Virtual Reality Design Quality-Check Tool for Engineering Projects

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Abstract
The recent adoption of Virtual Reality (VR) interfaces linked with Building Information Modeling (BIM) has appeared as a means to support the participation of professionals with extensive experience when operating in BIM-based work environments, regardless of their practical BIM-modelling skills. As such, this paper aims to verify the existence of a significant difference between the number of design/modelling errors recognized when complementing the use of conventional systems (i.e., BIM tools) with immersive VR environments.
The study employed a quantitative comparative approach, and statistical analysis was conducted through a non-parametric test, Wilcoxon Signed Rank Test.
Results show that the number of modeling errors detected after the test of the two interfaces (time factor) was statistically significant. Also, it was possible to conclude the existence of statistical evidence in the identification of a greater number of modeling errors when participants first tested the BIM authoring tool and then the VR interface.

Keywords: Building Information Modeling, Virtual Reality, Quality-check, Usability, Wilcoxon Signed Rank Test

1 Introduction

Despite the recognized reluctance among the agents of the Architecture, Engineering, Construction and Operations (AECO) sector regarding the acceptance of new technologies and innovations (Ning Gu & London, 2010), largely due to the fragmented nature of the industry (Johnson & Laepple, 2003), the trend towards digitization is a phenomenon that is transversal to most sectors of industrial activity. In fact, in recent years, the AECO sector has been gradually adapting to Information Technologies (IT), showing favourable results in areas such as maintenance (Costa et al., 2015), projects information management (Gheisari & Irizarry, 2016);

decision making and revision process (van den Berg et al., 2017; Du, Zhengbo, et al., 2017; Dunston et al., 2011); training of work teams, safety and quality (Azhar, 2017; Lee et al., 2014; Sacks et al., 2015); among many others.

The implementation of IT has fostered rather disruptive changes in how the AECO sector operates by contrast with more traditional methods. For instance, the adoption of the Building Information Modeling (BIM) methodology drives the sector towards a more digital and integrated approach to the life cycle of construction projects. Additionally, initiatives carried out by public authorities and government bodies foster and specify requirements for BIM use in public procurement (Ghaffarianhoseini et al., 2017; Smith, 2014). However, BIM adoption rate has been realized slower than initially anticipated (Alreshidi et al., 2017; Howard et al., 2017; Walasek & Barszcz, 2017), possibly reflecting the current lack of awareness of the advantages and clarification of the responsibilities of each stakeholder (Ning Gu & London, 2010); significant investment in training, formation as well as software and hardware requirements (Ghaffarianhoseini et al., 2017; Plesner & Horst, 2013) (Liu et al., 2015); lack of confidence, motivation, know-how and difference in skills towards BIM (Alreshidi et al., 2017; Walasek & Barszcz, 2017) as well as the reported steep learning curve of some of the tools (Olawumi et al., 2018). Hence, the need for adaptations and more supportive technologies emerges as a way to improve collaboration and inclusiveness amongst all parties. As advocated by Kerosuo et al. (Kerosuo et al., 2015), there is a demand for developments able to leverage BIM towards a more flexible range of technologies, more focused on the people and their tasks within construction projects, therefore, boosting the technology acceptance by all teams and stakeholders.

In recent years, scientific research on VR applications to the AECO sector has been showing positive results in the various phases, processes, and tasks of a construction project. Several examples can be seen in areas such as real-time interaction with BIM modeling tools, namely at the level of Design (Dinis and Poças Martins, 2016; Du et al., 2018); Design review, Maintenance and Communication (Du, Shi, et al., 2017; Dunston et al., 2011; Yangming Shi et al., 2016); Acoustic Comfort (Iachini et al., 2012); Safety(Azhar, 2017; Sacks et al., 2013); Engineering Education (Dinis, Martins, et al., 2018b; Messner et al., 2003). Nevertheless, given the diversity of VR interfaces developed, the difference between the methodologies used to validate the potential benefits of this technology becomes increasingly evident. No case was found in the literature regarding a holistic methodology that allows the validation of VR interfaces in the AECO sector. However, it is imperative to stress the work of some authors in the field of usability assessment methodologies (Dinis, Martins, et al., 2018b; Paes & Irizarry, 2018).

This paper will focus on the role of BIM-based immersive VR environments developed for applications in the AECO sector as well as the evaluation process of one of the components of usability, efficacy ("ISO 9241-11 Ergonomics of human-system interaction — Part 11: Usability: Definitions and concepts", 2018), in the particular case of recognizing modeling errors in construction projects using different technologies. In detail, comparative tests were performed in order to answer the question: "Is there a significant difference between the number of design/modeling errors recognized when complementing the use of conventional systems (i.e., BIM authoring tools) with immersive VR environments?". The methodology, test plan and results of a case study are presented in later chapters. In particular, the methodology and procedure used are presented in Chapter 2. Data analysis and results of the case study are described in Chapter 3. Chapter 4 presents the conclusions and recommendations for future work.

2 Methodology

2.1 Test Plan

In order to assess the usability of a system (or interface), it is necessary to refer to the domains to be evaluated and their respective adaptations to a particular case study. For the purposes of this article, some of the principles and methodologies used in usability evaluations will be considered. Moreover, assessing usability as a composite concept ought to comprise balancing the weight of the different domains that compose it, as in a summative evaluation.

ISO 9241-11 ("ISO 9241-11 Ergonomics of human-system interaction — Part 11: Usability: Definitions and concepts", 2018) states that usability is a concept composed of several domains: effectiveness, efficiency, and satisfaction. On the other hand, several authors propose additional aspects to define this concept (Abran et al., 2003; Dix et al., 2004; Jakob Nielsen, 1993), making it difficult to obtain a unanimous definition. However, for the immediate effects of this study, only the efficacy domain will be gauged. Additionally, Nielsen (Jakob Nielsen, 1993) states that a test plan should be developed in advance to conduct a usability assessment.

Table 1 includes 14 of the main 16 issues that a test plan should include as recommended by the author. The remaining 2 items were not considered in this assessment because they relate to the response time of the systems/network and the criterion for affirming the success of the interface related to previously set usability goals.

Table 1. Test Plan

Item	Description
1) Test goal: What do you want to achieve?	Determine if there is a significant difference between the number of design/modeling errors perceived through more conventional solutions (i.e., BIM authoring tools) and immersive VR environments
2) When and where will the test take place?	Tests will be carried out during the period of one week These will take place in a Higher Education institution.
3) What is the expected duration for each test session?	Each session will have a maximum estimated duration of 35 minutes.
4) What kind of computer support will be needed?	HTC Vive Head Mounted Display (HMD) and Desktop computer that complies with the minimum requirements for the HMD and for the Game Engine.
5) What software must be prepared for the test to take place?	The game and Autodesk Revit BIM modeling tool must be installed.
6) What should be the state of the system to start the test?	The system should be close to a final version since it will be gauged in comparison to a BIM authoring tool.
7) Who will the test experimenters be?	The test will be monitored by the developer (programmer).
8) Who will be the participants, and how will they be selected?	Participants will be users with an academic background in Civil Engineering and previous experience with BIM modeling tools. As such, participants with some geographical proximity or connection to the institution where the tests will be taking place will be part of the convenience sample.
9) How many participants will be needed?	14 participants will be needed.
10) What are the tasks to be done by the participants?	Participants will be asked to evaluate two interfaces where they will have to find and report modeling errors (excluding geometry overlays).
11) What criteria will be used to determine when participants will have completed each task correctly?	The identification of modeling errors may occur for a maximum of 15 minutes per interface. After this period, there will be a pause where the experimenter will communicate to the participant which modeling errors are valid. During the second interface test (15 minutes), the participant should begin by identifying the validated errors (previous

	test), as well as trying to find other possible errors until the end of the established time period. Half of the participants tested the BIM interface before the VR one. This order was reversed for the other half.
12) What kind of help will be made available to the participants (manuals, online help, etc.)?	No help will be available during the test period (15 + 15 minutes).
13) To what extent may the experimenter assist participants during the test?	Only during the pause period can the experimenter explain to the participant which of the modeling errors (previously identified in the first stage) should be considered in the second part of the test.
14) What information will be collected and how will it be analysed?	The number of modeling errors identified in each of the interfaces will be counted. Afterwards, a comparative analysis (Wilcoxon's test) will be done to gauge if there is a significant difference between the number of errors detected through more conventional solutions (i.e., BIM authoring tools) and immersive virtual environments (VR).

A case study was conducted where usability tests were subdivided into two phases, each with a maximum duration of 15 minutes. The only task was to identify the maximum number of design/modeling errors. The group was divided into two groups which tested the interfaces in a different order: i) "Path A" - 50% of the participants first tested the BIM authoring tool (non-immersive) and then the immersive VR interface; ii) "Path B" - the remaining 50% started the test with the immersive VR interface and concluded it with the BIM tool. Before the test, the experimenter stated that the participants should not consider errors related to 3D objects with overlapping geometry, as this type of error is already performed automatically by BIM authoring tools.

The present article intends to verify the existence of a significant difference in the identification of modeling errors in addition to those that would normally be recognized through automatic tools, such as geometry clashes in BIM models. Prior to the tests, two pilot evaluations were conducted to detect most of the usability errors that could be identified by experienced users that were not directly linked to the development of the system. Two participants who had previous experience in Civil Engineering and the use of VR interfaces took part in these tests. According to feedback from the evaluators, some color combinations could mislead the participants when identifying modeling errors in the VR interface. This issue was addressed by changing the colors of the objects. Additionally, and after this assessment stage, future participation of the evaluators in the case study was automatically excluded in order to avoid the presence of skewed results.

2.2 Procedure

A sample was collected in which all individuals had the following characteristics: i) academic training in areas related to the AECO sector; ii) familiarity with a BIM authoring tool (Revit). It should be noted that the test intended to ascertain possible significant differences between the results achieved by participants with prior knowledge of the use of BIM tools. Therefore, the universe of people without this set of skills and that would be able to assess the quality of the models with the use of VR tools is vastly greater.

During the test two moments (15 minutes each), participants identified modeling/design errors using different interfaces: (i) a BIM model in Revit (Figure 1) and (ii) a 3D model in an immersive VR environment (Figure 2). In order to prevent biased results, all the participants tried the VR equipment for a maximum of 5 minutes before the test so that they could familiarize themselves with the immersive environment. This training session comprised a few minutes to practice with the controllers and the HMD. The implementation of training sessions is recommended by Nielsen (Jakob Nielsen, 1993) in the sense that the tests do not reflect an eventual excessive effort from the participants still trying to get accustomed to the new interface, its commands and/or techniques.

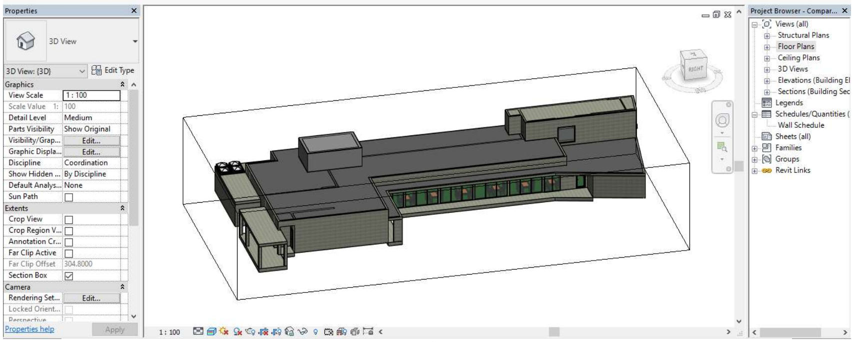

Figure 1. BIM model (Autodesk Revit) adapted from Thiago Cruz, in WIQI GEQUALTEC ("Modelo Revit FEUP Edifício Cafetaria (0) - WIQI GEQUALTEC", 2017).

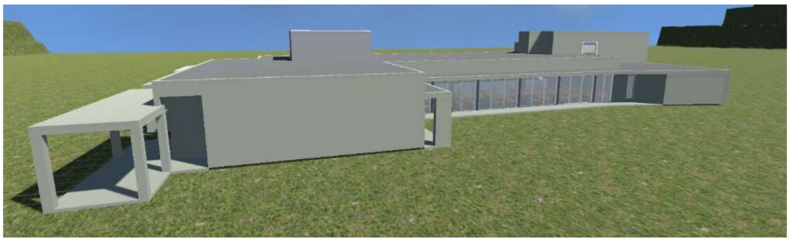

Figure 2. VR environment in Unity 3D.

3 Data analysis and results

Given the challenge in reaching a high number of participants that met the characteristics desired for the test and in order to minimize individual variability, a within-subject approach (Jakob Nielsen, 1993) was followed. Hence, the participants (N = 14) were asked to perform two evaluations (15 + 15 minutes), interspersed by a pause moment and clarification about the identified errors (5 minutes). The small size of the sample, together with the type of variable (number of modeling errors - discrete variable), restricted the statistical methodology to be applied, excluding the use of parametric tests (Montgomery and Runger, 2003). The statistical analysis of the data was conducted through a non-parametric test, Wilcoxon's test (Siegel, 1977), Wilcoxon Signed Rank Test, considering the organization of the data (paired).

Table 2 shows the data with no regard for the order of the test moments (i.e., it includes results for "Path A" and for "Path B"). The table presents the number of modeling errors found by each participant, as well as additional information related to the Wilcoxon test.

The hypotheses and other relevant considerations were as follows:

i. Null hypothesis, H0: There is no difference between the number of modeling errors found at the end of the test of the two interfaces. Alternative hypothesis, H1: There is a difference between the number of modeling errors found after testing the two interfaces.

ii. An analysis of the bilateral type and $\alpha = 0.05$ (level of significance) was considered, which is currently more commonly used in similar case studies (Alhalabi, 2016; Sacks et al., 2013).

iii. N = number of participants. To this value will be subtracted the null differences between the number of modeling errors found.

The notation of N arises to avoid possible duplication of notation as a consequence of the use of n_i in the first column of Tables 2, 3 and 4.

Table 2. Modeling errors chronologically found

n_i	1st trial (Xi)	2nd trial (Yi)	Signal	|Xi - Yi|	Ri
1	8	17	-	9	10,5
2	3	16	-	13	13
3	9	16	-	7	8,5
4	8	12	-	4	3
5	9	15	-	6	6,5
6	3	10	-	7	8,5
7	5	16	-	11	12
8	8	10	-	2	1
9	9	13	-	4	3
10	10	19	-	9	10,5
11	18	18		0	
12	5	10	-	5	5
13	17	11	+	6	6,5
14	14	10	+	4	3
					t = 9,5

Attending to the limited sample size (N = 25), Siegel's table was used (Siegel, 1977) (Table G) to find the critical T value and its associated level of significance.

Excluding cases where | Xi - Yi | = 0, it is verified that the test statistic, T - the lowest value of the sum of the stations with the same signal, does not exceed the critical value, t = 17, (value obtained by Table G, for N = 13 (Siegel, 1977) for the significance level, $\alpha = 0.05$. Thus, the null hypothesis may be rejected (H0), as there is statistical evidence that the two distributions are different. The difference in the number of modeling errors detected after the two interfaces is significant.

Table 3 and 4 take into account the testing sequence. Table 3 shows the number of modeling errors found by the participants who followed "Path A" (BIM interface to be followed by the immersive VR interface trial).

Table 3. Modeling errors found in "Path A"

n_i	BIM interface (non-immersive)	VR interface (immersive)	Signal	|Xi - Yi|	Ri
1	8	17	-	9	5
2	3	16	-	13	7
3	9	16	-	7	3,5
4	8	12	-	4	1
5	9	15	-	6	2
6	3	10	-	7	3,5
7	5	16	-	11	6
					t = 0

It was considered:

i. Null hypothesis, H0: There is no difference between the number of modeling errors found after the test of the two interfaces according to "Path A" (BIM authoring tool test followed by the VR interface). Alternative hypothesis, H1: The difference in the number of errors perceived is greater according to "Path A".

ii. An analysis of the unilateral type and $\alpha = 0.025$ was considered.

As can be seen from Table 3, the differences between the number of modeling errors always appear in the negative sense, which is natural since the participants tend to seek to confirm the occurrence of errors detected in the previous phase of the study. It can also be said that the sum of the negative stations is rather different from the sum of the positive stations (t = 0) or that the sum of the positive stations is very small (see also Siegel, 1977).

Additionally, it can be verified that T does not exceed the critical value, t = 2 (obtained through Table G, for N = 7, (Siegel, 1977)) for the associated significance level ($\alpha = 0.025$), thus allowing to reject H0. Therefore, it can be assumed that there is a significantly greater difference in the number of modeling errors detected along "Path A".

Table 4 presents the values for the errors found in both interfaces according to "Path B".

Table 4. Modeling errors found in "Path B"

n_i	VR interface (immersive)	BIM interface (non-immersive)	Signal	|Xi - Yi|	Ri
1	8	10	-	2	1
2	9	13	-	4	2,5
3	10	19	-	9	6
4	18	18		0	
5	5	10	-	5	4
6	17	11	+	6	5
7	14	10	+	4	2,5
					t = 7,5

Similarly to the previous case, the following was considered:

i. Null hypothesis, H0: There is no difference between the number of modeling errors found after the test of the two interfaces according to "Path B" (test of the VR interface followed by BIM the authoring tool). Alternative hypothesis, H1: The difference in the number of errors perceived is higher according to "Path B".

ii. A unilateral analysis and $\alpha = 0.025$ was considered.

In this particular case, the value of the sample size is 6 because there is a pair whose difference (| Xi - Yi |) is 0. Being t = 7.5 and according to the values presented in Table G (Siegel, 1977) for the case of a unilateral analysis with $\alpha = 0,025$, it is concluded that H0 should be preserved. In sum, for N = 6 and according to the observed T value being higher than the critical T (t = 0), there is no statistical evidence that the distributions are different.

4 Conclusion

Similarly to other relevant industry segments, the AECO sector is faced with more competitive and complex projects (Chan et al., 2004; Pham et al., 2017) with continuously shorter budgets and due dates, highly demanding quality assurance and monitoring needs resulting in added costs and pressures. Moreover, AECO is recognized for its low productivity (COTEC Portugal – Associação Empresarial para a Inovação, n.d.) which lead to digitalization as a way for the sector to pursue more performance and accuracy among the processes, minimizing costs and streamlining production.

The digitalization of the AECO sector has been propelled by public and governmental entities, thus verifying the need for the key players in the industry to better realize how to address new methodologies such as BIM. Initiatives have already paved the way towards BIM integration from various countries (e.g., Norway, Denmark, Finland, South Korea, Singapore, USA, and the U.K ("BIM adoption around the world: Initiatives by major nations", 2017)), a fact that has been supported by the Directive 2014/EU, Article 22, encouraging the use of BIM for public procurement. Moreover, the recent approval of an international standard for BIM, ISO 19650-1:2018 ("ISO 19650-1:2018 - Organisation and digitisation of information about buildings and civil engineering works, including building information modelling (BIM) - Information management using building information modelling -- Part 1: Concepts and principles", 2018) on project life cycle information management stirs the pervasive notion of a paradigm shift and the resulting necessity for adaptation. Notwithstanding, BIM is still not fully collaborative among all stakeholders, with the opportunity to further developments in the way of interacting, accessing and exchanging BIM data.

Research has shown that human-computer interactions may be improved through alternative approaches such as the implementation of immersive applications (Dinis et al., 2017; Meža et al., 2015). Indeed, immersive systems have been introduced to the AECO sector during the last few years, consequently causing a profusion of case studies that draw new paradigms for the industries involved. VR applications can be used to perform many activities in the AECO industry, such as supporting the design quality control of construction project models as a complement to current methods and approaches. In the particular case of BIM models, there are several commercial tools whose features are dedicated to the identification of certain types of errors in case of geometry clashes and overlays. However, as described in the present work, other types of modelling errors may be more easily recognizable through immersive interfaces as opposed to "more traditional" BIM authoring tools. Hence, this study was intended to identify, through comparative tests, the existence of a significant difference in the number of design/modelling errors detected through more conventional solutions (i.e., existing BIM authoring tools) and immersive VR environments. The results show that the number of modelling errors detected after the test of the two interfaces (time factor) was statistically significant. Regarding the paths, it was possible to conclude the existence of statistical evidence in the identification of a greater number of modelling errors when the test was established according to "Path A", that is, recognizing modelling/design issues through the BIM interface followed by the VR interface.

This study adds and contributes to the recent research interest in the comparison of VR and desktop interfaces such as the work of Paes et al.(Paes et al., 2017), Wolfartsberger (Wolfartsberger, 2019), and Horvat et al. (Horvat et al., 2019).

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