D drawings (Gírbacia et al., 2012; Kozhevnikov & Dhond, 2012; Roupé, 2013). Consequently, limited spatial understanding can lead to misinterpretations when reviewing a design (Elf et al., 2019; Lindahl & Ryd, 2007).

As a response to this lack of understanding, Building Information Modeling (BIM) has been used as one solution to aid project members understand the design (Bosch-Sijtsema et al., 2017; Eliwa et al., 2022; Sebastian, 2011). One of the main explanations for this increased understanding of the design is how BIM software is capable of categorizing, structuring and storing project information connected to the design (Phiri, 2016b). Another solution is how extraction of the 3D design directly from the BIM allows Virtual Reality (VR) models to be used. In these VR model, users can experience the 3D model in 1:1 scale (Johansson, 2016). As a result of the increased spatial understanding, an integration toward the design could be achieved.

In this context of users being immersed in a virtual environment of the design, Collaborative Virtual Environments (CVE) systems have been developed to support collaborative processes with CVE systems, where multiple users can “step into” the design and be immersed into a simulation of the designed building in a virtual environment. An example of a CVE system is head-mounted-display (HMD) VR that allows visualization and representations of the 3D design. With HMD-VR, users can experience the design from a self-centered perspective. Moreover, recent advances have enabled design reviewing with multiple users in the same VR-model, which enhances collaborative understanding (Johansson & Roupé, 2022; Shi et al., 2016; Truong et al., 2021).

Still, the limitations of using VR for design reviewing purposes is not yet fully researched. There is still a lack of knowledge of how different technical features (e.g., multi-user, use of mark-up tools, object manipulation) influence end-users' spatial understanding and ability to provide feedback to design team members such as architects (Horvat et al., 2022; Lapointe et al., 2021). Furthermore, there is little understanding on how design reviewing is influenced when visualization of different types of information, usually presented in separate user-interfaces, are shown in VR (Nikolić & Whyte, 2021). VR is only one of many available CVE user-interfaces in the design process that informs decision-making (Mitterberger et al., 2023) and there is a need to work towards an integration of multiple user-interfaces.

Efforts have been made to develop a new type of CVE system that integrates multiple user-interfaces in the same design tool. One example is the Virtual Collaborative Design Environment (ViCoDE) system (Roupé et al., 2020). ViCoDE offers multiple user-interfaces (e.g., projector screen, multitouch table, HMD-VR) that allows users to make changes to the design layout on a multitouch table, such as placement of walls, equipment and furniture. These changes appear simultaneously on all the other user-interfaces, allowing project members to better understand how different design layouts could be perceived by building occupants' in their daily working activities. For this reason, a satisfactory collaborative understanding is more likely to emerge as a result of an increased spatial understanding. But this increased spatial understanding does not necessarily help with understanding of how different design layouts comply with either the quantitative requirements or the requirements describing furnishment listed in design recommendations. Moreover, with both types of these requirements perceived as ambiguous by users such as facility planners, who primary interpret design recommendations, it becomes difficult to evaluate what is considered a "good design" in relation to building occupants' needs.

To resolve this point, efforts have been made to understand how these types of requirements in design recommendations could be explicitly written and visualized for increased understanding. This has been done with the aim of making design guidelines, and specifically the requirements listed in design recommendations, more accessible for not only the primary users (e.g., facility planners and architects) but also building occupants to ensure that compliance with design recommendations is also validated by those who are directly affected by the design (Soliman-Junior et al., 2021; Sydora & Stroulia, 2020).

However, the literature does not provide an explanation of how to integrate viable user-interfaces (e.g., VR, rule algorithm) within the same design tool, allowing both visualization of the design layout that simultaneously comply with requirements listed in design recommendations. One explanation is that the literature have mainly studied different viable user-interfaces separately and to a lesser extent, how these can be combined. Another explanation is that formulation of requirements in design recommendations have primarily been studied in the context of developing compliance-checking software, compatible with BIM models. Still, the user-interface to these compliance tools has been demonstrated to be far from user-friendly. This prevents direct involvement of users such as building occupants who can provide input based on their knowledge and experience of their daily tasks when design recommendations are reviewed.

Therefore, the aim of this thesis is to improve the knowledge about how different viable user-interfaces can be integrated into the same design tools, to ensure that a virtual collaborative understanding can emerge when reviewing design recommendations. As such, the goal is to create an understanding for how CVE systems could be integrated with design guidelines to support building occupants' daily work.

1.1 Aims and research questions

The overall aim of this thesis is to advance the understanding of how design guidelines can be used in virtual collaborative environments in the design process, in order to facilitate end-user involvement.

RQ1: How can design guidelines be implemented in the design process to support both end-users and design team?

RQ2: How can requirements in design guidelines be reviewed and understood?

RQ3: How is end-user involvement influenced by different technical features in VR?

2 Chapter Two: Previous studies

This chapter begins with a description of how the building design affects building occupants' ability to work efficiently. This is followed by providing an overview of relevant studies of user-involvement and the different visual and information mediums affecting end-users' ability to assess the design. Next, relevant literature on ICT systems such as design guidelines and BIM are presented, to understand how these systems can facilitate a more informed decision-making process. Lastly, CVE-systems with support for multiple user-interfaces are introduced to describe how these systems can facilitate collaborative understanding for the design.

2.1 Design layout affects building occupants' work efficiency

To ensure that the design of a building is considered effective, it is important to consider the needs and wants of end-users such as building occupants. Previous literature has highlighted the importance of involving of building occupants in the design process, as the design layout of a building has been observed to influence building occupants' daily working tasks (Frelin & Grannäs, 2021, 2022; Martin, 2002; Mourshed & Zhao, 2012). One example is how single room patient accommodation in healthcare design has shown to prevent nurses from gaining valuable "peripheral information" that is common in open-plan environment (e.g., ability to check on multiple patients at the same time during night duty, sightlines to communicate with colleagues), which could undermine effective staff teamwork (Donetto et al., 2017). Another example is the importance of furnishing the same healthcare space for different purposes. In this context, the recent COVID-19 pandemic showed the importance of being able to divide contaminated and non-contaminated areas from each other to prevent virus spread as well as furnishing existing spaces so that they can meet the demand for emergency care and Intensive Care Unit (ICU) beds for infectious diseases (Capolongo et al., 2020; Pandey et al., 2020).

Therefore, identifying these different design issues linked to building occupants' daily working tasks requires an understanding of user-involvement. Still, there are challenges such as a lack of conceptual consensus on what different terms mean (e.g., Participatory Design, Co-design) (Caixeta et al., 2019). One example is how terms such as Participatory Design (PD) includes both broad and more niched definitions, where on the one hand user-involvement is described in past studies as affecting both the design process and its outcome (Granath et al., 1996) whilst recent definitions describe how PD as an approach to design contextually suitable solutions, together with end-users (e.g., building occupants) (Sanders et al., 2010; Shanthi Priya et al., 2020). Another challenge is the choice of medium used in communication and decision-making processes (e.g., use of 2D drawings, 3D models, mock-up rooms) used for involving end-users (Kim et al., 2016). Specifically, how do these different methods help end-users such as building occupants and projects managers identify and address design issues?

2.2 Collaborative practices

2.2.1 User-involvement and collaborative practices

The established theoretical framework for user involvement was introduced in the late 1960s in the field of public administration, published in Arnstein's "A ladder of Citizen Participation" (Arnstein, 1969). The author argued that a redistribution of decision-making among participants could enable shared understanding of the decisions made. Arnstein (1969) defines redistribution of decision-making as a shift in authority and control from those in position of power to the users affected by the decisions. Following this definition, she argues that by increasing community members sense of ownership and responsibility towards the outcome, they are more likely to actively engage and take ownership of the decisions made. This argues that this redistribution of decision-making could address the problem that those with authority make interpretations and decisions on behalf of others, causing what the literature refers to as an "illusion of involvement" (Few et al., 2007). To this point, a redistribution of decision-making is argued to set the conditions for more inclusive user-involvement as end-users gain

The redistribution of decision-making is illustrated in studies by a ladder-based model with eight different levels of involvement (e.g., informing, consultation, citizen control) that "correspond to the extent of citizens' power in determining the end product" (Arnstein, 1969). Later, various authors have redesigned this ladder-based model (Tritter & McCallum, 2006) to extend its limitations. Examples of limitations were the assumption that decision-makers hold all the power (Dresher, 2007), the lack of methods and feedback systems used when involving different users (Tritter & McCallum, 2006) as well as the implied idea that climbing to the top of the ladder is always the main objective (Davidsson, 1998). Moreover, studies linked to service projects (Bate & Robert, 2007; Visser et al., 2005) and information technology (Barcellini et al., 2015; Frauenberger et al., 2015; Hess et al., 2013) have instead made efforts to address these limitations by presenting terms that reflect different levels of involvement. Examples of these different levels of involvement are Participatory Design (PD) and Co-design. These aim to describe the level of user-involvement required of project members to achieve a desired outcome. Still, the past literature emphasizes the lack of consensus on how and when these terms should be used (Caixeta et al., 2019).

Consequently, studies investigating user-involvement in the field of building design have used different terms when addressing different types of participation particularly in the context of urban planning (Caixeta et al., 2019; Fröst et al., 2017). Still, literature in the field of building design has also acknowledged the lack of clarity in their use of terms. As a result, authors argue that a knowledge gap has emerged between practitioners and researchers due to these terms being used arbitrary and interchangeably (Caixeta et al., 2019). An explanation is that PD and Co-design have overlapping definitions for user-involvement, as both terms describe end-users (e.g., building occupants) as partners in the design process, rather than mere sources of information (Sanders & Stappers, 2008). Additionally, the literature highlights how even though collaborative practices are used, end-users can be held as "hostage" for the decisions made due to lack of sufficient authority in decision-making as well as understanding of the design process they are involved in (Larsen et al., 2021). As a result, decision-making runs the risk of being based on a false premises and users being viewed as alibis in the design process.

However, there are studies that have observed how these terms can aid collaborative understanding of decision makings in design reviews (Olsson et al., 2022). Specifically, it is suggested that by adopting different levels of user-involvement such as participatory design, that it can help both the design team and end-users identify design issues more accurately due to being more informed on what level of involvement that is appropriate (see figure 1 below). Consequently, the direct involvement of end-users is argued to offer end-users a sense of ownership in the decisions they have made together with the design team (Larsen et al., 2021; Pemsel et al., 2010; Tzortzopoulos et al., 2006).

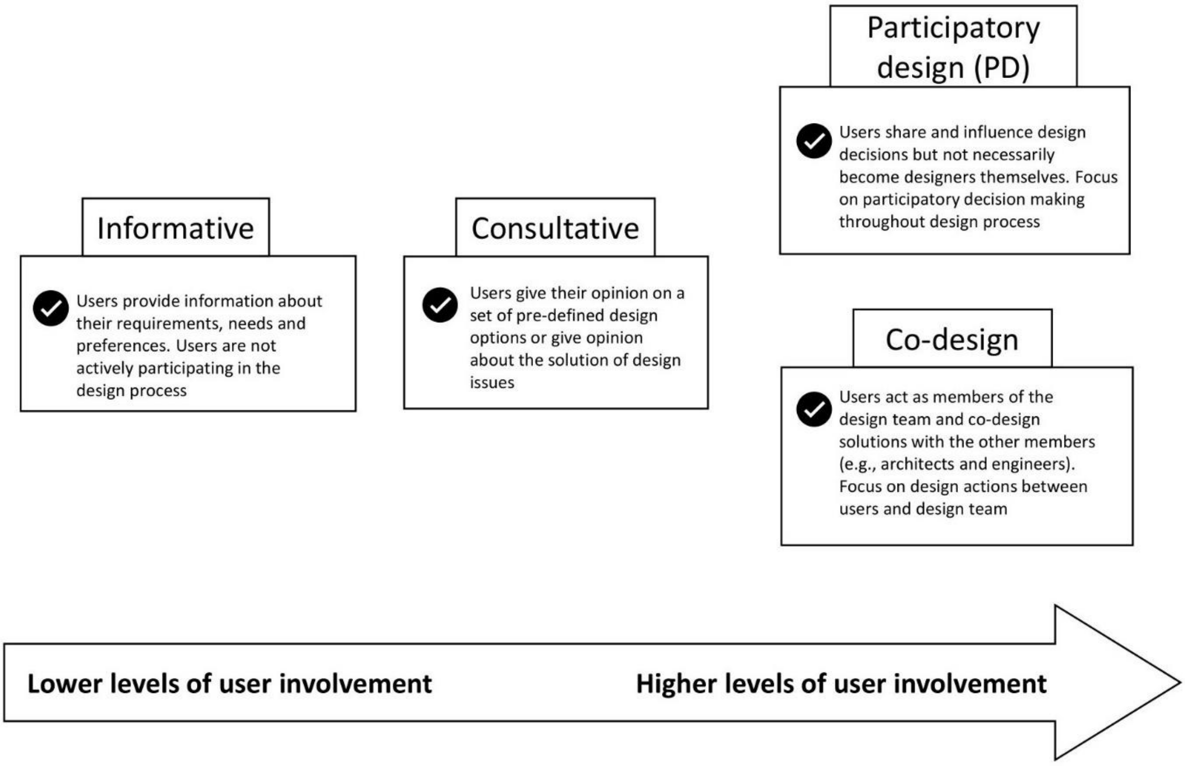

Figure 1. Different levels and classification of collaborative practices in building design. Illustration based on literature review study by Caixeta (2019).

In regard to the discussion above, Caixeta et al (2019) recently demonstrated by conducting a systematic literature review on user-involvement in building design, how conceptual clarity of the various definitions of user-involvement (e.g., PD, Co-design, consultative) can assist architects find the most appropriate level of user-involvement for the design that is being developed (see figure 1 above). This was explained to be due to increased understanding of what each level requires in terms of design demands, user profile and building type. Yet, studies also recognize the need to understand the information and visualization medium itself (e.g., 2D drawings, 3D models, Virtual Reality) used for user-involvement that are the most appropriate to gain the full benefits of each different level of involvement (Caixeta et al., 2019). Therefore, the following section will be presenting how the past literature’s has studied user-involvement in different visual and information mediums.

2.2.2 User-involvement in different visual and information mediums

Various visual and information mediums (e.g., 2D drawings, 3D models, Virtual Reality) can influence user-involvement differently. Specifically, building occupants’ understanding of how their daily working tasks are influenced by the design layout differs when using these visual and information mediums. As a result, it is common in the projects’ design phase to use a combination of these (Kim et al., 2016; Roupé et al., 2020). For example, 2D drawings have been observed to support understanding of relationship between spaces and objects and orientation of different objects, i.e., an allocentric frame of reference (Coburn, 2017). On the other hand, studies also show how 2D drawings, in comparison to 3D models and VR-models, place high cognitive demands on the stakeholders when it comes to interpretating the information into a self-made mental representation of the project (Roupé, 2013). Consequently, this cognitive demand can lead to end-users misinterpret drawings into spatial reasoning and understanding.

In relation to the point above, misinterpretation when reviewing 2D drawings can prevent end-users from involvement in the design process. Previous studies have suggested how difficulties with interpretating leads to less efficient decision-making when design reviewing with 2D drawings (Y. Liu et al., 2020; Mastrolembo Ventura et al., 2019). In comparison, design reviewing with 3D models have been shown to offer a more efficient ways for communicating design ideas to end-users (Balali et al., 2020; Biederman, 1990; Bouchlaghem et al., 2005; Du, Shi, et al., 2018; Mastrolembo Ventura et al., 2019). Moreover, by visualizing the design, 3D models are experienced as less spatially abstract than 2D drawings (Shi et al., 2020). Consequently, visualization of the design can enhance communication between end-users and the design team (Carreiro & Pinto, 2013; Hartmann et al., 2008). Yet, studies also show how the use of 3D models may not provide sufficient spatial understanding for end-users to make sufficiently correct assessment of the design (Lukačević et al., 2020). As a result of this insufficient spatial understanding, end-users such as building occupants may experience difficulties in understanding how to find a design solution. The literature explains lack of spatial understanding to be due to how 3D models viewed on a flat screen facilitate an allocentric spatial reasoning process, e.g., comparing object-to-objects to get an understanding of space in the virtual environment (Kozhevnikov & Dhond, 2012; Lukačević et al., 2020; Wann & Mon-Williams, 1996). Consequently, end-users such as building occupants may experience difficulties in understanding depth perception of reviewed 3D models (Gírbacia et al., 2012). Difficulties in gaining depth perception makes it difficult for end-users to identify design issues such as hidden sightlines and size of a design layout. As a result, the design team risks being provided with incorrect feedback from end-users when design reviewing.

Considering the challenge of gaining spatial depth, studies have explored how use of Virtual Reality (VR) can address this problem by allowing users to be surrounded by the virtual environment. This experience of users “stepping into” the design is what the literature refers to as an immersive experience (Johansson, 2016). With users being immersed in VR, due to the wide field of view (Steed et al., 2005), the ability to perceive volumetric qualities of a building are better than when 2D drawings and 3D models are used (Chowdhury & Schnabel, 2020; Satter & Butler, 2015). Also, the immersive experience users have in VR has shown to support end-users gaining a more representative understanding of how the final building design could be. One explanation for this is that the brain has access to more visual cues (e.g., size, shape, location) when immersed in the virtual environment which creates a lifelike experience of the building design, as compared to 3D models viewed on a flat screen (Hermund et al., 2017). Another explanation is that the wide field of view users experience in VR allows users to experience the design from a self-centered point of view, or what the literature refers to as an egocentric frame of reference (Feldstein et al., 2020; Paes et al., 2023; Roupé et al., 2019). This immersive experience users have in VR has shown to be particularly useful when design reviewing due to the collaborative understanding that emerges. For instance, by having tasks-based scenarios when design reviewing with VR, both the design team and end-users such as building occupants can better understand how daily working tasks are influenced by the building design (Nikolić & Whyte, 2021; Roupé et al., 2020). Consequently, the literature highlights how end-users’ increased spatial understanding can reduce overall misinterpretation of the design in the project, as is common with traditional information and visualization mediums (e.g., 2D drawings and 3D models) (Mastrolembo Ventura et al., 2019; Ventura et al., 2020). With this increased understanding for one another’s perspective, conversations during design reviewing can then shift from ensuring that the design is correctly understood to instead be driven by understanding how building occupants' daily working tasks should be considered (Dunston et al., 2011; Y. Liu et al., 2020; Nikolić & Whyte, 2021; Roupé et al., 2020).

However, previous literature has also identified limitations with using VR. One example is how end-users experience disorientation in large VR-models which prevents them from gaining a clear overview of the design layout and understanding how different spaces are connected (Y. Liu et al., 2020). Another example is how VR is commonly implemented on a single-user basis (Shi et al., 2016; Yan et al., 2011), which limits users from mutually engaging in both verbal and nonverbal communication. This loss of presence between users can then prevent design team members and end-users from establishing common ground during decision-making processes (Du, Zou, et al., 2018; Nikolić & Whyte, 2021). As a response, recent efforts have aimed to address these abovementioned issues experienced in single-user VR. For instance, the ability to switch in the VR model between stereoscopic 1:1 scale and 1:40 scale (i.e., viewing the building design as a miniature model) has shown to address the problem of spatial disorientation, as users can make use of both allocentric and egocentric visual cues (Johansson & Roupé, 2022). Similarly, multi-user in VR has shown to increase users' sense of presence due to sharing the same frame of reference, which helps identify and resolve design issues more quickly when design reviewing (Haahr & Knak, 2022; Shi et al., 2016; Truong et al., 2021).

Whilst these studies show how VR enhances building occupants' spatial understanding, project information such as design requirements listed in design guidelines could further ensure that the design supports building occupants' daily working tasks. For instance, an understanding of how ongoing design issues have been reviewed in previous projects could result in a greater assurance that the same mistakes are not repeated. In other words, the way that project information is organized and managed within a project can facilitate a clearer design understanding among project members. To that end, information communication technologies (ICT) are used to ensure that relevant information is collected, stored and made accessible to all parties, which will be further discussed in the following section.

2.3 Information Communication Technology (ICT)

2.3.1 Information structure

In this thesis, information structure refers to the way information is organized and managed within a construction project. This includes the ICT system itself used for documentation (e.g., cloud-based database) as well as processes such as collaborative practices (e.g., Participatory Design, Co-design) that are put in place to ensure that relevant information is collected, stored and made accessible to all parties involved in the project. Both aspects need to be considered in order to ensure that relevant information linked to the design is collected, stored and shared among project members. As a result, the same information is accessible for all relevant parties which can lead to more informed decision-making as miscommunication is reduced. By making more informed decisions on the design, a more collaborative understanding can then emerge when design reviewing.

Recent studies further support this idea that collaborative understanding emerges as a result of having access to many sources of information (e.g., information provided by building occupants regarding daily working tasks) (J. Carthey, 2021; Tétreault & Passini, 2003; Wanigarathna et al., 2021). It is further suggested that access to these different sources of information could address challenges in the design process. These challenges could for example be learning from previous projects (J. Carthey, 2021; Mills et al., 2015), uncoordinated use of design guidelines on a national level (Mills et al., 2015) and how subjective requirements (i.e., use of words including “good enough”, “close enough”) in design recommendations need to be interpreted (Soliman-Junior et al., 2022a). These challenges are also described as causing additional challenges related to collaborative understanding in the design process. For instance, a lack of documentation and appropriate user-interfaces to understand documented information can reduce both end-users’ and the design team’s ability to identify common design issues in current and future projects (J. Carthey, 2021; Støre-Valen, 2021). When design issues are then identified based on insufficient knowledge from past projects, it can become more difficult to recognize when certain end-users such as building occupants and facility planners need to be involved in the design process (J. Carthey, 2020; Lindahl et al., 2010). To this point, there is a risk that design team members such as architects start to interpret project information such as subjective requirements in design guidelines, on behalf of building occupants’ (J. Carthey, 2021; J. F. Carthey, 2013). In other cases, the user-interface itself can be perceived as complicated (Roupé et al., 2014). The lack of user-friendly user-interfaces can then not only result in exclusion of users when design reviewing but also cause users to experience a loss of ownership in made decisions (J. Carthey, 2021).

However, the literature also suggests that use of design guidelines as the main source of information could address the abovementioned problems. Specifically, a collaborative understanding between the design team and end-users could emerge, provided that end-users such as building occupants have the appropriate conditions (e.g., access to relevant building information in user-friendly interfaces) to express their wants and needs about the design (J. Carthey, 2021) and from architects’ perspective, better understand how developed design proposals comply with design guidelines (Soliman-Junior et al., 2022a, 2022b). Therefore, the next section will present how the past literature has explored the idea of using design guidelines as the main source of information in the design process.

2.3.2 Design guidelines

Design guidelines has shown to be useful as a starting point in the design process, to ensure a consistent knowledge and best-practice of design requirements and solutions across different projects to avoid reinventing the wheel (J. Carthey, 2020; Cruickshank et al., 2013; Phiri & Chen, 2014b; Tétreault & Passini, 2003). Design guidelines have been particularly used in the design process of healthcare projects. The design process for healthcare projects is considered complex, partly due to the challenge of considering the needs of many different project members (e.g., building occupants, facility planners, architects) in the design process and partly due to how the building design directly impacts on the healthcare services provided in the finished building (J. Carthey, 2021; Lindahl et al., 2010; Mills et al., 2015; Salonen et al., 2013). In this context, studies show how informed design decision-making can emerge when design guidelines provide access to information such as the design layout for different standard rooms (e.g., surgical room, ICU unit) together with related design requirements. Moreover, access to a database that contains the 3D models intended for use in these standard rooms (i.e., furnishment such as medical equipment) has shown to further aid the design teams and end-users’ understanding for what is required to support daily working tasks. Consequently, studies suggest how access to this type of information in the design guidelines can help set the conditions for more efficient decision-making in the design process. Specifically, when end-users are more informed on what is considered a good design layout, i.e., supporting building occupants’ daily working tasks, they more willingly accept the reasoning and decisions made by the design team (J. Carthey, 2021; Mills et al., 2015). Therefore, by letting decision-making be driven by informed choices, a mutual understanding for the design layout of standard rooms can be achieved.

The literature also suggests how this mutual understanding of the design layout is difficult to facilitate on a cross-project level. One explanation for this is the lack of centralized and accessible documentation on how design guidelines have been used in different projects, resulting in difficulties with learning from different projects (Mills et al., 2015; Phiri & Chen, 2014c). Another related explanation described in the literature is the challenge of validating whether the design guidelines are up-to-date in terms of reflecting ongoing changes in healthcare delivery (Lindahl et al., 2010). Also, researchers describe how there is an absence of explicit descriptions in design guidelines on how the final building design should support building occupants' daily work tasks. As a result, it is difficult to understand on what basis follow-up on the finished building is made due to vague and normative descriptions, using sentences such as "white ceilings should have a calming effect" without further references to support these type of statements (Elf et al., 2019). Consequently, this lack of explicit description results in difficulties with understanding how, and if, follow-up of the design is linked to building occupants' daily working tasks.

These different explanations showcase the difficulties in enabling cross-project learning when using design guidelines. One of the main consequences that follow from this lack of understanding is that each new project risks "reinventing the wheel" (J. Carthey, 2021; Lindahl et al., 2010; Tétreault & Passini, 2003). As a response, studies have looked into the use of building information modelling (BIM) to understand if BIM can address the problem of cross-project learning by integrating BIM with design guidelines (Bouazza, 2019; Phiri, 2016a). For example, research has shown how use of a database containing furnishment linked to different standard rooms could help centralize information, and as a result, enhance communication between the design team and end-users (Bouazza, 2019; Robson et al., 2014). Therefore, the next section will discuss how BIM could be used to facilitate collaborative understanding by offering visualization and data storage capabilities.

2.3.3 Building Information Modeling (BIM)

To better understand how to achieve a collaborative understanding of the design, studies have investigated how BIM software could incorporate guidelines (Phiri, 2016a; Phiri & Chen, 2014c). For example, Ahmad et al (2014) studied how the design team gained a better visual understanding via the BIM 3D model on how different design layouts of a standard could support building occupants' daily work tasks. Other studies have explored how BIM could also be used to categorize, structure and store information connected to design guidelines (Baldauf et al., 2021). Additionally, studies have explored how this storage of information can be used for the purposes of fully automated compliance checking with design guidelines, or what authors refer to as checking for compliance with "rules" (e.g., spatial requirements in design guidelines) (Ghannad et al., 2019; Soliman-Junior et al., 2022a). Since manual compliance checking is considered highly time-consuming and error-prone (Eastman et al., 2009; Soliman-Junior et al., 2021), efforts have been made to determine whether this manual process could be automated by development of software.

However, there are challenges to the software that prevents fully automated rule-compliant checking. For instance, the subjective and ambiguous descriptions of rules (e.g., use of words such as “should”, “good enough”) makes it difficult to translate these into a machine-readable format that requires quantitative and explicit descriptions (e.g., exact number of components in a room, distance across a given space) (Dimyadi & Amor, 2013; Soliman-Junior et al., 2022b). As a result, automated rule-checking is limited to the quantitative requirements and is made more challenging due to how these studies have hard-coded a fixed sets of rules, essentially preventing users from changing the rules that being checked (Amor & Dimyadi, 2021; Soliman-Junior et al., 2021). This hard-coding requires programming experience and knowledge of the internal structure of the BIM model, something that cannot be undertaken by those who would be considered the most appropriate users (i.e., building occupants). Consequently, consistent update of rules or addition of new rules would not only require someone with the appropriate programming expertise such as a system developer (Ghannad et al., 2019; Ismail et al., 2017), but also would be a costly task (Dimyadi, 2016). The lack of these user-friendly interfaces hinders the involvement of users, those that the literature refers to as “human experts” (Soliman-Junior et al., 2022b), whose daily work tasks are essentially what the rule-checking is intended to check. To this point, the lack of appropriate user-interface to involve human experts such as building occupants, also makes it difficult to accurately validate this rule-checking process (Ghannad et al., 2019; Sydora & Stroulia, 2020).

In an effort to address these challenges, researchers have investigated alternative approaches for rule-based compliance-checking when using BIM. One such alternative is the use of generative design for design layouts that comply with design guidelines. For instance, Sydora & Stroulia (2020) showed in their study the possibility of developing rule-compliant design proposals by relying on the open BIM standard Industry Foundation Class (IFC) when checking compliance with rules. These rules were generated and are shareable via a user-friendly interface in a rule-editor where rules were grouped into different rulesets, based on functionality such as alignment of furniture and walls. Moreover, translation of ambiguous requirements in guidelines into explicit, computer-interpretable format only required users to refer to geometrical concepts (distance, relative positioning etc.) and numerical and logical functions (e.g., number of a specific component in the room). As a result, end-users such as building occupants can instead of reviewing whether the design complies with guidelines, focus on evaluating from a set of rule-compliant design proposals which one that has the specific layout of furnishment that best supports their daily working tasks. Nevertheless, evaluation of furniture arrangement in a design layout requires a spatial understanding of the design that end-users do not necessarily gain by viewing a 3D model. Instead, use of Virtual Reality (VR) could help end-users more accurately evaluate and validate how different design layouts of a room can support daily work tasks. The next section will therefore discuss the results of studies in the literature that have studied the use of VR, and specifically how increased spatial understanding via VR could help end-users such as building occupants provide more accurate feedback on their future working space.

2.3 CVE-systems

2.3.1 Virtual Reality (VR)

Collaborative Virtual Environment (CVE) is a concept referring to a system that allows multiple users to collaborate and provide input on complex design issues in a shared virtual space. Complexity is defined as design issues that require more knowledge than a single individual possesses and thereby the need for all involved participants to communicate, understand, collaborate and participate with each other to achieve a higher quality and intended design outcome (Arias et al., 2000; Fischer et al., 2005).

With these design issues involving multiple stakeholders, conflict and change (Acharya et al., 2022; Arias et al., 2000; Heldal & Roupé, 2012), CVE systems have been found to address complex design issues by providing the design team and end-users the conditions to better understand each other's perspectives, as a result of shared perception and understanding (Arias et al., 2000; Fischer et al., 2005). A shared perception and understanding refers to the design process itself where the design of the future workspace (i.e., the environment in which daily work tasks take place) is reviewed. A shared perception and understanding also involve being aware of the locations, activities and contributions of other facility users in order to play an important role in working collaboratively and effectively during the design process (Gutwin & Greenberg, 2002; He et al., 2020). By understanding the activities of others in the virtual environment, users such as building occupants can gain context for their own activities (Bullinger-Hoffmann et al., 2021; Dourish & Bellotti, 1992). It is this awareness of individual and group activities that the literature views as a requirement for successful CVE systems (Gutwin & Greenberg, 2002).

However, there are limitations experienced by users in CVE systems, which the literature has acknowledged prevents mutual understanding of the design. These limitation are, for example, the ability to view design changes in real-time during the design process but also users' inability to fully express themselves such as using hand gesture to interact with the design and pointing at something of interest to gain the attention of other users. These limitations prevent both the design team and end-users from gaining the necessary conditions to understand one another's perspective on what is considered in the design. With these limitations hindering cooperative understanding, it becomes difficult to establish efficient decision-making regarding design that best supports building occupants' daily working tasks. Moreover, recent studies have shown how task-based scenarios in CVE systems play an important role in allowing building occupants to experience how their cooperative activities (i.e., daily working tasks) are constrained or enabled by the building design (Bjørn et al., 2021; Mitterberger et al., 2023).

As a response to these limitations, Virtual Reality (VR) is often used in CVEs to create a fully immersive and interactive virtual environment for collaborative decision-making (Le Chénéchal et al., 2015). In a VR environment, end-users and the design team can experience a shared virtual space and interact with each other and spatial components in the VR model in real-time, allowing for new forms of activity to communicate, which are not possible in physical environments or with CSCW systems (Churchill & Snowdon, 1998; IJsselsteijn & Riva, 2003; Philippe et al., 2020). Examples of these activities are offering collaboration independent of users' physical location, personal communication via non-verbal cues as well as increased spatial awareness that allows users to orient themselves in the virtual environment and understand the location of other users and objects (Al-Sharaa et al., 2022; Johansson & Roupé, 2022; Truong et al., 2021). By being immersed in the virtual environments, users gain an increased sense of presence which increases engagement and understanding of performed task during collaborate design reviewing (Paes et al., 2017, 2021). Moreover, studies suggest that increased sense of presence in VR can lead to improved collaboration during design reviewing as users are better able to remember and discuss details and aspects of the design. With increased sense of presence, misunderstandings are likely to be reduced since all the participants in the virtual environment share an experience of the spatial (Johansson & Roupé, 2022; Paes et al., 2021; Truong et al., 2021).

However, studies also indicate that this sense of presence VR can distract users from their main tasks during design reviewing, which can result in inefficient design-reviewing (Umair et al., 2022; van der Land et al., 2013). Nevertheless, the literature has also demonstrated that by providing users the ability to independently investigate and interact with the virtual environment (e.g., testing logistical flow via manipulation of spatial objects such as furnishment) a more explorative problem-solving approach takes place when design reviewing (Berg et al., 2017; Conniff et al., 2010; Weissker et al., 2020). Likewise, multi-user functionality that enables real-time communication among remote VR-users has been suggested to further facilitate mutual spatial understanding as users not only share the same frame of reference but are also able to experience non-verbal cues and verbal communication between one another (Johansson & Roupé, 2022; Shi et al., 2016; Truong et al., 2021). This mutual understanding of the design has been shown to accelerate decision-making during design reviewing when building occupants negotiate with the design team. This decision-making process has been explained by researchers to be due to the increased confidence building occupants gain when understanding the connection of a design layout and how well they can perform their future daily working tasks in that virtual environment (Bjørn et al., 2021; Roupé et al., 2020). For instance, Chowdhury & Schnabel (2020) observed that compared to traditional design reviewing tools such as 2D drawings and 3D models, VR triggers conversations and questions related to the design among participants which could be used to evaluate and generate design proposals in task based scenarios in the virtual environment. Similarly, Roupé et al (2020) demonstrated how use of task-based scenarios in VR can speed up decision-making processes as users are able to iteratively experience and provide feedback on different design proposals. It is of further interest to note how the use of certain technical features (e.g., object manipulation, multi-user) in the studied task-based scenarios is what helped facilitate the collaborative understanding. Therefore, the last section of this chapter will present a more in-depth discussion of both the design tool used in the abovementioned studies called ViCoDE, but also similar design tools aimed towards facilitating collaborative understanding.

2.3.2 Virtual Collaborative Design Environment (ViCoDE)

The literature has highlighted the importance of CVEs supporting certain criteria that enable collaborative understanding. These are a shared context, awareness of others, negotiation and communication, transitions between shared and individual activities and flexible and multiple viewpoints (Churchill & Snowdon, 1998, 1998; Mitterberger et al., 2023). Therefore, attempts have been made to combine multiple user-interfaces that satisfy these criteria. In this thesis, such examples of CVE systems with support for multiple types of user-interfaces is viewed as collaborative design systems. An example of such a combination is a prototype presented by Faliu et al (2019) in the context of urban planning where a multitouch table and VR enhanced spatial awareness and understanding as a result of multiple user-interfaces. Similarly, Imottesjo & Kain (2022) in a system that integrated web-based desktop, VR and Augmented Reality (AR), demonstrated how users in an urban development context gained new understanding for the connection of adjacent neighborhood blocks as they adopted each other’s viewpoints to address design issues linked to hidden sightlines.

However, limitations in the abovementioned studies such as an experimental setting make it difficult to assess and validate whether the performed tasks were solved via the system as intended in a real-life and how absence of multi-user functionality could have influenced participants’ mutual understanding of the design (Faliu et al., 2019). Likewise, with the user-interface developed toward only a specific type of user (e.g., end-users such as project leader or facility planner), it becomes difficult to understand how communication would emerge on a larger scale between more types of users and how design issues would be negotiated and addressed (Imottesjo & Kain, 2022).

To that end, the collaborative design system called ViCoDE (Virtual Collaborative Design Environment) had been developed and evaluated in a real-life case study of a high-tech healthcare facility (Roupé et al., 2020). ViCoDE features seamless integration of several immersive HMD VR systems and a multitouch table that provides collaborative and interactive design work with immediate feedback. Moreover, with users having access to both an individual as well as a collaborative workspace (Arias et al., 2000; Fischer et al., 2005), an increased participation, understanding and communication takes place between different project members. For instance, the seamless integration of multiple interfaces (i.e., design changes done in one medium is updated in others as well) enabled participants to experience different design spaces – both collaborative and individual, which enabled different actors recognizing each other's perspectives. Moreover, the ability to change placement of furnishment and structures of the walls in real-time via the multitouch table (i.e., object manipulation) enabled a more rapid understanding of design issues when task-based scenarios were performed by end-users such as building occupants and project managers, leading to a reduction in overall time when design issues were discussed and negotiated. This ability to receive almost immediate feedback and object manipulation, was observed to aid participants in evaluating different furniture arrangements in multiple design proposals. As a result, building occupants were able to develop design proposals alongside the architect. Consequently, building occupants' knowledge and experience of their daily working tasks was the driving factor when developing different layouts of the room. By increasing the spatial understanding of the building occupants as well as providing them the opportunity to express their ideas in the different user-interfaces (e.g., testing logistical flow for different furnishment layouts), the architect better understood what was required for efficient daily working tasks. Furthermore, these different user-interfaces also corresponded to different frames of references, i.e., allocentric and ego-centric frame of reference, which satisfied the criterias of what is considered a successful CVE system in terms of offering *Flexible and multiple viewpoints* and *Transitions between shared and individual activities* (Churchill & Snowdon, 1998; Snowdon et al., 2001). Therefore, Roupé et al (2020) argued that ViCoDE as a design tool could as a CVE system with support for multiple user-interfaces achieve a better and more time-cost effective design process compared to traditional processes using 2D drawings and 3D models. In this thesis, ViCoDE has been observed to understand how it as a collaborative design system facilitates collaboration when design reviewing.

3 Research Design

3.1 Research methodology

Design science research (DSR) is a research approach that aims to develop and evaluate innovative solutions to complex problems through the design, implementation, and evaluation of artifacts (Hevner & Chatterjee, 2010). DSR differs from natural science and social science research in that it is concerned with creating new artifacts, such as models, methods, and tools, rather than studying existing phenomena (March & Smith, 1995). DSR is appropriate when traditional research approaches are insufficient to address complex, real-world problems, and when a pragmatic, problem-solving focus is required (March & Smith, 1995; Vaishnavi & Kuechler, 2015).

As such, artifacts are an essential part of DSR and are defined as "*any object that has been created or modified by human intervention for some specific purpose*" (Johannesson & Perjons, 2014b, 2021b). In DSR, artifacts can take many forms, such as software systems, models, frameworks, and processes. They are created through a systematic and iterative design process defined as *activities*, that start from developing an understanding of the problem to the design and development of an artefact that addresses this problem to the evaluation of the artefact itself (see figure 2).

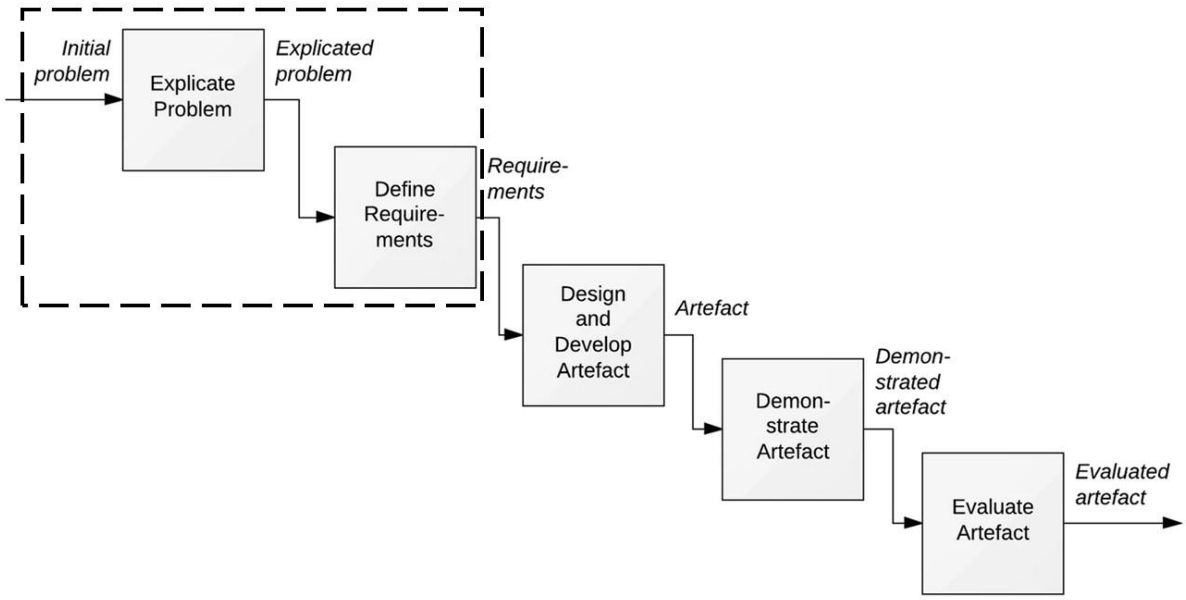

Figure 2: The different activities that make up the method framework for design science research. This thesis focuses on the activities highlighted in the marked area. Illustration based on Johannesson & Perjons (2021a).

In this thesis, the focus is on the first two activities of the DSR framework: *Explicate problem* and *Defining requirements*. The purpose of the first step, *Explicate problem*, is to formulate the initial problem precisely, justify its importance and study its underlying causes to address the following question: "*what is the problem experienced by some stakeholders of a practice and why is it important?"* (Johannesson & Perjons, 2014a). Moreover, different stakeholders in this thesis refers to both design team members such as architects and BIM coordinators as well as end-users such as building occupants, client representatives and facility planners. The studied phenomenon is understanding *how end-user involvement in the design process is influenced by multiple user-interfaces in the same collaborative design system*. The problem this thesis aims to understand is *how design guidelines can support the design of standard rooms that allow building occupants to perform their daily work tasks more efficiently*. Therefore, the first activity step helps create a better understanding for how different project members, and particularly end-users, experience user-involvement when using VR. Due to the design team and end-users having different experiences, it could result in them having different views of the problem, i.e., how important they consider end-user involvement via VR to be in the design process. Moreover, gaining the perspective of multiple stakeholders can help define the problem more accurately. This is turn could better understand the gap between current state and the desired state of doing a practice (Johannesson & Perjons, 2021c).

According to Johanneson & Perjons (2014a) when the problem has been appropriately defined, the next activity in the method framework outlines a solution to this defined problem. Specifically, suitable requirements for a proposed artefact are identified, with the purpose of addressing the defined problem from the previous activity. In other words, the question that the second activity in DSR intends to address is the following: "*what artefact can be a solution for the defined problem and which requirements for this artefact are important to the stakeholders?"* (Johannesson & Perjons, 2014a). As such, artefact in this thesis refers to communication artefacts used in the collaborative environment. Also, for the sake of simplicity and to avoid confusion with the term requirements associated with design guidelines, this thesis will use the term *functions* when describing DSR "requirements" of the collaborative design system.

To ensure that all relevant stakeholders related to the studied problem has been identified, the Industrial Network Approach (IMP) has been adopted. This goes beyond those already identified by the DSR research method. The IMP approach is suitable for assessing stakeholders on a cross-project level. The central themes in IMP studies are social interactions and relationships among different stakeholders within a specific network (Håkansson et al., 2009; Håkansson & Snehota, 1995; Havenvid I & Linné, 2016; Sundquist et al., 2018; Wagrell et al., 2022). In this thesis, network refers to the different regions that use design guidelines and how they interact. In other words, the IMP approach can help address the question in the second DSR activity, which is to identify suitable functions for a proposed communication artefact that can serve as a solution to the problem studied in this thesis, i.e., *how design guidelines can support the design of standard rooms that allow building occupants to perform their daily work tasks more efficiently*.

In regard to identifying suitable functions for a communication artefact, it is important to identify functions that consider how different stakeholders perceive the use of the communication artefact as well as functions related to how the communication artefact works and is perceived in situations of use. In this thesis, the following functions are of particular interest due to the variety of stakeholders intended to use the proposed communication artefact in collaborative environments:

- *Usability*: the effectiveness with which a user can use an artefact to achieve a particular goal, i.e., how can a collaborative design system that supports visualization as well as compliance with design guidelines, help end-users (e.g., building occupants, facility planners) identify design layouts that make daily work tasks more efficient?

- *Suitability*: the degree to which an artefact is tailored to a specific practice, i.e., how can collaborative design systems integrate recommendations in design guidelines to enhance daily work task efficiency in different standard rooms?
- *Learnability*: the ease with which users can learn to use an artefact, i.e., how does the design of user-interfaces in collaborative design systems impact end-users' ability to quickly understand and provide feedback?
- *Customizability*: the degree to which an artefact can be adapted to the specific needs of a local practice or user, i.e., how can different technical features in VR help end-users interpret subjective requirements described in design guidelines?

3.2 Case study research

In order to address the research questions of this thesis, a qualitative research approach has been adopted, namely case studies. Also, the phenomenon in this thesis, user-involvement in virtual collaborative environments, affects many type of different stakeholders, resulting in complex projects. To this point, hospital projects and school projects have been selected.

Moreover, case study research can be characterized by the following: focus on a specific case, use of multiple data sources, emphasis on context as well as adopting an inductive approach. *Focus on a specific case* involves the in-depth analysis of a specific case, which can be an individual, group, organization or phenomenon (Yin, 2017). This allows researchers to explore complex issues in real-life contexts (Baxter & Jack, 2008). *Use of multiple data sources* such as interviews, observation, documents and artifacts are used to provide a broad understanding of the case (Stake, 1995). *Emphasis on context* refers to the need to have an emphasis on the context in which the case is studied in, as this can have a significant impact on the findings (Flyvbjerg, 2006). Finally, an *inductive approach* means that the researcher starts with specific observations and data and develops a theory or explanation based on these (Eisenhardt & Graebner, 2007). This allows for a deeper understanding of the case and can lead to the development of new theoretical frameworks (Baxter & Jack, 2008). Simply put, the setting in which the case is studied in, informs of the degree of generalization. Therefore, it is important to establish clear criterias when selecting cases and interpreting the data as well as select cases similar in terms of context, characteristics and outcomes.

3.3 Research context

3.3.1 VR in the design process

3.3.1.1 Hospital projects

In paper one and two, seven real-life case studies were analyzed to understand how VR facilitated the involvement of end-users (e.g., building occupants, project managers and facility planners) in the design process of 6 different hospital projects (parts of the project) and 1 school project (the whole project). The choice to select these two type of projects, was to analyze variety in the data. Specifically, by observing the phenomenon of this thesis in different complex projects, different insights on user-involvement in VR were gained. Concerning the choice of cases, the criteria were 1) used VR for both design reviewing as well as informative purposes (i.e., not including end-users' feedback into the design) 2) design phase in which VR was used, 3) availability and use of technical features in the VR-models (e.g., multi-user, object manipulation) and 4) outcome of having used VR in the project (e.g., did VR address the design issues that necessitated its use in the first place?).

Regarding technical features, the different cases varied in terms of either being static or interactive. With cases including static and interactive VR-models, data could be analyzed to understand how end-user involvement in VR is facilitated by different technical features. Interactivity in this context is based on the definition presented by Steuer (1992), describing interactivity as *the degree to which users in VR can participate in modifying the form and content of a mediated environment in real time*. Following this definition, examples of interactivity observed in the different case studies are for example multi-user (i.e., collaborative) and object manipulation (i.e., users' ability to influence furnishment in the virtual environment). The table below presents which of the appended papers in this thesis used hospital projects as case studies and which one that used school projects.

Five of the six hospital project cases used immersive, HMD VR system whereas case E (see Figure 3) used virtual collaborative design environment (ViCoDE). The HMD based VR system consisted of a VR-ready computer to smoothly run the VR-models, without risking triggering motion sickness in users. Connected to the PC was a VR-headset (e.g., HTC Vive, Oculus rift) with external sensor mounts for accurate position detection and to set the boundaries for the space that users can physically move within. Lastly, handheld controllers enable users to navigate the virtual environment via teleportation, a Virtual Locomotion Technique (VLT) (Al Zayer et al., 2020). This means that when users teleport, they are instantaneously repositioned to the target location, by aiming with the controller and selecting the specific location. Finally, in one case (case F), controllers allowed users manipulation of spatial components (e.g., placement and furnishment of spatial components).

As a CVE system with support for multiple user-interfaces, ViCoDE features seamless integration of several immersive VR systems in the form of VR-headsets and a multitouch table that facilitates collaborative design work with immediate, real-time feedback (i.e., object manipulation). The multitouch table client uses a top view to visualize the facility. Users can pan and zoom in this view using the same standard multitouch interaction features found in most smart phones. Different BIM-based components (static avatars, furniture, and medical equipment) coming from the Swedish national healthcare database, PTS (program for technical standard), can then be added to the scene by drag-and-drop. Once added, a component can be repositioned, rotated, or removed, using the multitouch interface. The component is then instantly updated in all the other connected clients' respective user-interfaces.

Figure 3 below shows when in the building process VR was used and the level of interactivity of the model. Interactivity in this context is based on the definition presented by Steuer (1992), describing interactivity as *the degree to which users in VR can participate in modifying the form and content of a mediated environment in real time*. Following this definition, we use multi-user (i.e., collaborative) and spatial object manipulation (i.e., users' ability to influence furnishment in the virtual environment) as the metric for interactivity. Time-line phases are based on RIBA Plan of work (Ostime, 2022).

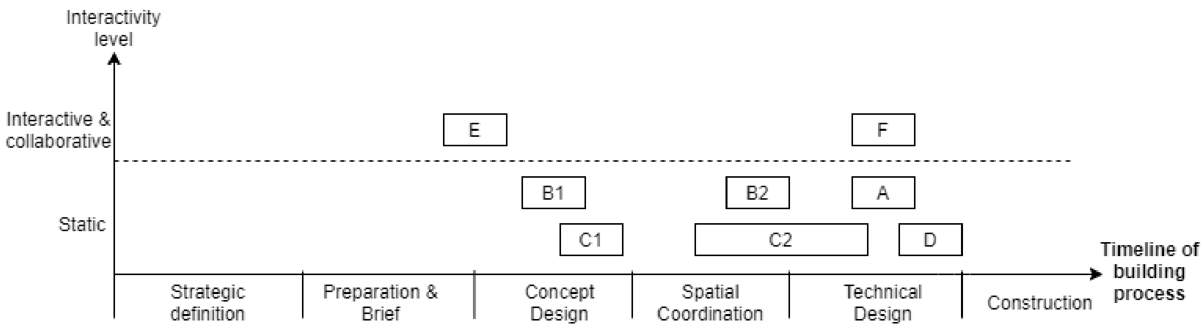

Figure 3. Graph illustrating how the observed cases map onto the various phases of the design process according to the RIBA Plan of work.

Lastly, four of the cases consisted of static VR-models (case A, B, C and D) while two (case E and F) were interactive and collaborative (e.g., multiple participants in the same VR-model). Further, the level of detail in the virtual environment varied with one of the cases for example having emphasis on being photorealistic (case A) whereas other VR-environments were presented with different levels of detail (see Figure 4 below).

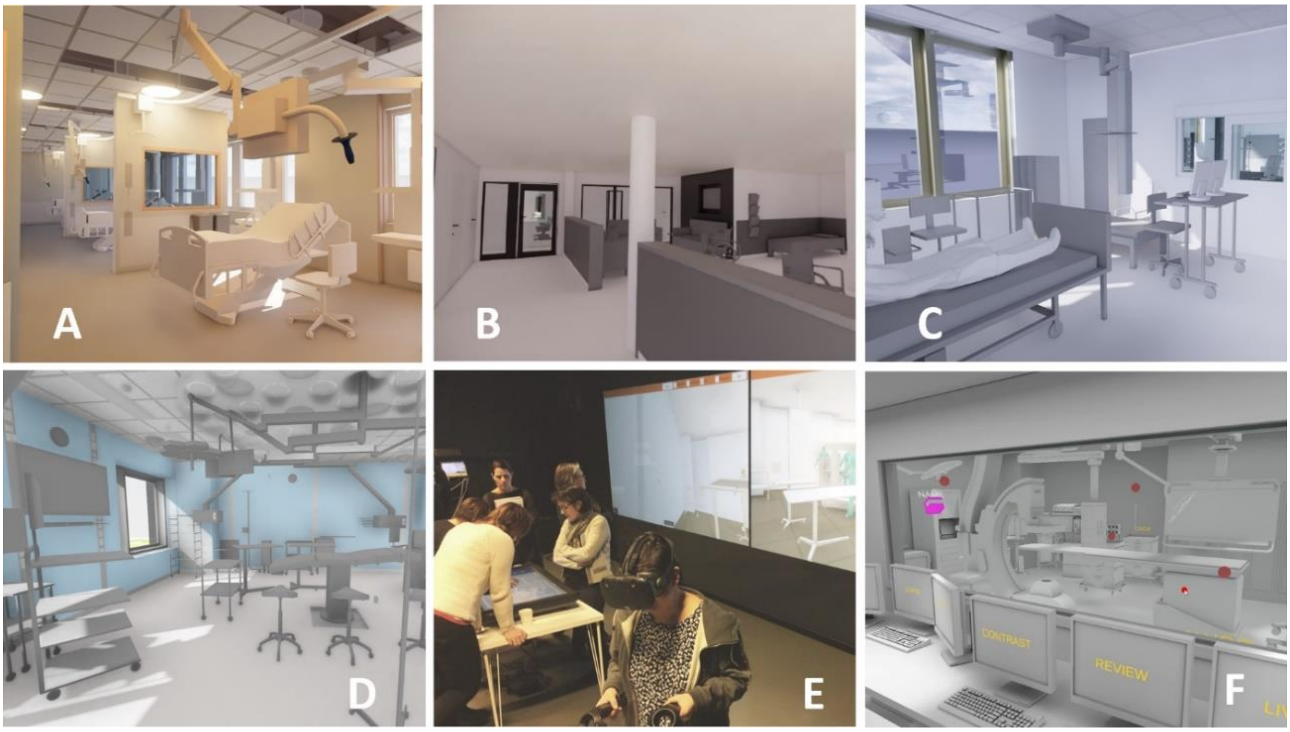

Figure 4. Screenshots from inside the VR-models as well as the set-up for case E with the multi-touch table together with the VR googles (ViCoDE) (Sateei et al 2021).

The table below shows the different cases based on project type, purpose of using VR, design phase, technical features as well as the total number of sessions VR was used in the project:

Case and project type	Purpose	Design phase, technical features and number of sessions
Case A. The ICU unit for a whole hospital floor	• Explore how alternative visual- and information mediums could provide better understanding for future workplace and validate design requirements	***Technical design phase*** • Freely exploring the virtual environment • Single-user • 4 VR-sessions
Case B1-B2. The psychiatric ward, including patient rooms, administrative area and dining area	• Inform healthcare staff of the design of the new facility and provide healthcare staff with an accurate insight of their future workplace	***Concept design & Technical design phase*** • Freely exploring the virtual environment • Single-user • 2 VR-sessions
Case C1-C2. (various facilities) Rooms pertaining to various types of operations and common areas independent of a particular operation	• Inform and explore how alternative visual- and information mediums could address certain design issues more accurately (e.g., sightline from ICU control room, logistical flow)	***Concept design, spatial coordination, and technical design phase.*** • Freely exploring the virtual environment • Single-user • 30 VR-sessions
Case D. ICU unit and hyperbaric chamber	• Explore an alternative visual- and information medium to validate set spatial requirements in final design review before construction document were handed over	***Technical design phase*** • Freely exploring the virtual environment • Single-user • 8 VR-sessions
Case E. (ViCoDE) – Unit of obstretics and gynecology - Robot assisted surgical room	• Explore an alternative visual- and information medium that can address design issue related to fitting new surgical room in existing space	***Concept design phase*** • Freely exploring the virtual environment • Influence furnishment of spatial components in the virtual environment • Multi-user • 2 ViCoDE-sessions
Case F. A single radiology room with adjacent corridor and common area	• Explore an alternative tool that can address design issue related to fitting new radiology operation room in existing space	***Technical design phase*** • Freely exploring the virtual environment • Influence furnishment of spatial components in the virtual environment • Multi-user • 3 VR-sessions

Table 1: An overview of the different hospital project cases that were studied

3.3.1.2 School project

The case study was to study a VR based design review process of a school project and analyze what type of discussion and design issues that were found during two VR-workshops connected to a new elementary school. The VR system that was used were three Oculus Rift S kits, together with the software BIMXplorer. The software supported direct import of IFC-files, from the design process, without any need for further optimization. In addition, technical features in the software were available to use, such as a measuring tool, taking screenshots, markups, and support for multi-user collaboration. During the VR-workshops, the participants used mentioned hardware kits together with a big screen display and two laptop displays (see fig 5).

Figure 5. The set-up during the first workshop (left). Different participants viewing and discussing potential design issue areas during the second workshop (right).

A key difference between the two workshops was the addition of furnishment in the VR-models in the second workshop, providing participants with a more detailed design and room layout. To this point, participants made use of the different display-options enabled in BIMXplorer; a virtual, miniature model (1:40 scale) of the building that enabled participants to crosscut the virtual model to view the building from a bird-eye perspective (i.e., a digital version of a 2D view) and the 1:1 scale option commonly associated with VR-models (see figure 6).

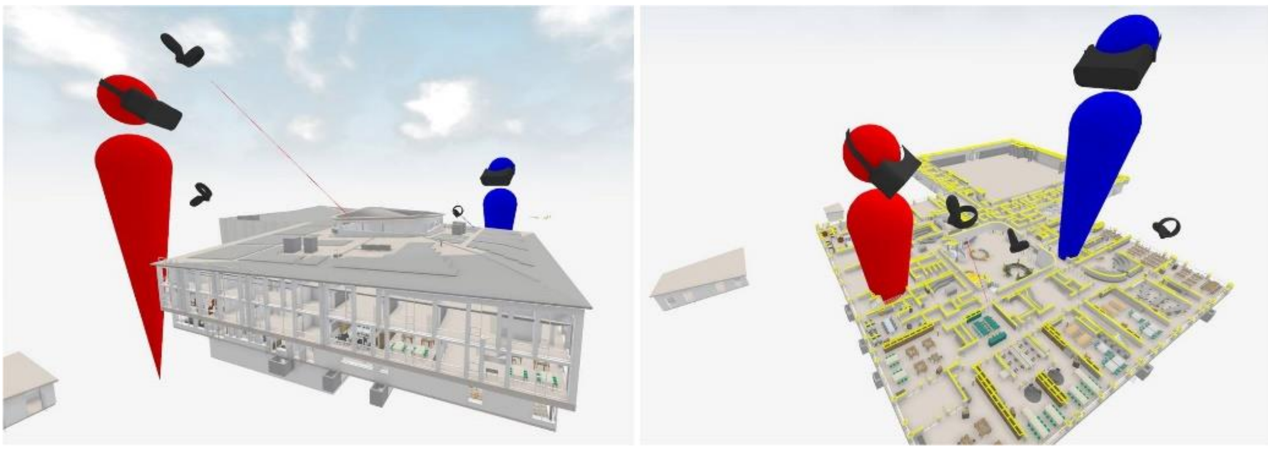

Figure 6. Miniature model showcasing the building in its entirety as well as sectioning of the various floors reviewed by the participants.

3.3.2 Classification and use of spatial requirements in design guidelines

In paper three and four, the use of the Swedish national healthcare project framework and database, PTS (Program for Technical Standard) was studied, and in particular the design requirements and design layout for different standard rooms. This was done with the aim of better understanding how design guidelines are used by various Swedish regions. This involved investigating how (and if) PTS could support decision-making during early design phases concerning compliance of design requirements as well as aiding in involvement of end-users in the design process.

The spatial components can be retrieved from the PTS object library consisting of multiple 3D Revit families that can be downloaded to a user's 3D model. In this regard, it should be noted that access to the PTS database and other available resources related to the design guideline, requires a fee-based membership. As for the classification of the various spatial components, the 3D Revit-families are named PTS-codes (see figure 7), a numeric code that describes what object group each spatial component belongs to. For example, a peg-rack is named as *381-3* (see figure 1) in *Type Name* and *381* refers to the category of equipment and *1* specifically referring to a specific type e.g., the peg-rack being a model used with a lifting harness.

Inredning/utrustning		
Fastighet		
301-7	Tvättplatsutrustning	1 st
382-2	Hållare för soppåsar	1 st
382-4	Hållare för bägarautomat	1 st
382-8	Hållare för flytande tvål	1 st
382-12	Hållare för torkpapper, stor	1 st
382-13	Hållare för handdesinfektion	1 st
385-6	Spegel B=450 H=600 (mm)	1 st
381-1	Kroklist 1 krok *Till lyftsele*	1 st
381-3	Kroklist 2x2 krokar	1 st
382-10	Hållare för ytdesinfektion	1 st
382-22	Hållare för munskydd	1 st
382-47	Hållare för visir	1 st
382-51	Hållare för engångshandskar/förkläden 5 paket	1 st
384-23	EU-skena B=600 (mm) *800 och 1200 mm ög.*	2 st
387-7	Dörrhandtag bygelhandtag "elefantöra"	1 st
387-18	Dörrtillslutare	1 st
480-5	Persienn	Ospec
521-4	Tvättställ stort utan bräddavlopp B=600 D=450	1 st
523-5	Tvättställsblandare bänkmonterad, förlängd spak	1 st
540-1	Andningsluftuttag för medicinskt bruk *Placeras i 444-9*	1 st
541-1	Andningsoxygenuttag för medicinskt bruk *Placeras i 444-9*	1 st
611-2	Elkanal väggkanalsystem, vertikalt placerad vid dörr	1 st

Figure 7: Example of categories with pertaining spatial components from the object library for a care-room for 1 patient (Program for Technical Standard, n.d.).

The three-digit numerical code ranges from 300 to 600 with each 100- numerical category containing a certain type of spatial component. For example, all spatial components starting off with 300 numerical combination is a type of facility fixed component (e.g., peg racks or light installation) whereas 400 is a reference to spatial components classified as furnishment. 500 and 600 entails components in heating and sanitation respective electricity.
Each standard room also has a specific PTS-code consisting of a type name for the room and a three digits number. These range from 1-221 with copying room for example having number combination 28 and an on-call room having PTS code 41.

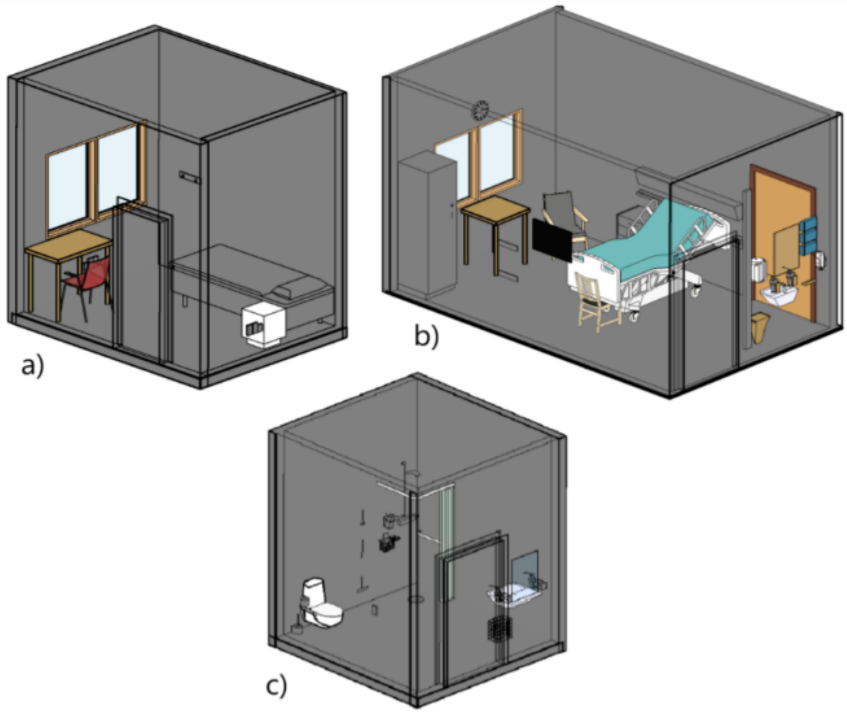

Figure 8: A) On-call room, b) care-room for 1 patient, c) RWC Shower

Apart from having access to these requirements and different standard rooms, PTS also arranges what is known as "PTS forum". PTS forum refer to the yearly meetings (2-3 meetings per year) that are arranged with the purposes of revising the information the design guidelines. The revisions are to ensure that the design guidelines are up-to-date in terms of supporting building occupants' daily working tasks. To this point, building occupants themselves do not participate in these sessions. Instead, their representatives from different regions, together with other types of end-users (e.g., facility planner, project leader) and design team members such as BIM coordinators participate. Together, participants coordinate and discuss through the revision of the design guideline, resulting in a document of feedback. This feedback is then handed over to the PTS's national requirement analyst and national system administrator for evaluation and a final decision on which spatial requirements and standard rooms that need to be revised. Lastly, PTS offers a web-based forum. The web-based forum provides users the possibility of asking for advice regarding how certain design issues were addressed in other regions. The purpose of this website is to further encourage cross-project transfer of knowledge by allowing for example users to ask and share experiences of using different PTS standard rooms.

3.4 Data collection and analysis

Table 2 below shows the data collected in the four appended papers of this thesis. The data is sorted according to type of participants (i.e., end-users and design team), type of involvement (e.g., semi-structured interviews, workshops) as well as the type of studied project and purpose of conducted interviews.

	End-users/Design team	Type of involvement	Type of project/purpose of interviews
Paper 1	3 BIM coordinators, 8 project leaders, 4 facility planners, 4 architects, 13 building occupants	32 semi-structured interviews supported by 2 ViCoDE workshops, several VR workshops (>10), a study visit	Healthcare projects that included 2 ICU units, a psychiatric clinic, a hyperbaric chamber, a robot assisted surgical room and a radiology room
Paper 2	An assisting project leader, a project leader, 4 client representatives, a design manager, an interior architect, 2 architects	2 workshops supported by open-ended discussion where participants shared experience of using VR for design reviewing purposes	New elementary school building
Paper 3	13 facility planners	6 semi-structured interviews from 6 different Swedish regions	Healthcare projects and learning about how interviewees experience the user-interface of a design guideline like PTS
Paper 4	15 facility planners, 2 property managers, the national system administrator for PTS	18 semi-structured interviews from 7 different Swedish regions	How PTS as a design guideline is used by various Swedish regions in healthcare projects

Table 2: An overview of the collected data in the four appended papers.

To achieve sample representativeness, interviewees in paper 1 were selected based on the following criteria: 1) role in the design process, 2) prior experience with design reviewing with traditional visual and information mediums (e.g., 2D drawings, 3D models, physical mock-up rooms), and 3) involvement in ongoing healthcare design projects. Similarly, interviewees in paper 3 and 4 were selected based on the following criteria: 1) direct interaction with PTS (e.g., using available 3D models in the design process) and/or 2) participated in the PTS forum days and lastly, 3) how long the regions had been part of the PTS network. In regard to the conducted VR and ViCoDE workshops, the main focus was to study end-user involvement when design reviewing with VR. Also, with the variety in type of healthcare project studied in Paper 1, different insight on user-involvement could be gained. This variety was also noticed in Paper 2 in terms of how the two VR-workshops differed. Specifically, with participants design reviewing with a furnished model in the second workshop, an understanding could be made on how furnished VR models affect participants' ability to design review effectively.

3.4.1 Interviews

Semi-structured interviews were used to allow for a more explorative interview, allowing the interviewee to talk more freely (Kvale, 1994) as well as enable a thematic approach to gain conversational depth (Qu & Dumay, 2011). Therefore, the interview questions were based on interview guides which differed in theme. For paper 1 and 2 that focused on the use of VR in the design process, the emphasis was on assessing the design team and end-users' experience with using VR as a visual and information medium for design reviewing purposes. For paper 3 and 4, the theme of the questions were centred around the perceived value and use of available design guidelines. For cases where video observations were made, these semi-structured interviews were conducted prior and immediately after design reviewing with VR was done. The interview questions were sent in advance to the interviewees, with interviews lasting 30-45 min. Questions were sent in advance in order to allow interviewees to prepare their responses and to ensure that they could organize their thoughts so that valuable information could be gained. Lastly, interviews were audio recorded, transcribed and to the interviewees for clarification and subsequent approval.

In order to analyze the data, thematic analysis was used, which is referred to as one of the most efficient methods in analyzing qualitative data to capture valuable information (Braun & Clarke, 2006). Furthermore, the thematic analysis helps identify similarities or differences in repeated patterns found within the data (Lochmiller, 2021). This was done by first familiarizing with the recorded data reading through interview transcripts several times and gain a deeper understanding of the participants' experiences and perspectives. Next, themes were developed by identifying specific words or phrases which emerged from the data. In the context of paper 1 and 2 involving the use of VR for design reviewing purposes, the words and phrases centred around the type of design issues that were identified and addressed by the participants (e.g., "sightlines", "sense of immersion"). For paper 3 and 4, the focus was instead on interviewees' experiences with using healthcare guidelines in the design process (e.g., words such as "user friendly", "standard rooms"). In both these studies, quotations from users that highlighted areas of similarity helped illustrate and reinforce the strength of the theme (Lochmiller, 2021). Finally, the research questions were used as a reference to evaluate whether the identified themes addressed these or not.

3.4.2 Video observations

Video observations were made to gain a deeper understanding of how design team members and end-users collaborate and interact during design reviews. Therefore, interactions were only observed via the video recordings whilst fieldnotes were taken during the interactions. Fieldnotes were made to quickly record observations on points of interest, such as when participants identified design issues when design reviewing or how client representatives and the project leader used different technical features to create a shared understanding of the problem (e.g., using mark-up tools, multi-user). The observations were conducted in the context of using VR and ViCoDE alongside traditional information and visualization mediums, such as 2D drawings and 3D models. Observing the decisions taken in this context (e.g., architect and facility planners expressing agreement on how a design issue should be addressed after having identified it in VR) is important as actions can have different meanings depending on context (Heath et al., 2010; Stivers & Sidnell, 2005). As such, video observations help understand why certain interactions took place, which includes verbal communication and physical gestures (Nassauer & Legewie, 2021). Therefore, the goal with video observations was to analyze the recorded design reviewing sessions. step-by-step, and examine when certain interaction happened, following what and leading to which subsequent development (Nassauer & Legewie, 2021). Studying the recorded videos carefully in this manner was done with the aim of understanding how different situations of interest (e.g., how certain participants used and perceived the value of VR) could be connected with each another and identifying general patterns of behavior. To this point, the video observations were done with two stationary video cameras which were placed in elevated positions to capture the participants' collaboration, movement and use of the different available information and visualization mediums. The video recordings for the different studies varied in length between 45 min and upwards 3h. The collected video data was transcribed for further analysis and later compared with the field notes and interview data to reinforce the made observations.

Similar to interviews, a thematic analysis was also applied on the data from the video observations. This was done to understand what was important to the task of addressing identified design issues or to a participant's goal in a moment of interest (diSessa et al., 2015; Ramey et al., 2016). As video recordings were made from two different points of view, the observations were compared to each other. This was done to clarify whether a particular action or interaction was performed (e.g., participants creating space for one another during decision-making) and to capture how certain decisions made by specific participants, such as architects, were perceived by client representatives. Next, relevant situations of interest that addressed the research questions were transcribed into text-format. The analysis then focused on developing a coding schema consisting of several categories, to which various design issues were mapped. Finally, these categories were utilized to create appropriate themes that addressed the research questions. This was done by identifying similarities and differences that were recognized by the majority of participants involved when design reviewing with VR.

3.4.3 Document analysis

In order to gain understanding on how documents in design guidelines are perceived and used by different project members, document analysis was used (Morgan, 2022; Wach & Ward, 2013). This was done by adopting a reflexive approach for analyzing the studied design guidelines, which involved interpreting the data through the researcher's own assumptions and understanding (Morgan, 2022).

The analytical procedure firstly involved selecting documents related to different standard rooms in the design guidelines, which included the classification of the recommended furnishment (e.g., number of hospital beds, electrical outlets for medical equipment), the website forum to the design guidelines of Program for Technical Standard (PTS) as well as selecting documents which illustrated the 3D illustration of certain healthcare standard rooms. Following the selection of documents, the data contained in these documents were then reviewed and combined. Next, this combined data was compared with the interview data of those who had used these documents in the design process to reinforce made observations, minimize bias and establish credibility to the findings (Bowen, 2009).

Additionally, an ontological approach was used to analyze the classification of the data contained in the documentations of the design guidelines. These documentations contained classification codes for different spatial requirements related to various healthcare standard rooms. This information was used to develop the ontologies (see examples below). Ontologies describe the explicit specification of a representational vocabulary for a shared domain of interest (Gruber, 1993, 1995). In this thesis, shared domain of interest refers to the understanding among both design team members and end-users of the PTS information structure. Typically, ontologies consist of a set of concept hierarchies which are described by their relationships to one another. The main components of ontologies are classes, attributes and relations. Classes represent concepts in a broader sense whilst attributes represent properties of each concept and relations represent the connection between concepts (Alaee & Taghiyareh, 2016).

In this context, the two different ontologies from Paper 3 were developed based on the data contained in the documents of the healthcare design guidelines. This was done with two-fold aim: first, to illustrate how ontologies could support knowledge sharing and help users of these documents such as client representatives and facility planners to gain a deeper understanding of important relationships from these document (Maedche & Staab, 2001; Yamaguchi, 2001). Secondly, by explicitly defining the relationship between the concepts that the documents consist of, ontologies can allow interoperability with a semantic-reasoner (Kaiya & Saeki, 2006; Lee et al., 2021; Z. Liu & Ma, 2015; Uschold & Gruninger, 1996). In paper 3, this means that ontologies served as the first step towards developing a recommendation system of design layout for PTS standard rooms, via the use of a rule-based algorithm. To this point, the ontology language used was OWL 2 whilst the Chowlk visual notation with its set of ontology diagram representations was used to provide visual blocks that represented each element from the OWL specification such as the classes, relationships and attributes (Chávez-Feria et al., 2021).

The first ontology illustrated what a standard room using PTS contains such as medical equipment and different measurable units (e.g., accessibility to the room, temperature). This involved first setting up the main class called *Facility* that had the subclass called *Room,* referring to a PTS standard room. The *Room* class was then further divided into three subclasses that are meant to illustrate what a standard consists of: *FacilityItem*, *OperationUnitItem* and *Surface*. Appropriate properties were then listed for the *Room* class such as *accessible* and *temperature* whilst the subclasses *FacilityItem* and *OperationUnitItem* were connected to an additional subclass of their own called *Item*. *Item* was then used in the second ontology which illustrated what type of furnishment a PTS standard room might contain and partitioned into three subclasses. These were: *Furniture, MedicalEquipment* and *Installation*, where *Furniture* was divided into the subclasses *FixedFurniture* and *NonFixedFurniture*. The classes *Items, Furniture*, *MedicalEquipment* and *Installation* are all either floor, wall or ceiling based. This is meant to highlight what would be the requirements for a semantic reasoner that could use a rule-based algorithm for automatic design layout of the standard rooms.

4 Summary of the papers

4.1 Paper 1

***From informative to Co-design: the role of Virtual Reality for user-involvement in healthcare design* - Sateei, S., Roupé, M., and Johansson, M. (2023) – work in progress**

4.1.1 Background and aim

Whilst studies have explored how VR could be used to increase spatial understanding among end-users during review, less emphasis has been put into different technical features that could facilitate understanding (e.g., object manipulation, multi-user). Similarly, integration of VR as a visual and information medium into collaborative practices (e.g., Participatory design, Co-design) has been less studied. As such the aim of this paper was to gain a better understanding of how various technical features can facilitate different collaborative practices in VR.

4.1.2 Method

Six real-life cases of healthcare projects were analyzed. Also, these cases were part of larger, ongoing hospital project in both Sweden and the US, where half of these were design of new healthcare premises whilst the other half were design in existing premises. Empirical data was gathered via semi-structured interviews with both design team members (i.e., architect and BIM coordinators) as well end-users (e.g., healthcare staff, facility planners). Moreover, video-observations were done of sessions were VR had been used both for design reviewing as well as for informative purposes (i.e., end-users feedback were not considered into the design process).

4.1.3 Results

The results showed that depending on available technical features in the VR-model, end-users are provided with different conditions to express their wants and needs about the design. Features such as object manipulation and multi-user could for instance allow task-based scenarios in VR where healthcare staff are able to better understand how their daily work tasks are influenced by different design layouts. Similarly, VR-models with a limited number of features (e.g., only able to freely explore the virtual environment) leads to end-users mainly having an increased spatial understanding of the design. In other words, technical features can facilitate different collaborative practices, allowing end-users to either evaluate the design (e.g., informative, consultative) or help develop design proposals together with the design team (e.g., Participatory design, Co-design).

4.1.4 Contribution to thesis

ViCoDE, a CVE system used in one of the cases, with support for multiple user-interfaces – multitouch table, projector screen and HMD VR – showed that a combination of different user-interfaces help facilitate a collaborative understanding. For instance, the multitouch table was observed to primarily serve as a user-interface were the architect and end-users (e.g., healthcare staff, project leader) used the object-manipulation feature to create different scenarios and view these as 2D representation. With these changes appearing simultaneously in HMD VR and projector screen, the remaining participants were able to reflect and review the different design layouts. In other words, with participants switching between the different user-interfaces, to develop and review design proposals, a collaborative understanding emerged between the architect and end-users such as the healthcare staff.

4.2 Paper 2

***Collaborative design review sessions in VR: multi-scale and multi-user* - Sateei, S., Roupé, M., and Johansson, M. (2023)**

This paper was included in the Proceedings of the 27th International Conference of the Association for ComputerAided Architectural Design Research in Asia (CAADRIA) 2022. Vol. 1, p.29-38

4.2.1 Background and aim

The past literature has highlighted how traditional visualization and information mediums such as 2D drawings are necessary for end-users (e.g., building occupants) to help with spatial orientation and understanding for how different spaces are connected with each other. At the same time, HMD VR can with its 1:1 scale provide a spatial understanding of the design that is otherwise difficult with traditional visualization and information mediums (e.g., identifying hidden sightlines, better perception of space). Still, few studies have explored a combination of these different spatial representations within the same medium. To this point, the aim of this paper was to understand how end-user involvement (e.g., client representatives, project leader) is influenced when users have the ability to switch between a mini-model/1:40 scale representation and immersive 1:1 scale option within the same HMD VR system.

4.2.2 Method

A new elementary school was used as case study were data gathering took place during two workshop sessions with both design team member (e.g., interior architect) and end-users (e.g., project leader, client representative). The idea to use VR in the design process in the project emerged when 2D drawings and 3D models could not provide sufficient level of spatial understanding among the end-users. Methods used for data gatherings were video-observations together with a follow up discussion after each workshop where participants reflected on their experience. In addition to the different view modes available, users also were able to use the multi-user feature to design review together in the same VR-model.

4.2.3 Results

Firstly, the results showed that switching back and forth between different spatial representations helped increase end-user involvement, as different design issues could be reviewed from the two spatial representations simultaneously. Secondly, the addition of furnishment in the VR-model was shown to trigger further discussions among participants, as furnished spaces helped provide a design reviewing context (e.g., testing logistical flow for different classrooms).

4.2.4 Contribution to thesis

Combining spatial representations which typically emerge in separate user-interfaces (i.e., 2D drawings and HMD VR) within the same medium, helped participants identify design issues they previously were unaware of when using 2D drawings and 3D models. Furthermore, by integrating these two different spatial representations as well as adding furnishment, helped end-users negotiate with the design team on requests and ideas of the design. As such, it could be argued that virtual collaborative understanding could be facilitated when enabling end-users to experience two different spatial representations in the same user-interface.

4.3 Paper 3

An ontological approach for a recommendation system of a requirement tool: the case of a national framework for hospital design **– Sateei, S., Roupé, M., and Johansson, M. (2023)**

This paper was included in the proceedings of the European Conference on Computing in Construction (EC3) 2022

4.3.1 Background and aim

Design guidelines for healthcare design include both statutory and guidance documents, and listed in guidance documents are recommendations of design layout for different standard rooms. These standard rooms are intended to support understanding for how different standard rooms should be furnished to best support the healthcare staffs' daily work tasks. However, few studies have investigated whether the requirements in these standard rooms reflect the healthcare staffs' current wants and needs as well as how the healthcare staff themselves can provide direct input on the design layout. Therefore, the aim of this paper was to investigate whether the current information structure of healthcare design guidelines (e.g., description of requirements, standard rooms) can be computer-interpretable, to allow increased involvement of healthcare staff in the design process of standard rooms.

4.3.2 Method

The studied design guidelines were The Swedish national healthcare project framework and database, PTS (Program for Technical Standard). PTS was developed in the early 90's with the goal of providing guidance in the early phases of the design process such as Preparation and Brief and Concept Design, with 20 out of 21 Swedish regions currently part of the PTS network. Using the different available standard rooms (e.g., patient rooms, ICU unit) and requirements describing the layout of these rooms (e.g., placement of medical equipment), two different ontologies were developed. These ontologies describe how both all the different standard rooms as well as the furnishment in these rooms can be divided into a hierarchy, consisting of multiple classes. Each of these classes illustrate the different requirements that make up PTS rooms and that needs to be complied with. Lastly, a conceptual syntax of a rule-based algorithm was developed. This was done to further show how breaking down the information structure of PTS via ontologies, could theoretically make the different requirements in design guidelines compatible with a rule-based algorithm.

4.3.3 Results

The results showed conceptually how rule-based algorithm could be applied when making requirements connected to standard rooms, computer-interpretable. In this context of using a rule-based algorithm, it is argued that design layout of standard rooms could be automated. Moreover, by allowing the placement of furnishment (e.g., medical equipment, electrical outlets) to be visualized in collaborative design systems such as ViCoDE, end-user involvement is more likely to be facilitated.

4.3.4 Contribution to thesis

By combining a rule-based algorithm that complies with requirements for different standard rooms, together with collaborative design systems such as ViCoDE, end-users are more likely for example to understand how certain design requests regarding design layouts, are not possible. Specifically, design reviewing could shift from assessing compliance of requirements for various standard room design layouts to instead determine the furnishment arrangement that best meets the current needs and wants of the healthcare staff. Therefore, with requirements for different standard rooms in design guidelines being computer-interpretable as well as combined with the visual understanding enabled via user-interfaces included in ViCoDE, different viable user-interfaces can help facilitate collaborative understanding.

4.4 Paper 4

Knowledge integration through resource combining – the case of a national standard framework for hospital design - Sateei, S. and Sundqvist, V. (2022)

This paper was included in the Proceedings of the 38th Annual ARCOM Conference

4.4.1 Background and aim

Design guidelines such as PTS provide different regions the opportunity to get access to nationally agreed upon standard rooms as well as exchange knowledge and experiences to help support cross-project knowledge. Yet, the literature has not studied how these different approaches of sharing cross-project knowledge and experience help support the design process of new healthcare projects across the regions. Accordingly, the aim of the paper was to explore how PTS design guidelines is used by the different Swedish regions, and specifically how these regions perceive the usefulness of integrating PTS resources in the design process (e.g., use of standard rooms and participating in yearly meetings to update these rooms).

4.4.2 Method

Those connected to PTS are part of a larger network of regions where members are able to exchange experiences and thoughts on how PTS standard rooms have been interpreted as well as participate in yearly meetings where these standard rooms are reviewed to ensure that they reflect the healthcare staffs' current wants and needs in terms of daily work tasks. Following this, PTS was conducted as a single case-study together with 12 semi-structured interviews from 7 Swedish regions. Semi-structured interviews included both the different regions (e.g., larger and smaller regions) as well as the national system administrator for PTS.

4.4.3 Results

Results show that PTS as a resource is difficult to use in the different regions, partly due to organizational structure of different regions and partly due to the digital competence (or lack thereof). Therefore, findings suggest that the potential for PTS as a resource for knowledge sharing and cross-project learning is not exploited to its fullest. Moreover, data from interviews imply that the absence of user-friendly interfaces when viewing the different standard rooms, i.e., use of 3D models, caused difficulty with interpretating the design layout. Interviewees also highlighted how this lack of user-friendly interfaces for assessing the design of standard rooms, led to healthcare staff relying on facility planners and architects for visual understanding. Lastly, the web-based PTS forum, used by the facility planners, was not perceived as a useful platform for the regions to share knowledge and experience on how they have used the different standard rooms. As a response, numerous study visits were conducted by all the regions to provide an alternative approach to cross-project learning. Still, the lack of proper documentation limited these study visits to creating engagement among the healthcare staff during the design process.

4.4.4 Contribution to thesis

Findings suggest an absence of different user-interfaces that prevents healthcare staff from making correct assessment of the design as well as facility planners from learning from their peers in different regions. Consequently, with healthcare staff reliant on facility planners and architects for gaining sufficient spatial understanding, collaborative understanding is less likely to emerge. Results further suggest that facility planners experience difficulties in understanding how standard rooms have been used in projects across different regions. The lack of collaborative understanding in individual projects is then further reinforced by these challenges. In other words, the absence of efficient documentation on how standard rooms have been used in different regions, prevent collaborative understanding from emerging in individual projects.

5 Discussion

This chapter discusses the findings of the thesis in regard to user-involvement in virtual collaborative environments in the building design process. Accordingly, first the information structure of design guidelines and its usefulness of in the design process for end-users is discussed, which is related to research question 1. Second, integration of design guidelines into CVE tools is covered, which is related to research question 2. Finally, integration of VR in collaborative design systems and how it facilitates end-user involvement is presented, which is related to research question 3.

5.1 Integration of design guidelines in the design process

Paper 3 and 4 shows how the usefulness of design guidelines is influenced by its user-interface. This is supported by the past literature which recognizes challenges with involving building occupants and creating a collaborative understanding of the design between building occupants and design team members (J. Carthey, 2021). Essentially, paper 3 and 4 reveal that collaborative understanding is difficult to facilitate due to the lack of useful documentation on how design guidelines have been used in different projects. Furthermore, the data from paper 4 shows how this lack of documentation, together with the absence of user-friendly interfaces that show the design layout (e.g., 3D models), prevent end-users such as building occupants from understanding how their daily working tasks are influenced by the design layout of standard rooms. As a result, building occupants experience a loss of ownership and involvement in made decisions when design guidelines are used. Also, with design guidelines intended to support understanding for the design layout of building occupants' future working spaces, it is important to understand how a shared understanding of the design is validated. For instance, if design guidelines are used by facility planners without consideration for building occupants' daily working tasks, it can become difficult to validate whether the design layout actually supports building occupants' daily working tasks. Moreover, paper 4 showed how this difficulty of validating the design layout, together with the lack of documentation, results in future projects repeating the same mistakes of identifying design issues when using design guidelines.

Apart from the need to ensure a shared understanding of the design layout and documentation among all users, paper 4 reveals that building occupants' limited spatial understanding leads them to depend on project managers and facility planners to interpret the spatial requirements in design guidelines (Paper 3,4). Moreover, with non-quantifiable spatial requirements being perceived as ambiguous (e.g., use of words such as "may", "should") by project and facility planners, it becomes further difficult to interpret how these guidelines should be used when considering building occupants' daily working tasks. Therefore, an argument can be made that user-friendly interfaces are needed to support increased spatial understanding among building occupants, which in turn could aid facility and project managers with better understanding building occupants' knowledge and experience in the context of their daily working tasks. Although previous literature have highlighted the challenges of interpretating ambiguous requirements.

The interpretation of ambiguous requirements have primarily been studied from the perspective of design team members such as architects (Soliman-Junior et al., 2021, 2022a). Similarly, recent literature have also highlighted the importance of user-interfaces that allow for "human expert" input to check compliance with guidelines when considering ambiguous spatial requirements (Amor & Dimyadi, 2021), without clearly defining who the "human expert" refers to. However, as identified in paper 1 and 2, use of VR as a user-interface can support human experts such as building occupants' to express their wants and needs about the design that is understandable for other end-users as well as the design team. Consequently, it can be argued that by increasing other end-users' and design team members' understanding for how building occupants daily working tasks are done, less room for misinterpretation of ambiguous requirement emerge. This is important as the ambiguity of spatial requirements have been described in the literature to be mainly due to being contextual (J. Carthey, 2021; Fenves et al., 1995). In this regard, as shown in paper 2 and 3, furnished spaces can provide a contextual understanding of the design layout, which is necessary to allow end-users to accurately assess how daily working tasks are affected by the design layout. As such, this thesis argues that VR as a user-interface can be used to check compliance with design guidelines. Specifically, by increasing end-users' spatial understanding of the design, VR can be an adequate solution to the problem of interpreting ambiguous spatial requirements.

In relation to the discussion above, it is important to recognize how understanding and use of design guidelines in one project does not necessarily always result in cross-project understanding for how design layout influences building occupants' daily working tasks (paper 3,4). Whilst providing visual understanding to end-users addresses the problem of interpretating ambiguous requirements in design guidelines, it is also important to understand why certain design layouts when using design guidelines are preferred in one project to another. For example, paper 4 showed how although building occupants' daily working tasks are somewhat similar across different regions, that differences in workload results in preference for different design layouts. In this context, sharing understanding between projects by means of study visits has not been shown to be an efficient solution to facilitate cross-project understanding (paper 4). Failing to understand how design guidelines were used in past projects has two consequences: firstly, it creates a reliance on end-users and design team members with previous experience in using design guidelines (J. Carthey, 2021; J. F. Carthey, 2013); secondly, it makes it challenging to encourage the use of design guidelines in new projects (J. Carthey, 2021; Mills et al., 2015). As a result, projects can run the risk of being carried out without sufficient knowledge and experience from previous projects, resulting in a failure to identify design issues in advance and therefore risk repeating costly design rework as previous projects (Adam et al., 2017).

Furthermore, when considering the perspective of design team members, gaining sufficient spatial understanding to interpret ambiguous spatial requirements, is not a primary concern for these users. Instead, it could be argued that it is the lack of access to decision-basis discussed above, that prevents design team members such as architects to understand how building occupants' needs should be considered when adhering to design guidelines. In this context, it should be noted that this thesis have only observed design team members' perspective of design guidelines in regard to accessibility, i.e., sign-in access on the design guideline website (paper 4). Still, past literature advocates open-access for design guidelines to support decision-making (Mills et al., 2015) and more recent literature point to how existing design guidelines with open access still cause challenges for both design team members and end-users in terms of validating how existing requirements reflect current working practices of building occupants (J. Carthey, 2021). On the other hand, with sign-in access limited to during project times, an argument that follows is that design team members have less time to get familiar with design guidelines. Consequently, the design team would be more incentivized to pursue aesthetic efforts (e.g., interior color schemes, materials and finishes of the design) rather than prioritizing functionality of design (J. Carthey, 2021; McGlynn & Murrain, 1994; Phiri & Chen, 2014a).

Connected to all of this is on what premises these interpretations in this thesis have been made when trying to understand the problem of collaborative work. Simply put, are the identified challenges faced by design team members and end-users relevant? With all studied cases being from real-life projects, with the majority being healthcare facilities in various phases of the design process (Paper 1,3,4), the cases have helped identify challenges with using design guidelines from the perspective of end-users as well as design team members (Paper 3,4). Moreover, paper 1,2 and 3 reveal how user-interfaces such as VR could be used to validate a shared understanding of the design between building end-users and the design team. Nevertheless, questions remain in regard to how design guidelines can be integrated with user-interfaces such as VR and what technical requirements that would place on design tools such as collaborative design systems. Therefore, the following discussion section will aim to address these questions.

5.2 Use of design guidelines towards a recommendation system

Paper 3 describes the information structure of PTS (Swedish national database for guidelines for healthcare facilities) and how an ontological approach can be used to provide an overview of what hospital standard rooms require when identifying design layout that best supports building occupants' daily working tasks. Results also show how an information structure and design guidelines can be a framework for a rule-based algorithm that support automation of room design layout. Furthermore, these automatically generated room design layouts could be used by the design team and end-users for discussing and evaluating the design proposals. This could be done using a user-interfaces such as VR. Evaluating design proposals via CVE tools such as VR is also highlighted in paper 1 and 2. These papers show how increasing end-users' spatial understanding via VR can support collaborative work by allowing end-users to focus on evaluation of the design rather than interpretating and understanding it as is common with traditional visualization and information mediums such as 2D drawings and 3D models. Consequently, paper 3 presents how this evaluation of the design in VR can be useful when validating design layouts based on the standard rooms available in design guidelines.

When considering the integration of design guidelines into the design process, Paper 3 also introduced the idea of automating design layouts compliant with design guidelines. Whilst past literature have investigated the possibilities of fully automated compliance checking after design proposals have been developed (Amor & Dimyadi, 2021; Soliman-Junior et al., 2022b), few studies have explored the idea of producing design proposals that are already compliant with design guidelines (Çubukçuoğlu, 2023; Merrell et al., 2011; Sydora & Stroulia, 2020). To this point, arguments can be made that less time would be required to spend on revising the design if it would already be compliant with design guidelines. Consequently, with less time spent on addressing design issues connected to compliance with design guidelines, more time could be put into evaluating different design layouts that have been generated and via VR understand how subjective requirements linked to placement of furnishment (e.g., "close enough", "in proximity of", "good enough") can support building occupants' daily working tasks. As a result, a suitable design layout can be identified more rapidly than in a traditional design process (i.e., use of 2D drawings and 3D models). In other words, by viewing design proposals in VR that are already compliant with the quantifiable requirements in design guidelines (i.e., explicit descriptions such as dimensional constraints for a standard room), design reviewing can instead be centred around how building occupants' daily working tasks are best supported by the subjective requirements.

However, interpretation of subjective requirements in design guidelines varies between building projects due to being perceived as contextual and ambiguous (Paper 3,4). Moreover, interpretation of subjective requirements on a national level would likely require efficient coordination between different regions. To this point, documentation on made interpretations of subjective requirement in different local projects would be an important step towards facilitating cross-project understanding of design guidelines (Eastman et al., 2009; Kiviniemi, 2005; Lindahl et al., 2010). Consequently, understanding for interpretation of subjective requirements in individual projects could result in an opportunity for incorporating feedback from completed projects into new projects (Lindahl et al., 2010). Still, it is important to understand what type of feedback (e.g., text-based notes, IFC files) that is gained from different local projects and how it would be accessible on a national level. As presented in Paper 4, study visits for purpose of understanding local projects' use of design guidelines did not result in cross-project learning due to inefficient documentation during and after these study visits.

In this context of cross-project learning, Paper 3 suggested how breaking down the information structure of a design guideline via ontologies could make both subjective and quantitative requirements for different standard rooms, computer-interpretable. Following this, the algorithm syntax also presented in Paper 3 proposes how a rule-based algorithm could be used to set up the boundary conditions for the standard room as well as populating the generated space with furnishment from the asset library of the design guideline. By integrating this with a collaborative design system such as ViCoDE (Paper 1), user could evaluate in the VR user-interface the placement of both types of furnishment, loose (e.g., hospital beds) and fixed (e.g., electrical outlets). Moreover, with Paper 2 demonstrating how furnished VR models provides end-users with a context when design reviewing, it could be argued that automated design layout would help facilitate virtual collaborative understanding. More importantly, it would allow end-users such as healthcare staff to be less reliant on their representatives such as facility planners and project leader for visual understanding, and instead, help develop different design proposals. Consequently, collaborative practices such as Co-design would more likely be possible. Nevertheless, the results from both Paper 3 and 4 showed the difficulties with cross-project learning due multiple challenges that have yet to addressed. Firstly, the object library of the PTS database design guideline did not include certain complex standard rooms (e.g., radiology room, robot assisted surgery room) as well as missing medical equipment in existing standard rooms. Following this, absence of necessary standard rooms and objects in the database limit abovementioned automated design layouts to the already existing standard rooms. Thirdly, the lack of useful user-interfaces in design guidelines on how different projects have interpreted subjective requirements could result in new projects making the same mistakes when evaluating different design layouts. Lastly, with Paper 4 showing the inefficient coordination of regions when revising the quantitative and subjective requirements connected to different standard rooms, an argument can be made that development of these requirements should be prioritized before applying rule-based algorithms. Simply put, by ensuring that both the subjective and quantitative requirements are mutually agreed upon on a national level (Paper 4), design guideline compliance of automated design layout would be based on current needs of the healthcare staff, rather than compliance with outdated requirements (i.e., not reflecting the healthcare staffs' needs for different standard rooms). In other words, whilst collaborative understanding via multiple user-interfaces would be possible, the abovementioned challenges makes it difficult to enable a recommendation system.

All in all, the idea of a recommendation system as discussed above would require the use of different user-interfaces such as one for the rule-based algorithm and VR for assessing the set of automated design proposals. Particularly VR is important to understand in the context of assessing the most suitable design layout that supports building occupants' daily working tasks. Specifically, with each project's most suitable design layout determined by the placement of furnishment, it is important to ask how technical features in VR (e.g., multi-user, object manipulation) can support collaborative understanding for the design layout. As revealed in paper 1 and 2, furnished VR models provide a contextual understanding of the design issues end-users aim to identify during design reviewing. To this point, collaborative design systems such as ViCoDE that include VR as a user-interface could be used during design reviewing to connect with a cloud-based database (Paper 1,3). Accordingly, it becomes important to understand how VR as a user-interface supports collaborative understanding together with other available user-interfaces (e.g., multitouch table, projector screen), which will be discussed in the following section.

5.3 Integration of VR in collaborative design systems

Findings from both paper 1 and 2 show how VR triggers new thoughts about the design which can help design team members better understand building occupants' knowledge and experience of daily working tasks. This increased sense of triggering new thoughts and ideas in building occupants is further enhanced by use of various technical features such as multi-user and object manipulation (e.g., placement and removal/addition of spatial objects in the VR model). Results also imply that use of VR during design reviewing, requires structured procedures such as preparing set-up of hardware and provide briefing to those intended to participate. Next, results seem to suggest that VR models furnished with spatial objects, compared to non-furnished models, resulted in increased discussions of design issues, as users were provided with a context to base their discussions on. The results from paper 1 and 2 also show how collaborative interaction emerged during design reviewing when VR was used together with other user-interfaces such as projector screens and multi-touch table.

These above-mentioned results show how VR as user-interface can serve as a space for both end-users and the design team to explore and understand the consequences of different decisions they make in the design (Arias et al., 2000; Fischer et al., 2005). For instance, by using object manipulation in the VR models via task-based scenarios, logistical flow of different design layouts can be assessed. This is what the literature refers to as an action space (Arias et al., 2000; Fischer et al., 2005). Similarly, VR can provide users with what studies also refer to as a reflective space (Arias et al., 2000; Fischer et al., 2005). This space allows users to reflect and negotiate on decisions made in the action space and specifically which of these decisions best support building occupants' daily working tasks (Paper 1,2). Consequently, the combination of both these spaces can help create a mutually understood context between end-users and the design team for the design proposal that is being reviewed. To this point, the contextual understanding can be enhanced by use of various technical features in the VR user-interface (e.g., object manipulation, markup-tool, multi-user), as presented in paper 1 and 2. Also as shown in paper 1 with the ViCoDE system, by using technical features when design reviewing with task-based scenarios, understanding for the design can be further facilitated (Kumar et al., 2011; Nikolić & Whyte, 2021).

In regard to the discussion above, it is of interest to observe how use of technical features can facilitate collaborative understanding by increasing end-users' sense of presence (Paper 1,2) (Horvat et al., 2022; Johansson & Roupé, 2022; Lapointe et al., 2021; Nikolić & Whyte, 2021; Wolfartsberger et al., 2023). For instance, as observed in paper 1 and 2, client representatives via the multi-user feature were able to coordinate and negotiate design requests more efficiently with one another as well as with the architect when sharing a mutual frame of reference (Du, Shi, et al., 2018; Johansson & Roupé, 2022; Shi et al., 2016; Truong et al., 2021). Moreover, by sharing a mutual frame of reference end-users and design team members can better understand each other's activities, e.g., drawing points of interest in the design via markup tools (Paper 2), and from this understanding of each other's activities, a larger context for each users' own activity can emerge (Bullinger-Hoffmann et al., 2021; Dourish & Bellotti, 1992). As a result, collaborative understanding is more likely to emerge when using multi-user VR compared to a single-user VR experience, as observed in Paper 1 and 2 (Johansson & Roupé, 2022; Shi et al., 2016).

Additionally, features such as object manipulation help design team members and end-users quickly test different design layouts and as a result, better understand how certain design layout influences building occupants' daily working tasks (Paper 1,2) (Mahamadu et al., 2022; Roupé et al., 2020; Wolfartsberger et al., 2023). With VR models furnished with spatial objects (e.g., chairs, tables), both design team members and end-users enhance their contextual understanding of the design that is being reviewed in VR (Paper 1,2). An interpretation that follows is that users gain an increased understanding of each other's context when VR models are furnished. Following this, it could also be argued that with an increased contextual understanding, building occupants' are less likely to be viewed as alibis in the design process (Olsson et al., 2006). As a result, the issue of decision-making taking place on the premise of false expectations (Choguill, 1996), would less likely take place.

However, as observed from Paper 1 and 2, using VR during design reviewing requires structured procedures such as preparing set-up of hardware and providing briefing to participants on what design issues that are set out to be identified. With the addition of technical features as discussed above, it can be argued that the necessity for structured procedures would be even more evident, as users would likely spend more time familiarizing themselves with the different technical features (Nikolic et al., 2019). Therefore, it is of interest to better understand how VR influences collaborative practices such as participatory design and co-design, where the experience of the built environment in operation (i.e., daily working tasks) can be understood during the design phase (Maftei & Harty, 2013; Whyte, 2002). The developed classification in paper 1 was developed with the purpose of providing an understanding of how VR can be integrated with collaborative practices. Specifically, there is a need to better understand how both an effective structure of VR-aided design review sessions (Harkness et al., 2018; Y. Liu et al., 2018; Mahamadu et al., 2022) as well as understanding the use of technical features may help promote conversations between design team members and end-users (Nikolić & Whyte, 2021).

When considering how VR enables collaborative understanding in combination with other user-interfaces (e.g., multi-touch table and projector screen), paper 1 and 2 showed how VR together with these other user-interface could be used both as an action space as well as a reflective space during design reviewing (Arias et al., 2000; Fischer et al., 2005). For example, with the multi-scale and multi-user feature shown in paper 2, end-users could identify and resolve design issues within the same VR user-interface. This resulted in them using the other available user-interfaces (e.g., projector screen) instead to validate and further discuss identified design issues. Explanation might be that out of many available user-interfaces, the one user-interface that best supports building occupants in creating a context for the working tasks (Bullinger-Hoffmann et al., 2021; Dourish & Bellotti, 1992; Maceachren & Brewer, 2004) as well as allows for multiple viewpoints and transitions between shared and individual activities (i.e., multi-scale and multi-user) (Churchill & Snowdon, 1998; Snowdon et al., 2001) becomes the main user-interface that the discussion of design issues are based on. Therefore, an argument can be made that by integrating technical features such as multi-scale and multi-user within a VR user-interface, the action and reflective space becomes further enhanced (Arias et al., 2000; Fischer et al., 2005). As a result, a virtual collaborative design environment can emerge between end-users and the design team.

Yet, to what extent this virtual collaborative design environment can take place on a cross-project level, remains somewhat of an unanswered question. As shown in paper 3, technical barriers such as documentation and traceability of decisions made in different projects regarding design layout of standard rooms, is currently difficult to be understood in new projects. Still, efforts in recent studies have explored how information contained in design guidelines, could aid building occupants with better understanding and assessing the design if these were shown in the VR user-interface (Buchanan et al., 2022). Similarly, studies have investigated integration of design guidelines into generative design to allow for code-compliant design proposals (Sydora & Stroulia, 2020). It can be assumed that these efforts of integrating multiple user-interfaces such as VR and design guidelines will continue.

6 Conclusion

The aim of this thesis has been to advance the understanding of user-involvement in virtual collaborative environments in the design process. Firstly, the results of this thesis show that opportunities for collaborative work between the design team and end-users are difficult to accomplish. A reason for this is that both design team members and end-users experience difficulties with using and understanding design guidelines. Another reason is the lack of user-friendly interface that support feedback between the design team and end users. Next, it is shown that the spatial requirements in design guidelines could be used for automated design layout if these are translated to a computer-interpretable format. To this point, the use of a rule language (i.e., language that is built on mathematical logical reasoning) could be a possible solution. Specifically, with end-users and the design team formulating both the subjective and quantifiable requirements in design guidelines into rules, based on already understood concepts (e.g., distance, relative positioning of furnishment in standard rooms), a more accurate interpretation and understanding of design guideline would be gained. Furthermore, the user-interface for a rule-language could enable direct feedback between end-users, such as building occupants, and the design team, facilitating a shared understanding of the design guidelines. Lastly, the use of technical features in the VR user-interface can support increased collaborative understanding between the design team and end-users and as a result, help design team members better understand building occupants' needs and preferences. As a result, a mutual understanding of the design is more likely to be facilitated.

These findings address the research gaps by firstly creating an understanding of what needs to be addressed during collaborative work from both a technical and non-technical perspective (e.g., studying the relationship between different regions in Paper 4). Specifically, understanding how different users' work practices influence their ability to mutually identify and address design issues connected to the operations of the building design. In this context, the four papers have helped create an understanding for what would be required of a design tool, such as a collaborative design system, to address challenges of collaborative work by considering different user-needs. In other words, the contribution of this thesis is understanding of how different user-interfaces such as Virtual Reality and design guideline documents can be integrated into one and the same design tool. Specifically, the integration of different user-interfaces can support the design team and end-users in more efficiently identifying and addressing design issues through collaborative work.

6.1 Practical and theoretical implications for end-users

The findings of this thesis have important practical and theoretical implications for end-users. Specifically, these concern end-users' ability to understand how the building design influences the operations of the building. For instance, the purpose of developing the classification of user involvement in VR was to provide guidance in determining the appropriate level of user involvement when using VR. To this point, facility planners and project managers, together with the design team, can use the classification of user-involvement to create a better basis for decision-making in the design process. Similarly, client representatives and building occupants could use the classification of user-involvement to negotiate design ideas and requests more confidently with the design team. Furthermore, since the classification for user-involvement in VR has been developed from multiple healthcare projects used as case studies, it can be argued that it is applicable to other complex building designs as well.

Theoretical contributions in this thesis suggest that use of ontologies as a methodological approach can help provide an understanding for the information structure of design guidelines. In this context, our findings indicate that involvement of client representatives and building occupants might be necessary to accurately interpret the ambiguous requirements listed in design guidelines. Therefore, it is implied that user-friendly interfaces are needed to aid with accurate translation of building requirements. Likewise, the results also imply that a user-friendly interface could provide client representatives and building occupants with a sense of ownership during decision-making processes.

6.1.1 Practical and theoretical implications for design team

From a design team perspective, the practical implications of this thesis are similar to those of end-users. The use of the classification of user-involvement can guide architects in understanding the needs of the client representatives better than traditional information and visualization mediums such as 2D drawings and 3D models. From the BIM-coordinator's perspective, an overview of which technical features correspond to a specific level of involvement (e.g., object manipulation associated with co-design) could help ensure that the degree of interactivity in the VR models reflect this intended level of involvement.

Theoretical contributions suggest that use of VR during design reviewing could cause architects to experience a loss of control and predictability in terms of decision-making (Caixeta & Fabricio, 2021; Cruickshank et al., 2013). In this regard, paper 1 and 2 indicate that architects would benefit from adopting a different approach to design reviewing when VR is used. Specifically, with end-users gaining an increased spatial understanding via VR, design proposals presented by the architect might be questioned to a higher degree compared to traditional design reviewing. As such, in order to facilitate collaborative work via VR, architects might benefit from understanding how VR as a design tool influences the architectural practice.

6.2 Future work

The purpose of this thesis was to advance the understanding of user-involvement in virtual collaborative environments in the building design process. To this point, healthcare and school projects have been suitable contexts to study user-involvement as the building design very much affects building occupants' daily working tasks (i.e., healthcare service and education). In this regard, the building design of these type of projects are considered complex. Therefore, it would be of interest to study if findings similar to this thesis emerge in other projects where the building design is considered complex. Also, with emphasis being on understanding user-involvement from an end-user perspective and specifically building occupants' point of view, it would be interest to study from a design team perspective. Specifically, how does architects and BIM coordinators experience user-involvement and collaborative understanding when using visual and information mediums such as VR? An example would be exploring how architects can use the developed classification for user-involvement in VR (Paper 1). Could architects gain an increased understanding for what a suitable level of end-user involvement is when using VR?

Finally, it would be of interest to conduct follow-up studies on the presented cases in this thesis. By conducting follow-up studies on the presented cases, validation can be made in regard to whether feedback from the VR sessions were in fact considered by the design team and what factors that prevented or led this feedback to be incorporated into the final building design.

Altogether, there are several different directions possible for future work when studying user-involvement in virtual collaborative environments. These are some areas of interest that will be studied:

- **Level of detail (LOD)** Past literature has described how the importance of knowing what LOD is more appropriate for certain design phases (Y. Liu et al., 2014; Ventura et al., 2020). However, there is no clear definition of what LOD refers to in the context of design reviewing with HMD VR. On the one hand, LOD as a terminology is used to describe geometric objects represented at a number of resolutions (*Level of Development Specification – BIM Forum*, 2022) and on the other hand, LOD refers to the number of spatial objects in the VR model (Y. Liu et al., 2020; Ventura et al., 2020). Therefore, to better understand how LOD can be mapped to different phases of the design process, a clearer definition is necessary.

- **Contextual understanding with LOD** The literature has suggested that users can feel distracted from sticking to their given main task during design reviewing with HMD VR if the model has high LOD due to increased cognitive load (Y. Liu et al., 2014; Ventura et al., 2020). This observation contrasts our findings (Paper 1,2) where end-users were able to gain a better contextual understanding of the design issues, they sought out to identify when the models were fully furnished (i.e., models with high LOD). Moreover, as shown in Paper 1, the collaborative design system ViCoDE allowed end-users via the multitouch table to add spatial objects on the fly in the VR models. In other words, these participants were able to set their own preferred LOD in real-time. Consequently, task-based scenario could be done efficiently by rapidly testing different design layouts that best supported building occupants' working tasks. To this point, it can be interesting to further study how this feature of object manipulation can be used during tasked-based scenario when design reviewing in VR. Similarly, it can be of interest to explore how collaborative understanding is influenced by allowing object manipulation directly in the VR user-interface (Zhang et al., 2023).

In the context of collaborative understanding it can be of interest to further study the design team's perspective and specifically the architect's in the following area:

- **Architects' resistance to using VR** The resistance in the architectural practice to use HMD VR during design reviewing has been documented in the literature, describing how it might be due to lack of knowledge on how to use VR (Zaker & Coloma, 2018) or that is takes time to implement design reviewing with VR (Shouman et al., 2021). As observed in our findings (Paper 1), an initial informative use of VR helped end-users identify and see the need to use VR for design reviewing purposes. This could be interpreted as architect initially experiencing difficulties with understanding how VR fits into the design process and as a result, fail to see opportunity for collaborative understanding. Another interpretation could be that working with design tools such as VR challenges the hierarchical position of architects who are used to predictable and controlled working methods (Caixeta & Fabricio, 2021; Cruickshank et al., 2013). Therefore, it can be interesting to further study how design reviewing with VR is experienced from an architectural perspective. By gaining an understanding from the architect's perspective, user needs could be identified which could prove useful when further developing collaborative design systems such as ViCoDE in terms of usability and experience.

Lastly, it is important to consider how cross-project understanding can emerge as a result of integrating multiple user-interfaces (Paper 3). Specifically, how can technical challenges such as choice of algorithm for interpretation of quantitative requirements, influence transfer of knowledge from one project to another? The following areas can be of interest to further study:

- **Design guidelines in VR** Recent studies have explored building occupants' understanding of the design by integrating healthcare design guidelines into the VR user-interface (Buchanan et al., 2022). Still, it is unclear whether this combination of user-interfaces results in increased understanding for the design layout of standard room or if it is experienced as distracting by end-users such as building occupants and facility planners. Can VR be used to help end-users with interpretating the subjective requirements in design guidelines?

- **Rule-editor and documentation** Our findings show how different regions have yearly meeting with the purposes of evaluating how up-to-date current design guidelines are (Paper 4). Yet, it can be questioned how efficient these meetings are in terms of documentation and evaluating the subjective, non-quantifiable requirements (i.e., words used such "close to", "good enough") in the design guidelines accurately. Can VR be used in these meetings to ensure a cross-regional understanding of ambiguous requirements in design guidelines? What should be considered when developing the user-interface to a rule-editor that allows interpretation of subjective requirements from different regions to be computer interpretable?

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