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Virtual Collaborative Design Environment (ViCoDE): supporting seamless integration of multi-touch table and immersive VR

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

Keywords: Virtual Reality, Collaborative Design, Collaborative Virtual Environments, CSCW.

1   Introduction

When designing new healthcare environments and hospitals, many different stakeholders and specialists from healthcare and construction are involved with different experiences, knowledge levels and ability to interpret information. In these design processes there are also pressures to reduce lead-time and costs, and to minimize defects and design errors, to finally increase client satisfaction and quality of the new facility (Elf et al. 2015; 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 realcontext, 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 agued 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
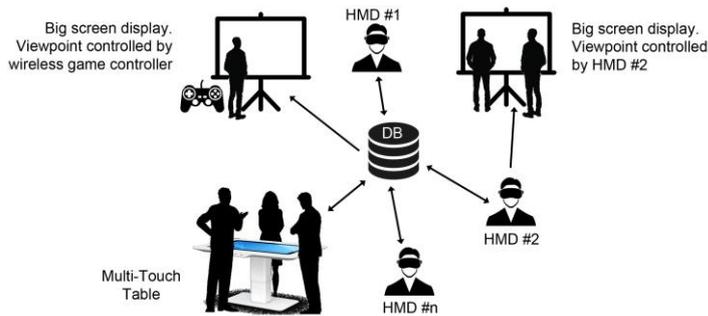
Fig. 1. *The collaborative design system supports seamless integration of multiple viewer and interaction clients through a database/server.*

2   The system

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

2.1   Multi-touch table and big screen display

The layout of the multi-touch table is shown in Fig. 2. It represents the top view of the operating theatre and supports the typical multi-touch pan and zoom features used in most Smart-phones. To better illustrate the scale, 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.
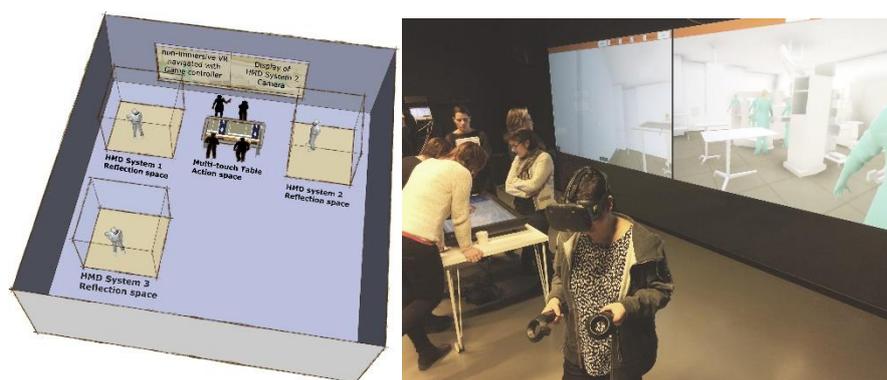
260

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

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
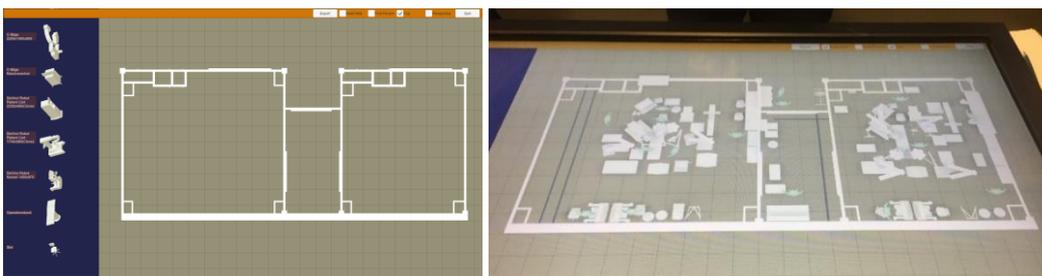
286   **Fig. 5.** *Left image:* The initial BIM layout of walls for the proposed operating theatre design from the architect. ***Right***

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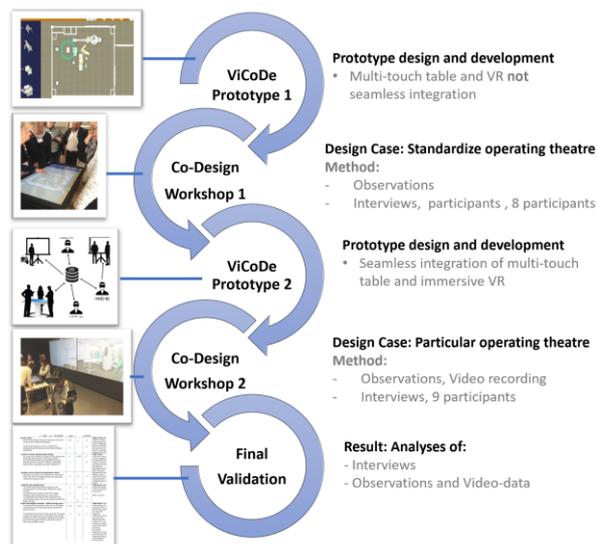
297
298 **Fig. 6.** *A simplified graphic illustrating of design science research process of this study.*

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 where 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.

4 Results

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

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

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

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

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

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

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

478

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.

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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