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How Could Virtual Reality Facilitate AEC Team Collaboration?

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HOW COULD VIRTUAL REALITY FACILITATE AEC TEAM COLLABORATION?

ABSTRACT

The new emerging technologies present questions regarding how new technology tools can support multidisciplinary team collaboration in the Architecture, Engineering, and Construction (AEC) industry. Building Information Modeling (BIM) is a powerful technology currently practiced in the AEC industry for collaboration. BIM has some limitations in terms of the ways AEC project stakeholders interact with design visualizations. In the current method of collaboration with BIM, the participation of all team members are limited since the 3D model is presented on a 2D shared screen while one person has the control over the viewpoint. Virtual Reality (VR) is a new technology that provides an environment which enables participants to have their own point of view while collaborating online with other team members using collaboration built-in tools in a more realistic representation of the building and simulated walkthrough of the project. AEC project team members have in-depth knowledge in their expertise, but they share a part of their knowledge understandable by other team members to collaborate and make a decision. This phenomenon is referred to as Shared Understanding. This paper shares the findings of a research study on how Shared Understanding is built in AEC industry practices using current technology tools. The results of this study lead to building the theory on how VR could facilitate building Shared Understanding by addressing the gaps in current technology tools that prevent teams from collaborating efficiently.

KEYWORDS

Team Collaboration, Shared Understanding, Virtual Reality, Building Information Modelling

INTRODUCTION

Construction projects require coordination of different Architecture, Engineering, and Construction (AEC) disciplines. Designers and builders need to exchange disciplinary knowledge while they vet design alternatives during different phases of the project. Project team members have in-depth knowledge in their expertise, but they share a part of their knowledge understandable by other team members in explaining design ideas, disciplinary constraints, and technical analysis to collaborate, find solutions, and make decisions. Team members need to come to a mutual understanding of disciplinary technical works, referred to as Shared Understanding, to make a team decision. Shared Understanding is studied in Psychology and researchers from other disciplines adapt the psychological research methods to their discipline. In this research project, the most common research methods in Psychology are reviewed, and three methods are selected to study how Shared Understanding is built in AEC industry practices using current technology tools and what challenges they face in communicating their disciplinary technical work.

One of the technologies AEC teams use for multidisciplinary collaboration is Building Information Modeling (BIM). BIM is a “digital representation of physical and functional characteristics of a facility." This technology is used by AEC project stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information to support and reflect the roles of that stakeholder (NIBS, 2008). BIM supports communication, documentation, data exchange, and data management (Ku et al., 2008). BIM tools have a clear definition, shared environments, and prescribed boundaries as team communication need to be based on shared rules and understanding (Dossick and Neff, 2011). The design issues that are reviewed in the BIM-based collaboration are categorized as geometrical issues which include special, clearance, and physical problems, and non-geometrical issues including systematic design error, missing information and inquiry (Mehrbod et al., 2015). The observed challenges in BIM-based design coordination due to BIM tool capabilities are (1) Inefficient transitions between artifacts which takes several minutes for transition and finding the required view, (2) Lack of easy to use basic BIM navigation that prevents the participants from navigating fast-paced in the meetings, and (3) Inadequate BIM coordination task capabilities since not all BIM tools have the same capabilities and require the team to transition between tools (Mehrbod et al., 2017). BIM tools support problem definition, but they do not support the dialogues between team members to brainstorm and create shared knowledge to resolve the problem and make a decision. It is observed that team members draw sketches, create markups on models and plans and discuss design options to come to a resolution for the problem (Dossick and Neff, 2011).

Virtual Reality (VR) is a new technology that simulates the reality human beings experience in the real world. It is a computer-aided technology that gives the user an illusion of being in a virtual world. While BIM displays the 3D model on a 2D screen, VR has the capability to enable the user to be immersed inside the environment. VR has a more realistic representation of the model and can provide a simulated walkthrough of the project. Research studies in the AEC industry on VR started back in times where VR was presented as projected photos and videos on large curved and cubic screens. Most of the research studies were focused on the user experience, and not on multidisciplinary team collaboration (Maldovan et al. 2006 & Westerdahl et al., 2006 & Wahlstrom et al., 2010 & Du et al., 2018). In an experiment, team collaboration in CyberGrid, a virtual workspace for globally distributed AEC teams which enables the team members to see each other as avatars in the model and collaboration office space, was compared to BIM-based collaboration where only one team member was able to share the desktop screen at a time using Sococo. Teams collaborating in CyberGrid had more Mutual Discovery of the model problems in comparison to teams using Sococo since the avatar was allowing each team member to control their own viewpoint in CyberGrid. This is while in Sococo, all team members were forced to look at one shared viewpoint (Dossick et al., 2014). The research team did not find any prior studies on the multidisciplinary team collaboration with current VR tools which enables the user to walk inside the model as a first person, collaborate with other team members online, and use built-in features like annotation capabilities in the fully immersive environment. The lack of prior research studies motivated the research team to conduct this research study.

In this project, interviews with AEC professionals and observational studies of two construction projects are conducted to understand how team members with different technical backgrounds collaborate to build Shared Understanding and what challenges they face in communicating their technical work to other project team members using current technology tools. The research results reveal the main factors important for building Shared Understanding among AEC team members and the limitations of current technology tools. The research results lead to building a theory on how VR features could support building Shared Understanding by addressing the gaps in current technology tools which could result in more efficient team collaboration.

SHARED UNDERSTANDING LITERATURE REVIEW

The term 'Shared' in Shared Understanding could have different aspects such as "similarity, agreement, convergence, compatibility, commonality, consensus, consistency, and overlap" (Mohammed et al., 2010). Two different interpretations of the term 'shared' can be found in the literature, shared as the joint possession of some resources versus the division of a resource between multiple recipients. The first definition is related to the meaning that is interpreted in Shared Understanding, while the second refers to the distribution of tasks or knowledge among different people (Smart et al., 2009). The term 'Understanding' is the ability to exploit bodies of knowledge to accomplish cognitive and behavioral goals (Smart et al., 2009). Teams with higher levels of Shared Understanding have greater team expectations that influence effective team behaviors (Rouse et al., 1992). Team members represent the understanding of their environment in the form of Mental Models (Langan-Fox et al., 2000). Mental Models are organized knowledge structures that let each team member interact with their environment, and helps to predict and explain the environmental behaviors or understand the relationship between different components (Rouse and Morris, 1985). Shared Mental Model and Shared Understanding are used interchangeably in the literature. To study Shared Understanding, Mental Model of each team member need to be elicited first. The shared concepts and links among the team members' Mental Model structures represent Shared Mental Model (Johnson and O'Connor, 2008). Mental Model elicitation methods capture the research-related concepts and the relationship between them in the individual Mental Model. The common Mental Model elicitation methods used in Psychology are as followed.

Cognitive Interviewing: This method can be conducted in three formats of (1) Open Forum, (2) Question-Answer, and (3) Inferential Flow Analysis. In the open forum format, team members are engaged in an open conversation. In the question-answer format, team members provide casual explanations about their domain of expertise. Finally, in the inferential flow analysis format, team members are asked to explain the relationship between the concepts in their expertise. Use of this method is recommended with caution since this method is heavily dependent on the researcher's interpretation of the participants' answers (Langan-Fox et al., 2000).

Content Analysis: In this method, formal written or verbal statements are analyzed to extract the critical concepts and their relationships. It is mostly used where the individuals are not available for an interview (Langan-Fox et al., 2000).

Qualitative: In this method, data is collected at the team level by observing the team interactions. Participants determine the concepts in their own terminologies and the gathered data is reach and non-disrupted by the researcher (Mehmet et al., 2010).

Questionnaire: In this method, the researcher selects the concepts and creates different statements with regards to these concepts. The team members are then asked to rate the statements on a Likert-type scale which is usually from "strongly agree" to "strongly disagree." Since the researcher selects the concepts, the results of this method can be influenced by the researcher (Langan-Fox et al., 2000). This method does not ask for knowledge content directly and mostly captures the individuals' perception of their work. As a result, some researchers like Mehmet et al. (2010) question the validity of this method.

Verbal Protocol Analysis: The researcher observes the participant interacting with a system while thinking aloud. The sessions are recorded and the researcher can extract the concepts and their relationships. This method is highly valid for tasks that the researcher is not familiar with but the researcher may not have access to all the cognitive structure that underlies the participant behavior (Langan-Fox et al., 2000).

There are also two other methods that use cards to elicit Mental Models. In these methods, concepts are either selected by the participant or the researcher. Then, these concepts are written on cards. In the *Card Sorting* method, the participant is asked to sort the concepts based on their relationship and explain the reason. In the *Concept Mapping* method, the participant determines the concepts that influence others both positively and negatively (Langan-Fox et al., 2000 & Mehmet et al., 2010).

During team collaboration, team members exchange disciplinary knowledge. Team members may use Explicit communication like using text, spoken language, media like image and video or Implicit communication like body language (Eccles & Tenenbaum, 2004). With each interaction and receipt of new knowledge, individual Mental Model and as a result Shared Understanding changes. Shared Understanding can be studies across the team and across the time during team collaboration (Johnson and O'Connor, 2008).

RESEARCH METHODOLOGY

Among the Mental Model elicitation methods, three methods of Cognitive Interview, Qualitative, and Content Analysis were selected to study how Shared Understanding is built in current AEC industry practices. Verbal Protocol Analysis was also used during the interviews where the interview was conducted at the interviewee's office. The Questionnaires method was not suitable for the purpose of this project, but it would be a practical tool to be used in experiments. The research team also did not find the Card Sorting and Concept Mapping methods an appropriate and efficient way of data collection and analysis, since these methods require training of the participants and have a time-consuming process. Considering AEC professionals are very busy individuals and there are various concepts related to their specific expertise which may not be of the research interest, these methods were not used.

DATA COLLECTION

To elicit Mental Models using Cognitive Interview method, the question-answer format was selected. The questions were designed to be open-ended to let the interviewees define the concepts and their relationships with their own technical terms without the interference of the researcher. Interviewees were asked to talk about the challenges they face in understanding the technical information provided by other team members from different disciplines, and the challenges they have in preparing their technical work understandable by other team members. The interviewees were also asked to explain and show how they use technology in this interdisciplinary collaboration process and the challenges they face. In this research project, interviews with seventeen AEC professionals with different architecture, engineering and construction management backgrounds were conducted. One Architect and two Owner Representatives, one interviewee with an architecture background and the other with a construction management background were interviewed. From engineering disciplines, interviews with two Mechanical Engineers, one interviewee with specialties in Energy Modeling and HVAC design and the other with specialties in piping design, a Structural Engineer, an Electrical Engineer, and an Acoustic Engineer were conducted. A Construction Project Manager, an MEP Coordinator, an Electrical Trade Project Manager, a Mechanical Trade Project Manager were interviewed from the Construction industry. Two interviews were also conducted with an Operations Program Manager and a Commissioning Agent.

The observational studies of two medical projects were also performed to use Qualitative method to study Shared Understanding. One project with Progressive Design-Build delivery method was observed in the early design phase when the team members were setting goals for team collaboration. Another project with Integrated Project Delivery method and BIM-based collaboration was observed for six months during the construction phase. The project documents of the second project were reviewed, and two hundred Construction Dispute Resolution (CDR) documents were analyzed using content analysis method.

RESULTS

The data collected from the interviews, observational studies, and content analysis resulted in understanding how AEC professionals collaborate with each other and build Shared Understanding by exchanging their disciplinary knowledge concepts and the reasoning for linking these concepts. The results are summarized as followed.

CONCEPTS AND THEIR RELATIONSHIPS

If a construction project is considered as a puzzle, each discipline provides one piece of the puzzle. While each of these pieces is unique, they are correlated to other pieces and need to be selected wisely so that their edges match the surrounding pieces to fit. AEC professionals perform their disciplinary jobs, but the decisions they make affect other disciplines and vice versa. They need to collaborate with each other to exchange their disciplinary requirements and provide reasoning for their requests from other team members. The Architect works closely with the owner to design the building based on the architectural standards and regulation that meets the owner goals. The Engineers design systems based on their engineering standards, codes and regulations. For example, the Structural Engineers design the structural system based on the building static and dynamic loads, the Mechanical Engineers design the HVAC system based on the occupancy and building envelope information to keep the building cool in summer and warm in winter and provide fresh air circulation for the occupants. The contractors perform cost analysis, scheduling, constructability reviews, and then fabricate and build the project.

This research study revealed that the Engineers have the most challenges among other disciplines in explaining their technical work to others since it requires other team members to have an engineering background. Engineers provide very simplified reasoning using common terms to make it understandable by other team members. For example, a Structural Engineer may state that if the team does not accept placing additional beams at the building entrance, the structural system will fail due to high shear force induced from the high weight equipment added to the space above the building entrance at the upper floor. The team usually accepts the reasoning provided by engineers without questioning it since they may not have enough engineering background. The main challenge occurs when the Engineer's decision causes a high impact on the schedule or the project cost. In this case, the Owner may hire a consultant or ask the Commissioning Agent to attend the discussion with the Engineer. Large facility owners may have their own internal engineers which makes building Shared Understanding much easier for the team by attending the meetings and collaborating with project consultants. Contractors also have challenges in explaining their disciplinary work as their knowledge is backed by experience. Sometimes it is challenging for the Contractor to convince other project team members to rely on the Contractor’s experience on topics like MEP system selection by the Engineer, constructability and scheduling. The Architects seem to have fewer challenges in communicating their work to other team members in comparison to other disciplines. They mostly refer to their architectural standards and regulations.

KNOWLEDGE EXCHANGE

Team members exchange disciplinary knowledge to collaborate and build Shared Understanding. The results of the research study with regards to knowledge exchange are summarized into four categories of (1) Exchange knowledge format, (2) Exchange Knowledge Content, (3) Knowledge exchanging process, and (4) Technology tools used to exchange knowledge as followed.

Exchanged Knowledge Format

The technical knowledge exchanged between the AEC team members can be categorized into two formats: Data and Visuals. Documents like project specification, schedules, cost estimation, and Operations and Maintenance (O&M) manuals fall under the Data category. Documents like 2D plans, 3D models, sketches, photos, videos, and graphs fall under Visuals category. The study results revealed that visualization has a significant role in building Shared Understanding. Team members try to use visualization to make their technical work understandable by other team members. As discussed before, Engineers have the most challenges in explaining their technical work. They typically do not share their engineering analysis with team members. They show the results of their technical work as 2D plans and 3D models along with notes to the contractors regarding the construction. Engineering consultants need to exchange technical information to other Engineers to perform their job. In this case, they also try to use visualization to prepare their work. For instance, Structural Engineers show the results of their shear forces analysis as graphs. Geotechnical Engineers show the settlement of the soil by creating contouring maps.

Mechanical Engineers create graphs of the system performance. Acoustic Engineer makes an animation of the vibration transfers in the building. Contractors use visualization to communicate their work to other team members, too. While Contractors have been using 2D plans to coordinate subcontractors, they have started using 3D models more frequently for this purpose since it creates a better understanding of the subcontractors' scope of work and BIM tools help them with understanding the system conflicts. Using 3D models help them with constructability analysis and communicating them to the team. The Contractors also create the animation of the construction sequencing which helps with explaining the schedule and activity impacts to the team. In the analyzed CDRs, whenever 2D plans are not capable of explaining the problem, a screenshot of the 3D model is provided for better visualization and understanding of the issue like showing the gaps. With regards to Owner’s operations and maintenance documents, written O&M manuals are most recently being replaced by visually searchable documents and training videos.

Exchanged Knowledge Content

AEC team members are dependent on the information they receive from other team members to perform their technical job. Each discipline sends the information required by other team members and receives information from other disciplines to perform their technical job. Professionals have set standards for the project documents to ease the information exchange process and document them from a legal standpoint. They publish documents like drawings, project specifications, Request for Information (RFI) in a standard format practiced in the industry. However, team members cannot wait for each discipline to finish their part and send the information in the formal format to them. They need to know of potential design options or anticipated outcomes to base their technical work on. This requires the team members to collaborate actively and exchange information throughout different phases of the project. For instance, the Structural Engineer asks the Architect to provide the schematic design options to do the preliminary study of the structural system options. The Structural Engineer also asks the Geotechnical Engineer to provide an estimated range of soil settlement before they finish their settlement calculation to let the Structural Engineer start analyzing the structure and have a better understanding of which structural systems should be considered. If the project has an integrated project delivery method, the Contractor would be able to estimate the cost of structural options and check if they may fit into the project budget.

Knowledge Exchanging Process

In the AEC team collaboration process, one team member with a specific discipline presents one or multiple design options to the team. Other disciplines then need to confirm if the design option/options would work for them. Team members start to exchange knowledge and information regarding the outcome of their technical work based on the suggested design option. If the suggested options do not work for a discipline, another option is suggested to the team. Team members continue exchanging knowledge and suggesting new design options until they find a design option that works for all disciplines and meets the project goals. Team members prefer to have everyone present during the collaboration. The absence of one team member could result in collaboration inefficiency since the present team members make assumptions about what information the absent party might need to know to perform the job, or what information the present participants need to know from the absent team member. Moreover, present participants may not realize the impact of their decision on the absent team member's scope of work. For instance, in the elevator selection process, multiple disciplines are involved, and they work with each other to finalize the elevator type that needs to be installed. The Architect specifies the number of elevators, the location of them, and their access to different building spaces. The Structural Engineer designs the foundation and the structure based on the specific elevator type. The Geotechnical Engineer provides soils report to the Structural Engineer to support designing the foundation. The Electrical Engineer provides the information for the elevator electrical needs, and the Contractor estimates the elevator and structural system cost and construction duration and checks the elevator availability in the market and constructability issues. All these disciplines work together to specify the elevator type that fits the project goals like budget and O&M cost.

Technology Tools Used to Exchange Knowledge

As stated previously team members need to exchange informal information throughout the project to perform their job and vet design options. After they come to a resolution and make a decision, they document the design option in a formal format like issuing drawings and RFIs. For informal knowledge exchange, the one-way communication methods like text messages and emails are the least preferred method since these methods do not assure the information sender that the receiver has read it and fully understood it. As a result, phone calls are more preferred especially in the one by one communication. The voice allows the information sender to guess from the voice tone if the receiver has fully understood the technical information. The video conferencing communication method is more preferred over teleconferecing since the facial expression and partial body language captured in the video assist in determining if all team members fully understood the shared knowledge. Face to face meetings are the most preferred method since team members can see both the facial expressions and body language, and it also helps them to collaborate in the same space, draw and sketch together. While in video conferencing they share their screen with other team members with limited simultaneous collaboration options.

The results of the observational studies on the BIM-based collaboration project show that when a team member who does not have the control over the model view talks about a solution or an explanation of a problem, the team member who has the control tries to use the mouse to point out to part of the model that the speaker is discussing. In the face to face meetings, the speaker may ask to have the control of the mouse or walk to the screen to explain the problem by pointing out to the screen using the hand. The speaker may also show structure parts with hands to make the issue understandable by others. In online meetings, only one team member can share a screen, have the control over the view and markup the model. Other team members are no more capable of pointing out to the model using body language or using the pointer to change the view which creates some collaboration challenges. In one of the MEP coordination meetings in the observational study, a Subcontractor was attending the meeting remotely. The subcontractor was trying to explain the location of the problem in the model by guiding the BIM Manager verbally. After spending some time explaining the problem, the subcontractor failed to bring all team members attending the meeting to the same page, and he decided to markup the model and send it to the team after the meeting.

CONCLUSION: BUILDING THE THEORY

The research study results have revealed the factors important for building Shared Understanding, and the limitations in current technology tools that prevent teams from collaborating effectively. Visualization has a significant role in building Shared Understanding. VR has a more realistic representation of the 3D models and enables the users to be fully immersed in the environment. This is while teams collaborating with BIM see 3D models on 2D shared screen. Implicit communication like body language is another important factor in building Shared Understanding. VR can capture voice, and the avatars in VR could capture partial body language. Project team members need to be present during team collaboration to build Shared Understanding while team members exchange disciplinary knowledge. VR is capable of enabling the team members to meet virtually online which could reduce the co-location expenses and enables more team members to attend the virtual meetings. This could reduce the rework due to wrong assumptions made for the absent participant’s scope of work. Since team members meet virtually in the same environment, the team collaboration could happen in the same virtual space inside the digital model while in BIM-base collaboration the collaboration environment is separated from the 2D representation of the 3D model which causes limitation for team collaboration. In VR, each team member has a pointer tool. The pointer tools enable the users to point out to objects far from the avatar arm reach. VR is capable of enabling team members to draw and mark up the models together during virtual team collaboration while in BIM-based meetings only one person has the pointer and is capable of marking up the model. Moreover, VR enables the team members to have individual viewpoints during collaboration while in BIM-based collaboration only one person has the control over the viewpoint and all team members are forced to look at the shared viewpoint. By comparing VR features with current technology tool capabilities, a theory can be built that VR could facilitate building Shared Understanding and save the extra time team members have to spend to communicate their technical work to others.

FUTURE STUDIES

This research study revealed the VR features that could facilitate building Shared Understanding and result in more efficient team collaboration. For future studies, experiments need to be designed to study each VR feature and its influence on building Shared Understanding. For this purpose, the Questionnaires and Qualitative Mental Model elicitation methods are recommended. The Questionnaires method would be suitable to be used in controlled experiments where the researcher can select the concepts based on the dependent variable and capture its relationship to the independent variables. Providing open questions in the Questionnaires would let the participants explain the relationship between the variables with their own words. Using Likert-type scale is recommended with caution since the researcher could influence the results by predefining the concepts and it only captures the participants’ perception of the concept relationships instead of direct knowledge structure.

Qualitative method is highly recommended for recording the team interactions and capturing Shared Mental Model across the time as team members collaborate and exchange knowledge.

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