

# *Virtual collaborative design environment: supporting seamless integration of multitouch table and immersive VR*

Article

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# 1 **Virtual Collaborative Design Environment (ViCoDE): supporting seamless**

## 2 **integration of multi-touch table and immersive VR**

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9 **Abstract.** During the design of a new hospital it is necessary for all involved stakeholders to understand,  
10 participate, communicate, and collaborate with each other to obtain a high-quality outcome. In order to  
11 support these creative and shared design processes, this paper presents the design and evaluation of Virtual  
12 Collaborative Design Environment (ViCoDE) – a new collaborative design system. ViCoDE features  
13 seamless integration of a multi-touch table and several immersive VR-systems that facilitates interactive and  
14 collaborative design work with immediate feedback. The system has been evaluated during two collaborative  
15 design workshops in a real-life context of designing new healthcare environments. The results show that the  
16 multi-touch table and VR-system complement each other very well by facilitating different design spaces –  
17 both collaborative, as well as individual – and that it fosters better understanding, participation,  
18 communication, knowledge sharing and collaboration among the different stakeholders. The contribution is  
19 two folded: presentation of new a collaborative design system and the evaluation of the use of it in a real-life  
20 design context, which demonstrate how these new technology-based workshops may facilitate design  
21 management.

22  
23 **Keywords:** Virtual Reality, Collaborative Design, Collaborative Virtual Environments, CSCW.

## 24 **1 Introduction**

25 When designing new healthcare environments and hospitals, many different stakeholders and specialists from  
26 healthcare and construction are involved with different experiences, knowledge levels and ability to interpret  
27 information. In these design processes there are also pressures to reduce lead-time and costs, and to minimize  
28 defects and design errors, to finally increase client satisfaction and quality of the new facility (Elf et al. 2015;  
29 Lindahl and Ryd 2007). Furthermore, it has been recognized that construction projects are becoming more

30 difficult to manage due to their increasing complexity and technologically advanced buildings (Bryde et al.  
31 2013; Chien et al. 2014; Winch 2010). Consequently, it is important to achieve better communication and  
32 understanding between disciplines (Bhatla and Leite 2012; Eastman 2016). There is also an increase in  
33 complexity in today's design and its amount of information (Van Berlo and Natrop 2015). The most common  
34 information media in these processes are documents, descriptions, 2D-drawings and pictures. However, these  
35 media can be difficult to interpret and understand, placing high cognitive demands on the stakeholders/viewer's  
36 ability to transform the information into a self-made mental image of the project (Roupé 2013). The self-made  
37 mental image could also be misinterpreted and it may differ depending on the individual's background,  
38 education, experience and interest (Roupé 2013). This means that important feedback from healthcare specialists  
39 (e.g. surgeons, nurses) can be lost during the planning and design process. These malfunctions are detected too  
40 late in the process, when the healthcare environment is already built (Elf et al. 2015; Lindahl and Ryd 2007).

41 One potential solution to this problem is to take advantage of immersive Virtual Reality (VR) instead of  
42 traditional 2D-drawings and pictures. Although the use of VR-technology has been limited in the past due to  
43 lack of available 3D data from the design process, the recent introduction of Building Information Models  
44 (BIM) within the AEC field has opened up new possibilities, by enabling extraction of 3D data directly from the  
45 architect's own design environment (Van Berlo and Natrop 2015; Du et al. 2018a; b; Eastman 2016; Johansson  
46 et al. 2014, 2015; Liu et al. 2020; Mastrolembo Ventura et al. 2019; Mastrolembo Ventura and Castronovo  
47 2018; Roupé et al. 2016; Xue et al. 2012). In this context, Du et. al. (2018a;b) focused on mapping objects in  
48 VR to the original objects in BIM authoring tools so the users can easily synchronize changes in from authoring  
49 tool (e.g. Autodesk Revit) to a visualization environment. Furthermore, use of real-time visualizations has  
50 become more accessible in practice (Johansson et al. 2014, 2015). With the use of a Head-Mounted Display  
51 (HMD) the different stakeholders can move around and experience the future planned healthcare environment in  
52 scale 1:1 and therefore share a common frame of reference (Paes et al. 2017; Roupé et al. 2016). However, with  
53 HMDs being primarily a tool for the individual, it makes it less suitable for active collaborative design work,  
54 which also relies much on face-to-face communication and gestures (Gugenheimer et al. 2017; Wang and  
55 Dunston 2008). In this context, it is also important to allow participants to express ideas and thoughts to the  
56 other members of the team by performing actual changes to the design.

57 In order to address the current situation this paper presents a new collaborative design system which uses a  
58 seamlessly connected multi-touch table and several VR-systems for interactive and collaborative design. In  
59 addition to describing technical details of the system, we present and discuss the results from using the system

60 during two design workshops held as part of an ongoing design of two new hospitals. By assessing both  
61 technical and social factors around the use of this technology in a real context, these results contribute to the  
62 body of knowledge on how and these new types of collaborative design systems and collaborative design  
63 workshops facilitate the design management process.

## 64 **1.1 Literature Review**

65 The rising complexity of construction projects sets new demands on how design should be conducted.  
66 Computer-Supported Cooperative Work (CSCW) approaches are often based on the assumption that complex  
67 problems require more knowledge than any single individual possesses and in this context it is necessary for all  
68 involved stakeholders to participate, understand, communicate and collaborate with each other to obtain a higher  
69 quality outcome (Arias et al. 2000; Fisher et al. 2005).

70 These types of design problems are often moving targets that do not have straightforward solutions but only  
71 have resolutions during the design process, and the context in which these problems exist is characterized by  
72 change, conflict, and multiple stakeholders (Arias et al. 2000; Heldal and Roupé 2012). The resolution of design  
73 problems grows out of the shared understanding that emerges as different stakeholders begin to better  
74 understand each other's perspectives (Arias et al. 2000; Fisher et al. 2005). Still, communication breakdowns are  
75 often experienced because stakeholders have different interests and agendas and belong to different cultures that  
76 use different norms, symbols, and representations. However, by creating a shared understanding through  
77 collaborative design, it is possible to provide opportunities and resources for design activities embedded in a  
78 social creative design process in which all actors can actively contribute rather than having passive consumer  
79 roles (Arias et al. 2000; Fisher et al. 2005).

80 As a way to facilitate and improve collaboration across different stakeholders, Collaborative Virtual Environments  
81 (CVE) are increasingly being explored. According to Snowdon et al. (1998; 2001) such a system should be able  
82 to support:

83

84 **Shared Context** - Representations of the design problem, which are supposed to enable shared understanding and  
85 interactive activity for the group and its different participants. The shared artifacts should be understandable,  
86 visible and available for communication and negotiation in the group and should support gesture or pointing  
87 during discussions.

88 **Awareness of others** - Through understanding of others tacit knowledge and activities related to the design  
89 problem, the team can build up shared understanding that emerges as different stakeholders begin to better  
90 understand each other's perspectives.

91 **Transitions between shared and individual activities** - relate to the process whereby individual work evolves  
92 into collaborative work. It is important that collaborators know what is currently being done and what has been  
93 done in the context of the task goals.

94 **Negotiation and communication** -Conversations and gestures are crucial for negotiation and communication  
95 during collaborative design activities. In this context, face-to-face communication is vital for supporting natural  
96 communication through human body features such as facial expression, gestures, postures.

97 **Flexible and multiple viewpoints** -Design tasks often require the use of multiple representations and  
98 visualisations, each tailored to different points of view and different subtasks and users.

99 Furthermore, Fischers et. al. (2000; 2005) highlighted two different spaces in their collaborative design  
100 environment – **action space** and **reflection space**. Action space provides a foundation for creative collaboration  
101 between the participants whilst reflection space supports the group members to validate and form their own  
102 opinions on the design. They also mention social creative aspect of the design process and stress the importance  
103 of interactive collaboration enabling actors to actively contribute rather than having passive consumer roles.  
104 More specifically, Fischer et al. (2005) argue that in order to support creation and progression in a social  
105 creative design process, it is important to provide systems that can:

- 106 • Create awareness of each other's work and provide mechanisms to help draw out the tacit knowledge  
107 and perspectives;
- 108 • Enable co-creation (in multiple forms: simultaneous, parallel, and serial);
- 109 • Allow participants to build on the work of others;
- 110 • Provide individual reflection and exploration (e.g. reflection space and action space).

111 Various types of technology can be deployed to achieve these aims. Multi-touch table interactive systems have  
112 been shown to aid such a creative collaborative design process (Arias et al. 2000; Fisher et al. 2005; Voigt, A.,  
113 Achleitner, E., Linzer, H., Schmidinger, E. and Walchhofer 2003). The multi-touch table has the possibility to  
114 give the participant the feeling of an active and meaningful role during the meeting (Jutraz and Zupancic 2012).  
115 Still, a common problem with 2D-based design environments is that the information is not presented in such a  
116 way that people can easily understand it spatially. In this context, real-time 3D visualizations (e.g. non-  
117 immersive VR) have been shown to offer an efficient communication platform (Balali et al. 2020; Biederman

118 1990; Bouchlaghem et al. 2005; Du et al. 2018a; Liu et al. 2020; Mastrolembo Ventura et al. 2019;  
119 Mastrolembo Ventura and Castronovo 2018; Sunesson et al. 2008; Westerdahl et al. 2006). Usability studies of  
120 non-immersive VR applications (Roupé 2013; Sunesson et al. 2008; Westerdahl et al. 2006) have shown that  
121 VR helps stakeholders with different backgrounds and knowledge to coordinate their perception and  
122 understanding of the project. One conclusion has been that VR fosters a more dynamic decision-making process  
123 (Roupé 2013). VR has shown the potential to be an effective communication tool that will allow different  
124 stakeholders in the planning and design process to better understand the project and each other. VR could  
125 provide the stakeholders with opportunities to identify and analyse problems and to jointly coordinate the  
126 project with the aim of improving their decision-making and thereby the designed environment. One way in  
127 which VR models facilitate decision making is by providing stakeholders with the same frame of reference with  
128 respect to the new building and the future environment (Balali et al. 2020; Roupé 2013; Roupé et al. 2014).  
129 With the ability to navigate freely through 3D scenes from a first-person perspective, it is possible to present and  
130 communicate ideas regarding future buildings in a way that facilitates understanding among all involved parties,  
131 despite their background or professional expertise.

132 To further enhance the user experience, it is commonly advocated to take advantage of immersive display  
133 technologies. Immersive-VR have been shown to be useful per se, whilst stereoscopy, large screen, resolution of  
134 the display and wide field-of-view provide additional benefits for perception of space (Castronovo et al. 2013;  
135 Heydarian et al. 2015; Paes et al. 2017; Shiratuddin et al. 2004; Thompson et al. 2004). Complementarily, the  
136 content of the virtual environment such as textures, known objects etc. are important during spatial processing  
137 (Paes et al. 2017). The visual cognitive process includes object recognition processes for sorting the information  
138 into patterns, which are then combined and associated with objects that the user has experienced earlier in life  
139 (Biederman 1990). These associated objects are then used in the spatial reasoning process of the 3D space. During  
140 this reasoning process the mind tries to create an understanding of the visual space within two parallel systems,  
141 i.e. a self-centred egocentric reference frame and an environment-centred allocentric reference frame (Plank et al.  
142 2010). Both systems interact during this processing and retrieval of spatial knowledge (Plank et al. 2010). In the  
143 egocentric reference frame, the viewer compares him/herself with the objects in 3D space and in the allocentric  
144 reference frame the viewer compares relations between object-object or environment-object. Studies have shown  
145 that different media and representations facilitate different reasoning processes about the design (Coburn 2017).  
146 For instance, flat 2D plan drawings or bird-eye views have been agreed to give opportunity for pattern recognition,  
147 which is suitable when studying spatial organization, relationship between spaces and objects and orientation of

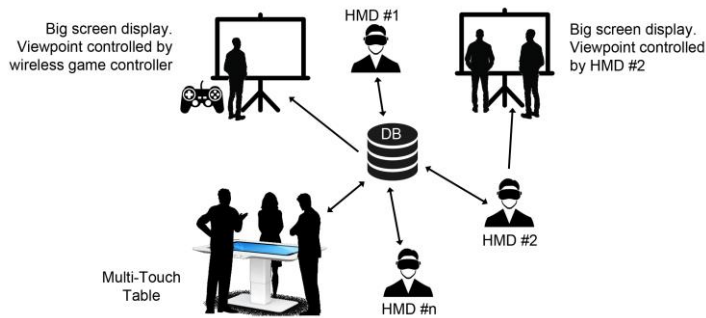
148 different objects i.e. allocentric reference (Coburn 2017). Furthermore, Immersive-VR gives the user the  
149 opportunity to compare themselves and their bodies with the environment in a view-dependent process i.e.  
150 egocentric reference. Research has also suggested that using the physical-human rotation and movement  
151 Immersive-VR provides a better understanding and spatial perception (Paes et al. 2017; Riecke et al. 2010; Roupé  
152 et al. 2014; Ruddle and Lessels 2009). In recent years, new Head Mounted Displays (HMDs) have been released,  
153 which support better stereoscopy, higher resolution of the display, wider field-of-view, physical-human rotation  
154 and movement. Recent studies have shown that space perception in the HTC-Vive starts to be comparable to real  
155 world space and distance perception, but still virtual environment feels compressed (Buck et al. 2018; Kelly et al.  
156 2017; Paes et al. 2017). Furthermore, other studies have shown that immersive VR may give a level of  
157 understanding and perception of space which is hard to experience using other type of visualizations (Balali et al.  
158 2020; Coburn 2017; Germani et al. 2012; Roupé et al. 2016). Nevertheless, when considering the integration and  
159 use of immersive VR within the actual design process, the current adaptation still suffers from a number of  
160 limitations, such as navigation and user interface, face-to-face communication and gestures, shared view and  
161 space, and multi-view projection (Beck et al. 2013; Kulik et al. 2011; Moghimi et al. 2016; Roth et al. 2016;  
162 Roupé et al. 2016).

163 To date, several different collaborative design systems have been proposed (Faliu et al. 2019; Whyte and  
164 Nikolic 2018; Xue et al. 2012). However, when comparing these systems against the recommendations stated by  
165 Arias et al. (2000; 2005) and Snowdon et. al. (1998; 2001), several limitations can be noted. For instance, face-  
166 to-face collaboration is difficult in current projection-based and HMD virtual reality systems because they do  
167 not provide a visually consistent shared space for all users and have limited support for gesturing, pointing,  
168 facial expression, postures (Beck et al. 2013; Du et al. 2018b; a; Gugenheimer et al. 2017; Ibayashi et al. 2015;  
169 Kulik et al. 2011; Xue et al. 2012) which would enable the *Negotiation and communication* and *Shared Context*  
170 aims of collaborative design systems Snowdon et. al. (1998; 2001). Other multi-touch table systems enable  
171 limited perception of space, provided by a VR system (Arias et al. 2000; Chi et al. 2013; Faliu et al. 2019;  
172 Fisher et al. 2005; Xue et al. 2012) and multiple views e.g. *Flexible and multiple viewpoints and Shared context*.  
173 Other systems enable limited creative interactive collaboration with the design (Beck et al. 2013; Du et al.  
174 2018b; Voigt et al. 2009). In a recent paper Faliu et al. (2019) presented a prototype with some similar  
175 technological setting as our system, e.g. combining multi-touch table and VR. However, the study targeted the  
176 urban planning process and developing a new kind of participatory platform, that enables urban designers,  
177 architects, and developers to co-design and communicate their projects with the public. Although there are some



178 similarities in the technology, urban planning and urban space is a different context and setting compared to our  
179 context of designing buildings e.g. new healthcare environments. More generally, existing work on the use of  
180 VR is mostly limited to testing the use of these technologies in experimental situations (Du et al. 2018a; Xue et  
181 al. 2012). Our study contributes to this literature both by presenting a new collaborative design system (with  
182 seamlessly connected multi-touch table and several VR-systems for interactive and collaborative design) and by  
183 evaluating the use of this technology in a real-life design context, with a view on how these new collaborative  
184 design systems-based workshops may facilitate the design management process.

185 In order to address the complexity of design projects such as hospital design, a promising approach would be to  
186 combine the CSCW approaches (e.g. multi-touch table) with VR (e.g. Collaborative Virtual Environment  
187 (CVE)) and BIM. The collaborative system presented in this paper supports the aims stated by Snowdon et al.  
188 (1998; 2001) -Shared Context; Awareness of others; Negotiation and communication; Transitions between  
189 shared and individual activities; Flexible and multiple viewpoints. The collaborative design system has been  
190 implemented with the intention to support better creative and shared design processes for the involved  
191 stakeholders compared to the traditional process and existing systems. To support this process, we have  
192 recognized that the system has to support design understanding, participation, communication and collaboration  
193 between different stakeholders and that the system must be user friendly. The hypothesis was also that the multi-  
194 touch table and VR-system complement each other by facilitating both the aims mentioned above (cf. Snowdon  
195 et al. (1998; 2001)) and different design spaces –collaborative (i.e. action space) as well as individual (i.e.  
196 reflection space), as mentioned by Arias et al. (2000). Combining technologies to support both self-centred  
197 egocentric and environment-centred allocentric reference frames could speed up the understanding, dynamics  
198 and transitions during collaborative work through the use of the system (Coburn 2017; Fischer et al. 2005).  
199 Building on this hypothesis, our system supports interactive collaboration in both spaces i.e. changes done in the  
200 multi-touch table or in VR are updated instantly in both spaces, as illustrated in Fig. 1, 2 and Fig. 3. Our system  
201 also supports direct import and interactive use of BIM from the design process. In this particular study, the  
202 equipment and furniture used in the system are BIM objects from the Swedish national healthcare database.



203

204 **Fig. 1.** *The collaborative design system supports seamless integration of multiple viewer and interaction clients*205 *through a database/server.*206 **2 The system**

207 The collaborative design system, Virtual Collaborative Design Environment (ViCoDE), has been developed in  
 208 the Unity Game Engine using C#. In essence, it consists of several viewer and interaction clients connected to a  
 209 central server which manages a database and changes to the system, as illustrated in Fig. 1. The system connects  
 210 network server and clients, where an IP network with multicast support was realized on top of the network  
 211 infrastructure. Through the network, any client can interact online with other remote clients. On one of the  
 212 computers in the network a Redis database is running on a Node.js server. The database in the central server is  
 213 configured and populated with 3D-components and the designed layout. The initial layout of the proposed design  
 214 can be imported from the architect's design BIM-software (e.g. Autodesk Revit) and the components in the  
 215 database are also BIM-objects. The 3D-components in the database have unique IDs (GUID), which makes it  
 216 possible to traces changes in the variously connected client/viewer applications. Changes of a component's  
 217 position or rotation in one client are uploaded to the server and then propagated to the other clients. However, as  
 218 described below, not all clients support all degrees of interaction. The different viewer and interaction clients have  
 219 different setup and configurations, which facilitate its specific purpose, such as support for the multi-touch table,  
 220 HMDs (HTC-vive) and VR-viewer for big screen display.

221 **2.1 Multi-touch table and big screen display**

222 The layout of the multi-touch table is shown in Fig. 2. It represents the top view of the operating theatre and  
 223 supports the typical multi-touch pan and zoom features used in most Smart-phones. To better illustrate the scale,  
 224 a 1x1 meter grid is applied on the floor as a texture. Furniture, medical equipment, walls and static avatars can

225 be added, deleted, translated and rotated. All available components are accessible from a scrollable panel on the  
 226 left side, and are added to the scene using drag-and-drop. The components are BIM-objects coming from the  
 227 national healthcare database, PTS (Program for Technical Standard). Pressing and dragging a component will  
 228 translate it whereas ticking it will show a circle for rotation and deleting. Furthermore, components that are  
 229 mounted in the ceiling are given a different nuance in order to better emphasize their vertical position, see Fig.  
 230 2. The interface also supports simulation of how the ceiling pendant systems and its multi-movement arms can  
 231 be moved around during surgery, making it possible to detect collisions with other equipment.

232 As seen in Fig. 2 and 3, the contents of the scene can also be displayed on a big screen from a perspective  
 233 controlled by a wireless game controller, i.e. non-immersive VR.



234  
 235 **Fig. 2.** *Left: The multi-touch table used together with a non-immersive VR display. Right: The layout of the multi-touch table*  
 236 *screen. Available components are accessible from a scrollable panel on the left side and are added to the scene using drag-*  
 237 *and-drop.*

## 238 2.2 VR-system

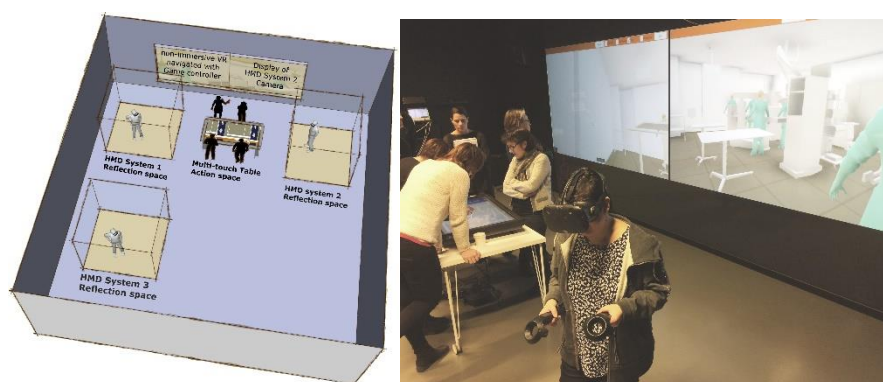
239 The HTC-Vive was used as the immersive display system and a teleportation locomotion mode was used for navigation  
 240 (Christou and Aristidou 2017). Within the VR environment, components can be translated and rotated. The user of the HMD  
 241 could interact within the VR environment by picking components and translated and rotated them using the HTC-Vive  
 242 controllers.

243 A component will be highlighted if it intersects with any of the HTC-vive controllers and pressing/releasing the  
 244 trigger allows a user to pick it up and re-place it within the scene. To help the user with the positioning, a  
 245 component is always restored to its up-right position at the correct elevation above the floor upon release (i.e. to  
 246 avoid tilting). As illustrated in Fig. 1, 2 and 3, it is also possible to display a user's view from VR on a big  
 247 screen display.

### 248 3 The study: use of ViCoDE during collaborative design workshops

249 The results of this paper are grounded in two workshops conducted in the spring of 2016 and 2017,  
 250 respectively. During these workshops, the collaborative design system was used in real-life contexts of  
 251 designing operating theatres. The participants were different stakeholders and specialists from healthcare and  
 252 construction, e.g. theatre nurses, anesthesiologists, architects and project managers, for the intended operating  
 253 theatres in Skaraborg and Östra Hospital, both located in Västra Götaland, Sweden. All of the participants had  
 254 previous experience of dialogue-based workshops using traditional information media, such as 2D-drawings and  
 255 pictures.

256 From a technical point of view, the main difference between the two workshops was that the first one  
 257 required an export of the scene to another application to be able to view it in HMD. Also, only one HMD was  
 258 available and it was not possible to move any of the components in the VR environment. The second workshop,  
 259 however, used the final system as described in the previous section.



260  
 261 **Fig. 3.** During workshop 2, three HMD-system were seamlessly used together with the multi-touch table and non-immersive  
 262 VR. This system supported both collaborative (e.g. action space), as well as individual (e.g. reflection space).

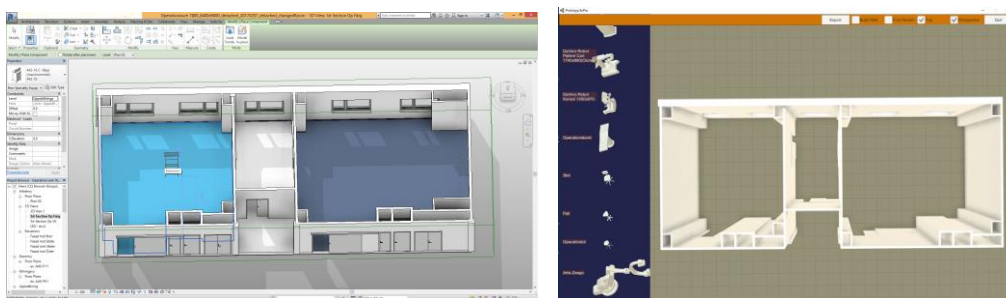
263 *The first workshop* had 8 participants and lasted for six hours. It consisted of two different design tasks: 1)  
 264 designing an operating theatre in a pre-defined space (approx. 8 x 9 meters) and 2) designing an operating  
 265 theatre without any constraints on room size. The time used for each design task was equal.

266 *The second workshop* had 9 participants and lasted for four hours. Fig. 3 shows the room layout and the different  
 267 collaboration and visualization systems used during the second workshop. The workshop consisted of two  
 268 different design tasks; the first one being to design an operating theatre in a standard sized room (approx. 8 x 9  
 269 meters, approx. 63 square meter), and the second one to design an operating theatre in a room of extended size

270 (approx. 10 x 9 meters, approx. 82 square meter). The small room located between the two operating theatres is a  
 271 preparation room, which supports both is operating theatre.

272 The time used for each of the design tasks was equal. The layout of the proposed operating theatre design  
 273 came from the architect's BIM project, see Fig. 4.

274



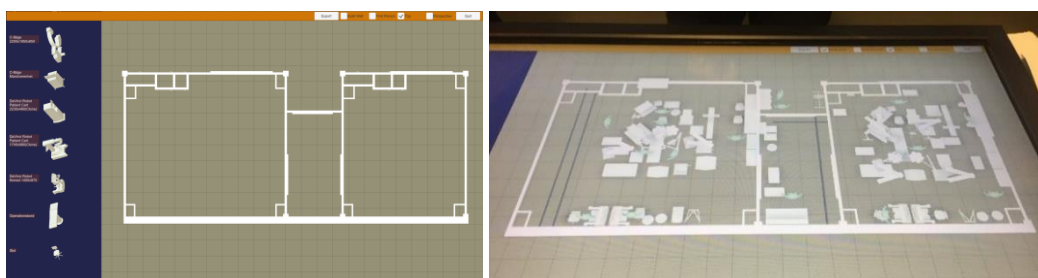
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276 **Fig. 4.** The left image: the BIM layout of the proposed operating theatre from the project. The right image: the proposed  
 277 operating theatre layout in. ViCoDE multi-touch table interface.

278 The workshop started with no equipment and furniture in the operating theatre and the task was to design the  
 279 layout of the equipment and furniture and to validate if the size was enough. As illustrated in Fig. 5, the workshop  
 280 resulted in adding furniture and equipment and reducing the size of some rooms (i.e. by adding and moving the  
 281 walls closer to the equipment).

282 The result and final version of the large room was approx. 8.9 x 9 meters and approx. 71 square meters with a  
 283 narrower preparation room to fit the general and overall design of the building.

284



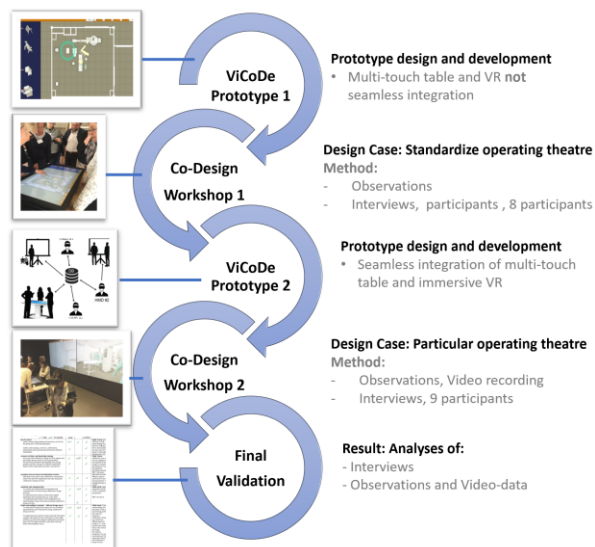
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286 **Fig. 5. Left image:** The initial BIM layout of walls for the proposed operating theatre design from the architect. **Right**  
 287 **image:** the final result and design from the workshop 2, where new walls (e.g. blue walls) and equipment and furniture are  
 288 added and the preparation room has also been reduced.

289 On both occasions, the workshop started with a 10 min introduction of the system to enable the participants to  
 290 familiarize themselves with the user-interfaces and the overall functionality.

### 291 3.1 Method

292 The study focusses on assessing the use of the virtual collaborative design system (ViCoDE) to support  
 293 performing design in real-life contexts. The research approach have been inspired by design science research  
 294 methodology (Hevner 2007), where observations and literature are analysed to develop the artefacts'  
 295 requirements, which are used as a base for designing and developing the prototype, that are later validated  
 296 during use in collaborative design workshops, see Fig. 6.



297  
 298 **Fig. 6.** A simplified graphic illustrating of design science research process of this study.

299 The method during the workshops have taken a qualitative research approach, the study draws on ethnographic  
 300 and video-based studies of naturally occurring interaction (Heath et al. 2010). During both workshops,  
 301 qualitative data was collected by means of direct and documented observations as well as informal, semi-  
 302 structured interviews with all the participants about their thoughts and experiences in relation to the  
 303 collaborative design system. On both occasions three researchers were present. The workshops were facilitated  
 304 mainly by the architect, with technical support from the researchers.

305 During and immediately after the workshops, the researchers interviewed the participants regarding their  
 306 experience and reflection on the collaborative design workshop and the system. The interview data consists of  
 307 17 interviews of 5-15 minutes each, which were recorded and transcribed. The main focus of the interviews was  
 308 to access the participants' views around: 1) how/if the workshop and system supported understanding,  
 309 participation, communication, and collaboration between the different stakeholders and 2) if the system was user  
 310 friendly.

311 The second workshop was recorded with two stationary video cameras which were placed in elevated  
 312 positions to capture an overview of the participants' movement around and across the different stations in the

313 workshop room. The collected corpus of video data consists of 3.45 hours of video data (from the second  
314 workshop) which was transcribed for further analysis and later compared to the field notes and interview data in  
315 order to reinforce the observations made. The video data was analyzed in a qualitative manner (Heath et al.  
316 2010), by drawing attention to the detail of the natural occurring interactions with the various technologies  
317 available in the setting and between the participants as they developed the design of the operating theatre. The  
318 verbal interaction between the participants was transcribed by one of the researchers. The transcription was  
319 added as subtext in the video data. Subsequently, the researchers separately analyzed and observed the  
320 collaboration, conversations and behaviour of the participants during the workshop. After these preliminary  
321 analyses, collaborative data review sessions were conducted for further scrutinizing the preliminary observations  
322 and developing the thematic categories. The preliminary coding schema and focus during video analyses was  
323 based on the literature study connected to collaborative design system (Snowdon et al. (1998; 2001), Arias et al.  
324 2000; Fisher et al. 2005). Additionally, together with interviews and observations during workshop the  
325 preliminary categories were recognized. The observed preliminary categories and themes were aggregated and  
326 compared across the research team and finally clustered. The result was compared to the field notes and the  
327 interviews taken during the workshop. The results that overlapped were selected for further detailed analysis  
328 towards the primary codes in table 1.

329

330 **Table 1.** Preliminary coding schema for observations based on CVE-literature.

331

332 Drawing on principles of video-based studies methods (Heath et al. 2010), the analysis draws on a collection of  
333 illustrative sequences supporting the thematic categories around the use of the collaborative design system during  
334 the design workshop. Due to the limited space in this paper, a fragment of approx. 21 minutes of video data was  
335 selected from the broader corpus of 3.45 hours of video data to illustrate the collaboration, the verbal and non-  
336 verbal interactions and the different behaviour of the participants during the workshop. The fragment selected for  
337 detailed analysis presented in this paper was extracted from the final part of the second workshop. The results  
338 section begins by summarizing this (21 minutes long) fragment, to provide a sense of the interactions emerging  
339 in the workshop and to convey the story line. The subsequent subsections of the results present the thematic  
340 categories emerging from the data, with a focus on the use of the collaborative design system for developing the  
341 design of the operating theatre.

## 342 4 Results

343 As explained above, the results section draws on a representative fragment of 21 minutes from the video data.  
344 The fragment was extracted from the last part of the second design workshop which lasted four hours. The  
345 fragment was selected to illustrate patterns of interaction around the use of the collaborative design system  
346 emerging through both workshops. This section begins with a short summary of the workshop to provide context  
347 for the selected episode. As the primary codes in table 1, in some cases interact and overlaps, we have choose to  
348 present the result use main thematic categories emerging from the data around: Designing using multi-touch table  
349 and VR; Different design spaces and understanding of space in different media; Support for better understanding,  
350 creativity, collaboration and participation. The section is therefore organized around these thematic categories.

### 351 4.1 Summary and sequence, workshop 2: Designing using multi-touch table and VR

352 The fragment presented in this section is part of the second design workshop which consisted of two different  
353 design tasks around designing an operating theatre in: 1) a standard sized room (approx. 8 x 9 meters, approx. 63  
354 square meters) and 2) in a room of extended size (approx. 10 x 9 meters, approx. 82 square meters). The  
355 participants started with the standard sized room, which was the room size decided by the project manager and  
356 the project designers as part of the general and overall design of the building. In the following table 2, a summary  
357 of observation from first part of workshop 2 is presented connected to coding schema based on CVE-literature  
358 from table 1.

359

360 **Table 2.** Summary of observation from first part of workshop 2, connected to CVE-literature categories.

361

362 The final version of the large room was approx. 8.9 x 9 meters and approx. 71 square meters compared to the  
363 original one which was approx. 10 x 9 meters, approx. 82 square meters.

### 364 4.2 Detail description of Observation Case 3: Re-design of the preparation room

365 The architect stressed that this new room did not fit the overall design of the building and would probably not be  
366 a possible solution. In response, one of the Operations Nurse at the multi-touch table said: – *The preparation room*  
367 *feels very big. Can we make the preparation room smaller?* (see Fig. 5, the preparation room is the small room  
368 which is located between the two operating theatres). Consequently, the architect questioned: - *Can we make the*



369 *room narrower?* Inquiring the size of the room, the architect added and moved some furniture using the multi-  
 370 touch table whilst communicating verbally with the nurses: - *The room is 3.45m in width. – I'm trying to*  
 371 *understand how big the room is? -What can you compare 3.45m with? Any one which have any know references?*  
 372 One of the Operations Nurse at the multi-touch table then said: -*How does our current room look like today?*  
 373 Subsequently, two Operations Nurses started to discuss the preparation room size and began to simulate the space  
 374 by stepping out the room size of 3.45m in the background. Joining them, the architect considered that- *There is*  
 375 *quite a lot of space you can say ... - How big does the room need to be?*



376  
 377 **Fig. 7.** Image/film sequence from the workshop showing how the architect and Operations Nurses 1 and 2, together tried to  
 378 create a mental image of how large the room is by stepped-out room in the background as the Anesthetic Nurse adding  
 379 equipment and furniture's to the preparation room using the multi-touch table.

380  
 381 The architect and Operations Nurses 1 and 2 tried to create a mental image of how the room looks in their current  
 382 hospital by describing the activities performed and the furniture in the preparation room whilst comparing it with  
 383 the stepped-out room. In the same time, the Anesthetic Nurse and the other nurses used the multi-touch table to  
 384 add equipment and furniture to the preparation room, as well as new wall, changing the width of the preparation  
 385 room to approx. 2 m. Anesthetic Nurse said to the architect and Operations Nurses 1 and 2 - *Now you have to go*  
 386 *in and test your new preparation room in VR.* Checking the multi-touch table, the architect noticed - *Now it's only*  
 387 *2.5m wide!!! - Great...*

388 While the Operation Nurse 2 started using the VR-HMD-system, the other participants began to add static avatars  
 389 / people to understand the size of the new room. Operations Nurse 1 started to refurbish the preparation room,  
 390 sharing her knowledge on how the room works in her current hospital and expressing her vision for improving it:  
 391 - *There we are two of us ... - I would like to refurbish a little here. -I would like to have preparation there... -*  
 392 *Trash there, two desk tables for preparation there ... etc. - So I'm standing there and "Operations Nurse 2" there.*  
 393 After Operations Nurse 1 finished her changes of preparation room, she asked Operations Nurse 2 which was in  
 394 VR - *How does it feel now?.*

395 Operations Nurse 2, using the VR responded- *For me it feels okay.* Architect -*Do you see yourself and*  
 396 *"Operations Nurse1" in VR?* OperationsNurse2 in VR - *Yes. – I think we need a little wider room... Anesthetic*

397 Nurse – *Should we move the wall a little?* Operations Nurse 2 in VR - *Yes.* Anesthetic Nurse moved the wall to  
398 approx. 3 m wide while Operations Nurse 2 using the VR validated the room by saying: - *It will not feel like you*  
399 *get into a small scrub/room. It's a spacious room - I could stand there the whole day... that's the same room size*  
400 *as my room is today ... Architect says, - Great...*

401 The different participants discussed, tested and validated the new smaller preparation room in the VR-HMD-  
402 system, reaching consensus that the new room worked and the design was satisfactory. Consequently, the architect  
403 noted: - *If we shrink the preparation room as we have designed here, we can probably managed to fit two of the*  
404 *new version of the operating theaters to the overall design of the building.* This was indeed the case, as the final  
405 design contained the two resized operating theaters with the newly designed, smaller preparation room between  
406 them.

### 407 **4.3 User Observation: Different design spaces and understanding of space in different media**

408 As seen above and from other parts from the video analyses, the data shows that it was difficult to understand the  
409 2D representation of the room (i.e. on the multi-touch table). One example of this challenge was the sequence  
410 when the architect and the nurses discussed the size of the preparation room, see Fig. 7. The participants had  
411 difficulty to understand the spatial dimensions of the current version of the preparation room. They tried to add  
412 known reference object (such as equipment and furniture) into the room using the multi-touch table, but still they  
413 thought it was challenging to develop spatial-reasoning with this limited information. They consequently started  
414 to physically walk in the background and step out the room size to establish a shared mental image and  
415 understanding off the room. This results show that it is difficult to understand 2D layouts (e.g. multi-touch table)  
416 and establish shared understanding between different participants with different education, experience and  
417 knowledge background. In this setting when only the multi-touch table was used, the participants experienced  
418 difficulty in understanding the 2D representation and the design problem fully. Furthermore, they had a limited  
419 *Shared Context* (Snowdon et al. 2001), i.e. shared understanding of the virtual room and the design problem. In  
420 this case, the nurses tried to share their knowledge and experience with the architect, by explaining how the  
421 existing preparation room looks and works. However, while the architect and the two operations nurses tried to  
422 establish shared understanding of the room, the other anesthetic nurse re-designed the room by using the multi-  
423 touch table and recognized VR as a tool for better understanding of the space and room size. This insight and  
424 knowledge came probably from her own experience when they re-designed the size of the large operating theatre  
425 rooms in the earlier part of the workshop by using the multi-touch table and the VR-HMD system to move a wall

426 and equipment, see described in 4.1 above, and Fig. 5. Invited by the Anesthetic Nurse to experience the room in  
427 VR, the architects and the two operating nurses recognized that VR can be used as a tool for better understanding  
428 of space. Subsequently, they started to use both VR and the multi-touch table to create shared understanding of  
429 the room and its space by re-designing layouts of equipment and furniture as they had discussed in the background.  
430 In this context, the multi-touch table, VR-HMD system, 3D-view from the projector, provided supported a shared  
431 understanding and communication about the design problem, see table 2, *Shared context and Multiple viewpoints*.

432 When it comes to spatial understanding and reasoning it is important to recognize the different visual cues in the  
433 VR-model. As mentioned in the introduction, the mind tries to create an understanding of the visual space within  
434 two parallel systems, i.e. a self-centred egocentric reference frame and an environment-centred allocentric  
435 reference frame (Plank et al. 2010). In this context it could be argued that the multi-touch table supported  
436 environment-centred allocentric reference frame, where the participants were able to compare relations between  
437 object-object or environment-object.

438 As described in 4.1, the participants used known reference objects such as equipment, furniture and static avatars,  
439 while conducting spatial reasoning about the virtual version of the space. When using the multi-touch table, the  
440 participants used the 1x1 meter grid applied on the floor as a reference to scale and size of the room. By counting  
441 the grid, the user could translate it into square meters and length of the room and for understanding the size of the  
442 room. The equipment and furniture enhanced the participants' understanding for evaluating functional and logistic  
443 aspects of the room (e.g. environment-centred allocentric reference frame comparing object to object). However,  
444 during the middle of the workshops it was observed and recognized that the "2D-top view" on the multi-touch  
445 table was not enough, as it was difficult to interpret and understand the space. As the design progressed, the  
446 participants started to observe several design errors in the 3D-view from the projector, see Fig. 3. Although the  
447 ceiling-mounted equipment had a different nuance to indicate its vertical placement, it was still difficult to  
448 perceive it correctly from the top-view in the multi-touch table. In particular, it was difficult to understand how  
449 much vertical space the equipment required. After the participants had identified this, they started working with  
450 both the multi-touch table and the 3D-view from the projector as a reference. Therefore, it could be argued that  
451 the 3D-view from the projector supported view dependent and egocentric reference frame better, as the viewer  
452 could compare him/herself with the objects in 3D space in a better way as compared to the multi-touch table.  
453 Furthermore, they started to test how the ceiling pendant system and its multi-movement arms moved around  
454 during surgery to avoid collision. During the second workshop, the participants also had the opportunity to do this  
455 validation in the VR-HMD system. After validating the smaller version, re- designed operating theatre in VR,

456 Operating Nurse2 said to Operating Nurse1: *“You must try this, it is an entirely different level off experience off*  
457 *the room, when you see it in VR. You can understand it in an entirely different way by actually being there and*  
458 *standing at the operating table and see all the ceiling pendant systems.”*

459 The VR-HMD system was emphasized by the participants as enabler for better understanding of how the operating  
460 theater would actually function and work. In this context, the users had the possibility to explore a combination  
461 of technologies supporting both self-centred egocentric and environment-centred allocentric reference frame and  
462 reasoning, which speeded up the understanding and communication and the collaborative work during the use of  
463 the system.

464 During both workshops, the participants used the HMD for reviewing and validating the design of the operating  
465 theaters. They had the opportunity to virtually stand by the operating table and make sure that they could see  
466 and reach all the equipment and understand the logistics of how the equipment can be moved during surgery. It  
467 could be argued that this was enabled by the VR-HMD system supporting better self-centred egocentric spatial  
468 reasoning. The participants used physical-human movement and view dependent movement of their body as a  
469 reference and they could use both allocentric and egocentric reference frame during spatial reasoning.

470 Furthermore, it could be argued that the immersive HMD-VR system facilitated a self-centred reflection space  
471 where the user had the opportunity to considerate, reflect, validate and confirm the design related to their future  
472 work environment and task performed in the operating theater.

473 In this context, it could also be seen that the multi-touch table facilitated allocentric reference frame, where the  
474 overview of the design was presented and where the interactive collaborative design was carried out. The  
475 different visualization and interaction techniques gave different support to the users during the workshop,  
476 effectively supporting different design spaces. Primarily, the multi-touch table supported a social creative  
477 process between the participants, i.e. action or collaboration space, see Fig. 8.



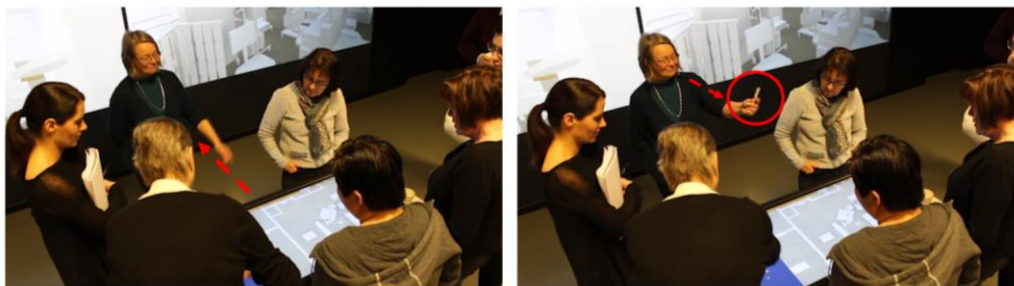
479 **Fig. 8.** *The multi-touch table supported a social creative process (Picture from workshop 1).*

480 The setting around the multi-touch table was highlighted as the most natural in terms of inter-communication  
481 as it supports face-to-face communication and gestures (e.g. (Snowdon et al. 2001)). However, the observations  
482 during the workshops also showed that the participants' ability to transform the multi-touch table information into  
483 self-made mental images in 3D was demanding, difficult and gave misinterpreted understandings as section 4.1  
484 shows (e.g. limited support for *Shared Context and Flexible and multiple viewpoints using multi-touch* (Snowdon  
485 et al. 2001)). However, the 3D-view from the projector and the VR-HMD system enhanced the spatial  
486 understanding. When using the immersive VR-system during the first workshop, the participants wanted to do  
487 detailed changes of the design and they communicated the proposed changes to the other participants while they  
488 were in the immersive environment. As a result of this, the second workshop had seamless integration of a multi-  
489 touch table and several immersive VR-systems that supported interactive and collaborative design work in  
490 different design spaces – both collaborative (e.g. action space, multi-touch table), as well as individual (e.g.  
491 reflection space, VR-HMD). Changes done in one of the spaces were updated in the other design spaces as  
492 presented in section 4.1 -e.g. added and moved furniture, equipment, avatars and the wall in the preparation room.  
493 Furthermore, the second workshop featured three HMD systems and one of them shared the 3D-view on a  
494 projector (see Fig. 3). In this setting it was also possible to make changes to design in the VR-HMD-system. The  
495 design changes performed in the VR-HMD-system during workshop 2 were often small distance changes such as  
496 moving the furniture and equipment in the egocentric distance near the body. The interviews with the workshop's  
497 participants reinforced the idea that the HMD display enhanced the understanding and perception of space and  
498 that it enables "*more detail changes in the design as displayed at 1:1 scale*". These findings support the argument  
499 that combinations of technologies support both self-centred egocentric and environment-centred allocentric  
500 reference frame, as well as action and reflection space (Arias et al. 2000; Fisher et al. 2005), which speeded up  
501 the understanding, dynamics and transitions during collaborative work during the use of the system.

#### 502 **4.4 User Observation: Support for better understanding, creativity, collaboration and** 503 **participation**

504 The observation and video analyses of the workshops indicated that the multi-touch table enabled shared  
505 understanding and that resolution and solution of design problems emerged as different participants/stakeholders  
506 began to understand each other's perspectives and the design task. The project manager and the architect had the  
507 layout and total size of the room (i.e. connected to overall design and construction cost of the building) on their

508 agenda, while healthcare staff focused on functionality and task-related aspects of performing surgery. As  
 509 discussed in section 4.1, the nurses brought their medical practice expertise into the workshop setting and  
 510 counter-argued the architect's and project manager' attempt to pursue the idea of a smaller operating theatre  
 511 room. During this process they built a shared understanding and collaboratively recognized the argument for a  
 512 larger operating theatre room. The architect gained a deeper understanding of the nurses working situation  
 513 during the workshop while they designed and added furniture and equipment to the small operating theatre  
 514 room. The video data showed that, during this collaborative design work the architect recognized that a surgery  
 515 is a lot about logistics around the equipment and patient moves during surgery, where and some equipment is  
 516 very big and hard to move and rotate such as the X-ray equipment (C-arch). In this context, the design problems  
 517 resolution and solution lead to the pursuit of another design solution. Whilst traditional design briefing and work  
 518 involves that the architect takes on the design work to incorporate users' ideas into graphic representations, the  
 519 presented collaborative design system enabled the possibility to do this together. The technological setting (the  
 520 multi-touch table) enabled the users to be actively engaged in the development of the design in a dynamic and  
 521 interactive way as presented, see table 2. For example, during workshop 2, the architect relinquished power over  
 522 the multi-touch table by stepping back from the table and handing over the pen to the users, as she recognized  
 523 the transitions of the collaborative workshop into an dynamic co-creation where expertise and knowledge  
 524 becomes interchangeable, see Fig. 9.



525  
 526 **Fig. 9.** Image/film sequence (e.g. time frame 14:08-14:09) from the workshop 2 showing how the architect relinquishes  
 527 power over the multi-touch table by handing over the pen to the users and stepping back from the table as she recognize the  
 528 transitions of the collaborative workshop into an dynamic co-creation.

529 This video data indicates a reconfiguration of the design process from the traditional design briefing towards a  
 530 more collaborative design process, through the architect's giving the other participants the possibility to design  
 531 through handing over the pen. Consequently, the participants used the drawing and design space via the  
 532 interactive multi-touch table, starting to collaborate and share knowledge of their medical practice expertise to  
 533 the design process. During the interviews, the architect highlighted that “the roles were changing, i.e. the

534 *architect became a facilitator and administrator of the workshop and healthcare staff became*  
535 *designers/architects*” and thereby more active and involved in the process, as can be recognized from section  
536 4.1. According to the architect and project manager, this had not been the case during earlier, traditional  
537 dialogue-based workshops. The architect indicated that the “*knowledge and experience transfer from the*  
538 *healthcare staff was better with the collaborative design system*”. Similarly, the healthcare staff perceived the  
539 ViCoDE system as enabler for better understanding of the design and for mobilizing their professional skills  
540 during the workshops. It could be argued that these perceived enhancements to the design process were driven  
541 by the collaborative design system based workshop’s fit with the aims indicated by Snowdon et al. (Snowdon et  
542 al. 2001) and Fisher et al. (Fisher et al. 2005), see table 1. During the first workshop, healthcare professionals  
543 from different hospitals exchanged knowledge and experience from their particular healthcare environments.  
544 The participants mentioned that some professions were missing during the workshop, such as facility  
545 management, operations, logistics etc., which they believed would also have benefited from using the system  
546 and could have communicated their professional knowledge in the design process.

547 The architect and project managers argued that this collaborative design system based workshops offered a more  
548 efficient process compared to the traditional design briefing. The architect explained that the traditional process  
549 often entails long cycles (e.g. weeks) between new proposals and feedback from end-users, whereas this new type  
550 of collaborative design process provided almost immediate feedback. The results from workshop 2 (section 4.1)  
551 indicate a collaborative and creative process where participants managed to re-design the operation theaters and  
552 the preparation room to fit the demands of the overall building design. The resolution of the design problem grows  
553 out of the shared understanding that emerges as different stakeholders begin to better understand each other’s  
554 perspectives (Fisher et al. 2005). In this case the architect recognized that the intended small operation theater was  
555 not optimal, but other solutions did not fit the general design of the building: “*We have a situation, when we can*  
556 *increase one operation theater and reduce another operation theater. But then we have two rooms that fall out of*  
557 *the overall building design and don’t fit.*” However, the final design result from the workshop addressed this by  
558 keeping the two larger version operating theaters whilst reducing the size of the preparation room between them.

559 Complex problems require more knowledge than any single individual possesses (Arias et al. 2000; Fisher et al.  
560 2005), aspect illustrated in the collaborative design workshops data. All involved stakeholders participated,  
561 communicated and collaborated with each other to obtain a higher quality outcome. The interviews with the  
562 workshops participants indicated the collaborative design system as user-friendly, fun to use, and enabler for  
563 better understanding, communication and effective solving of design task.

564 The data showed that the participants became easily familiar with the user interface and started to use the  
565 system directly after the introduction. The participants indicated that the workshop was a socially creative design  
566 process in which all participants could actively contribute with both their knowledge and experience. The data the  
567 workshop as a very creative design process, where the different participants shared knowledge and experience.  
568 The different visualization and interaction techniques gave different support to the users during the workshop,  
569 effectively supporting different design spaces. Primarily, the multi-touch table supported a social creative process  
570 between the participants, i.e. action or collaboration space, see Fig. 8. They used the multi-touch table interface  
571 for designing and used the 3D-view from the projector as a visualization medium for understanding 3D-space  
572 better and for validation of the design. The workshops indicated that immersive VR (e.g. HMD) gave another  
573 level of understanding and perception of space, which was difficult to experience in other type of visualizations.  
574 The VR-HMD system also supported ego-centric reflection space where the user could validate the design.

## 575 **5 Discussion**

576 Based on Snowdon et. al. (1998; 2001) and Fischers et. al. (2000; 2005), the aim was to design and evaluate  
577 the system according to the three criteria of supporting: a creative and shared design processes; better  
578 understanding, participation, communication, and collaboration between the different stakeholders; and  
579 facilitation of different design spaces – both collaborative and individual (Arias et al. 2000) through the  
580 combination of the multi-touch table with the VR-system in a complementary way.

581 The results based on the use of the ViCoDE system in the collaborative design workshops demonstrate that  
582 ViCoDE supported all of the initially stated aims and criteria, see table 1, 2 and 3.

583

584 **Table 3.** Summary of validation of the ViCoDe-system and Co-design activities connected the CVE requirements,  
585 observation connected to technology and collaborative design activities.

586



587 Furthermore, the participants only got approx. 10 min introduction to the system, which proved to be sufficient  
588 for the users (e.g. the nurses) to learn how to interact with the system. This shows that the system is user-friendly  
589 and there were no barriers for non-technical users to interact and use the system. In fact, it could even be argued  
590 that the successful outcome of the workshops was a result of the system actually supporting the above stated  
591 collaborative aims. Multi-touch table combined with non-immersive VR, supported interactive collaboration by  
592 enabling *shared context*, understanding and *awareness* and it provided mechanisms for *co-creation* and creative  
593 collaboration through tacit knowledge transfers, see table 3. By providing seamless integration, usage and  
594 collaboration between different systems, ViCoDE facilitated collaboration in simultaneous, parallel, and serial  
595 design spaces and support for *flexible and multiple viewpoints*, *transitions between shared and individual*  
596 *activities* for different tasks during the workshop, as seen in table 2 and 3. The workshops participants could build  
597 on the work of others, which lead to *negotiation and communication* through collaborative design activities using  
598 the multi-touch table. As the results showed, the multi-touch table and the VR-system complement each other by  
599 facilitating different design spaces – both collaborative (i.e. *action space*) and individual (i.e. *reflection space*) as  
600 stated by Fischers et. al. (2000; 2005). It could be argued that the immersive HMD-VR system facilitated a self-  
601 centred egocentric reference frame and reflection space, where the user had the opportunity to consider, reflect,  
602 validate and confirm the design. In this view dependent self-centred egocentric reflection space, the user/viewer  
603 mostly compares him/herself with the objects in designed 3D environment. The multi-touch table facilitated  
604 allocentric reference frame where the overview of the design was presented, and the interactive collaborative  
605 design was carried out (e.g. action space). In this allocentric reference, the users/viewers studied relationship  
606 between spaces and objects and the spatial organization of the designed environment. Action space provides a  
607 foundation for creative collaboration between the participants and reflection space provides a foundation for the  
608 group members to validate and form their own opinions on the design. Both these spaces connected to the system  
609 aim to support *Flexible and multiple viewpoints* for different subtasks and users and *Transitions between shared*  
610 *and individual activities*. The bird's-eye view from the multi-touch table gave opportunity for pattern recognition,  
611 which is suitable when studying spatial organization, studying relationship between spaces and objects and  
612 orientation of different objects e.g. in the allocentric reference frame (Coburn 2017). While the immersive VR-  
613 systems enabled the participants to compare themselves and their bodies with the environment in a view-  
614 dependent process i.e. egocentric reference frame, which enhanced the spatial understanding of the design  
615 environment (Coburn 2017; Roupé et al. 2016). By supporting both media and spaces, the system enabled a better  
616 understanding of the designed environment and a better collaborative design process. In comparison to other

617 systems, our system seamlessly supports interactive collaboration in both spaces, i.e. changes done in both multi-  
618 touch table, non- and immersive VR-systems are updated seamlessly in both spaces. However, the results of the  
619 workshops showed that the participants primarily wanted to engage in the collaborative design around the multi-  
620 touch table and did not take the time to reflect and do design review in the VR-HMD. This might relate to the  
621 participants prioritizing the collaborative design activities and changes performed around the multi-touch table.  
622 However, when the participants took the time to reflect and perform the design review in VR, they found it useful  
623 for contributing to the design. During these design review sessions, the participants stated that the HMD enabled  
624 an enhanced level of understanding and perception of the space and of design problems which they could not  
625 experience using other media. Our study thus reinforces the argument that multiple design spaces are, indeed,  
626 needed in order to foster a collaborative and creative design environment (Arias et al. 2000; Fisher et al. 2005).  
627 What was also recognized in this study was that this new type of collaborative design system based process  
628 provided almost immediate feedback and change on the design through supporting interactive and dynamic  
629 collaborative editing of the design work in comparison to static traditional design reviews. The architect and the  
630 project manager explained that the traditional process often entails long cycles (e.g. weeks) between new proposals  
631 and feedback from the end-users. As can be seen from the results, workshop 2 was a collaborative and creative  
632 process where the participants managed to re-design the operation theaters and the preparation room to fit the  
633 demands of the overall building design in less than 4 hours. It could be argued that this type of collaborative  
634 design systems and process could achieve a better and more time- and cost-effective design process compared to  
635 traditional, dialogue-based design workshops as it encouraged users to solve design tasks more effectively  
636 together. In this context, the design management processes are often pressured to reduce lead-time and costs, and  
637 to minimize defects and design errors, increase client satisfaction and quality of the new facility (Elf et al. 2015;  
638 Lindahl and Ryd 2007). The early stage of the design process is also categorized as a process of gather important  
639 end-user feedback regarding the design and its requirements and in this context exist a lot of changes, conflicts,  
640 and multiple stakeholders (Arias et al. 2000; Heldal and Roupé 2012). However, as our result show, as all the  
641 involved stakeholders participated, communicated, shared tacit knowledge and collaborated with each other, it  
642 could be argued that this type of collaborative design system and process may enhance the quality of design  
643 compared to traditional design processes. It could therefore be argued that the presented collaborative design  
644 systems and process could facilitate and provide a more efficient design management process in the early design  
645 stage of a building. The design problems grows out of the shared understanding that emerges as different  
646 stakeholders begin to better understand each other's perspectives (Arias et al. 2000; Fisher et al. 2005).

647 A limitation of the study is that it was conducted on the setting of designing a high-tech healthcare facilities  
648 e.g. new robot operation theater. The complex nature of such healthcare environment might have had a positive  
649 effect on the results in comparison to less complex facilities such as ordinary healthcare facilities or schools or  
650 offices. In this operation theaters context, the operating nurses have the habit to work together standing around  
651 the operating table for hours. The similarity of this setting with the multi-touch table might have affected the  
652 results of this study. Another limitation is that the study was conducted in a Swedish setting, where the culture is  
653 to perform dialogue-based workshops and come to consensus when it comes to group decision-making. How did  
654 the Swedish setting influence the outcome of the workshop and the results of this study? These issues would be  
655 interesting to be explored in the future using different design settings.

656 For future work it would be interesting to evaluate some of the suggestions given by the participants, such as  
657 collision detection among components and color-coding the different equipment according to professional  
658 disciplines to better illustrate different responsibilities. Additionally, more usability evaluation of these new  
659 emerging technologies and systems would be interesting to explore how they may support new ways of working  
660 and how such co-design workshops may improve the design process. Furthermore, seamless integration of BIM-  
661 systems would be a natural extension of the system, e.g. trace changes and update the BIM automatically similar  
662 to Du et. al. (2018a;b). This would then also make the system support other project types, e.g. schools, urban  
663 environments, construction sites. Moreover, the virtual models can function as a platform to engage medical and  
664 operational staff in facility co-design. By doing so, digital tools become enablers for evidence-based design  
665 outcomes that optimize healthcare facilities to the benefit of patients, staff and visitors alike. This could also  
666 facilitate and create a very powerful database and tool for continual development of the facility as well as enabling  
667 sharing of concepts and solutions to other projects. If connected to an open database, this could also be part of a  
668 larger knowledge-based system, where technologies such as machine learning and recommendation systems can  
669 support the users during the workshop. This could eventually be used as a feedback loop to the Swedish County  
670 Council standard, Program of Technical standard (PTS), as it would capture knowledge from new design solutions  
671 based on different developments of hospitals facilities.

672 For future work, it would be interesting to evaluate and explore Snowdon et al.' and Fisher et. al.' models (Arias  
673 et al. 2000; Churchill and Snowdon 1998; Fisher et al. 2005; Snowdon et al. 2001) in other specific combinations  
674 of technologies – such as where users are co-located or distributed-located, using different technologies such as  
675 VR-HMD and multi-touch tables and to explore whether there are optimum systems for multi-users interaction.  
676 Is the collaborative design around the multi-touch table that important or could collaborative design using VR-

677 HMD be enough, or could a distributed-located collaborative design systems support tacit knowledge sharing  
678 from experts from different parts of the country/countries or from different hospitals? It would also be interesting  
679 to explore how machine learning based recommendation systems could be implemented to support the  
680 collaborative design system in a social creative way. Exploring in more depth the effect of other social contexts,  
681 such as building on the work of others and the power distribution between users of the system is another interesting  
682 avenue for future research.

## 683 **6 Conclusions**

684 The results show that the ViCoDE system and the collaborative design activities, using the multi-touch table  
685 and VR-system complement each other very well by facilitating better understanding, participation,  
686 communication, knowledge sharing and collaboration among the different stakeholders. For instance, multi-touch  
687 table enabled the users to be actively engaged in the development of the design in a dynamic and interactive way  
688 and supported knowledge sharing, negotiation and face-to-face communication and gestures, while the users had  
689 problem when came to understanding the 2D and creating spatial-understanding of the design. However, VR gave  
690 better understanding of the space and how operating theater would actually function and individual activities in  
691 VR gave input to multi-touch users of how the operating theater would actually function and work in reality. By  
692 supporting seamless integration of the multi-touch table and VR-system it was recognized that they complement  
693 each other very well by facilitating different design spaces – both collaborative, as well as individual. It could be  
694 concluded that the ViCoDE supports the aims stated according to Snowdon et. al. ( 1998; 2001) and Fischers et.  
695 al. (2000; 2005), and that these aims had a positive outcome and enabled co-creation of design in a real-life  
696 context.

697  
698 Furthermore, the real-life design case shows that collaborative design systems and activities could achieve a  
699 better and more time- and cost-effective design process compared to traditional (e.g. 4 hours vs. weeks), as  
700 traditional process often entails long cycles between new proposals and feedback from the end-users. The  
701 collaborative design systems and activities also encouraged users to solve design tasks more effectively together  
702 by communication, knowledge sharing and negotiation in a creative environment, which reduces conflicts of  
703 interest. Also, the design and problem grow out of the shared understanding that emerges as different stakeholders  
704 begin to better understand each other's perspectives, which could facilitate and provide a more efficient design  
705 management process together with end-users. To conclude, the contribution of this study is two folded:  
706 presentation of new a collaborative design system and the evaluation of the use of it in a real-life design context,

707 which demonstrate how these new technology-based workshops is conducted. By assessing both technical and  
 708 social factors around the use of this technology in a real-life context, these results contribute to the body of  
 709 knowledge on how these new types of collaborative design systems and collaborative design workshops could  
 710 facilitate the design management process.

## 711 **7 Data Availability Statement**

712 Some raw data used in this study were collected during video recording of workshops. This data is sensitive to  
 713 sharing without the approval from the participants in this study and could be provided with restrictions from the  
 714 corresponding author by request.

715

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