Evaluation of building use scenarios by crowd simulations and immersive virtual environments: a case study

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Abstract –

Virtual reality (VR) is becoming common in the AEC/FM industry, closely linked to BIM implementation. VR tools can be used to anticipate operational issues, simulating them in a virtual prototype since early design. The paper investigates such a topic in relation to access, space and use performance of an existing hospital facility. A case study has been developed considering a pavilion where both medical and food spaces are located, causing a clash between flows of end-users in critical time-slots. Crowd simulations and immersive virtual environments have been tested as occupancy evaluation tools. Post-occupancy evaluation (POE) data have been translated into a dynamic simulation of the existing occupancy conditions within the BIModel of the pavilion and considering various profiles of end-users. Subsequently, both the BIModel and the crowd simulation have been imported into a game engine to be visualised and experienced in a VR-headset, switching from the analysis of flows to the perspective of end-users (i.e. able-bodied users, person in a wheelchair, visually-impaired person). The use of VR enables a clear visualisation and communication of the existing conditions. Moreover, POE data translated into a dynamic simulation of the building use scenario could be applied for the pre-occupancy evaluation of internal layout reconfigurations. Finally, the combined use of crowd simulation and immersive VR enables the users to perceive crowding in the occupancy evaluation and adds the user experience as design input, representing an innovative approach that goes beyond traditional resources such as personal experience and regulations.

Keywords –

Occupancy evaluation; Virtual reality; Crowd simulation; Immersive virtual environment; Building performance

1 Introduction

The use of Virtual Reality (VR) is becoming common in the Architecture, Engineering, Construction and Facility Management (AEC/FM) industry, closely linked to the implementation of Building Information Modelling (BIM) tools and processes. VR tools (e.g. game engine, immersive virtual environment, crowd simulation) can be used with different purposes, such as visualisation, communication, analysis, design optioneering and training [1] [2] [3]. For example, they can be implemented to analyse the eventual possibility of construction and operational issues in design proposals, simulating them into a virtual prototype since early design. A virtual prototype is, in fact, a digital representation of a design proposal that can be explored, tested and evaluated before being physically realised [4] [5]. Moreover, VR can be applied to evaluate if a design proposal satisfies a performance-based requirement. For example, considering operational outcomes, a pre-occupancy simulation can be applied as evaluation method in order to simulate how the space will be used by the end-users during their activities and, at the same time, improving the understanding of the client about the design proposal [6]; in this way, the human experience is added to the project before it is built [1] [7] [8]. For example, compliance of a design proposal with requirements that relate to access for people with disabilities could be demonstrated by simulating their movements within a virtual space [9]. In the case of an existing building, a virtual simulation can be developed based on Post Occupancy Evaluation (POE) data related to the current in-use condition to provide feedback about how the building is used and produce a benchmark for the possible need for renovation. Furthermore, several examples of immersive VR applied to the iterative design review and feedback process exist in literature. For example, immersive VR can be effectively applied as a communication tool in user-centred design processes based on the feedback of stakeholders [10]. Virtual prototypes developed in immersive environments can support collaborative design review sessions since early design stages, improving the communication among stakeholders [11] and allowing the evaluation of behaviours and preferences of end-users, given different design scenarios [12].

In the following paragraphs, a case study is described in which VR has been applied to the simulation of operational issues in an existing building with communication and analysis purposes. The implemented method and the obtained results are illustrated. Further considerations for future works are also introduced.

2 Case Study

A case study has been developed to test the implementation of two different types of VR technologies (i.e. crowd simulation and immersive virtual environment), regarding communication and analysis of access, space and use performance of the current in-use scenario of an existing hospital facility. The VR-aided analysis has been performed in collaboration with the contracting entity (CE), who wanted to evaluate the benefits of digital approaches to reconfigure spaces and services offered in the asset. In order to narrow the scope of the case study, a VR concept has been developed to communicate and analyse a specific critical in-use condition considering a pavilion where both medical (i.e. emergency entrance from the ambulance parking, elevators to the wards located at the upper floors) and food spaces (i.e. hospital canteen, cafeteria) are located (Figure 1). In critical time-slots (i.e. lunch time, 11:45 am – 2:45 pm) the access to the hospital canteen is likely to cause major queues (Figure 2). This increases the waiting time for the personnel, which has a limited amount of time to have lunch, and interferes with the access of internal and external users (e.g. personnel, patients, visitors), who head towards the elevator to go to the wards in the upper floors of the pavilion. The result of that current use scenario is a clash between flows of end-users.

The CE conducted a traditional POE to collect data for investigating such critical situations. Resulting data have been attached to a public call for feasibility studies to improve the current service response to the needs of end-users, while considering the possibility for a low-budget internal layout reconfiguration of the pavilion at ground-floor, among other solutions. The research group started from this specific case to experimentally evaluate (1) how VR could support the CE in communicating its needs, effectively considering the perspective of end-users and (2) how VR could support the CE in evaluating design proposals.

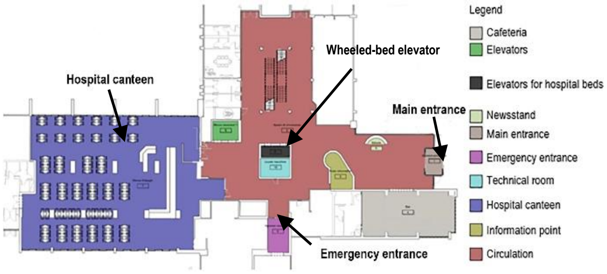

Figure 1 Ground-floor of the analysed hospital pavilion. Main entrances, wheeled-bed elevator and hospital canteen are highlighted

Figure 2 The queue in front of the elevators during the critical time-slot with people arriving from the emergency entrance

3 Crowd simulation of the existing building use scenario

A crowd simulation tool has been used to represent and simulate the existing building use scenario based on the POE integrated with additional data sources. The aim is to understand if such a simulation could support the CE to answer the following questions: how do the access, space and use scenarios perform in the existing hospital pavilion? Are the needs of end-users satisfied in using spaces and services?

3.1 Data collection regarding the current in-use condition

The case study integrates three data sources, which have been used to evaluate the current building use scenario:

1. existing surveys and building use data collected during the POE by the CE have been analysed
2. focus groups and thematic tables have been

organised with the CE, when critical issues have been discussed in detail, as well as the possibility of introducing a digital approach to the problem evaluation

3. further on-site surveys and walkthroughs have been carried out in order to (1) understand usual movement paths walked by the various profiles of end-users moving and using services in the pavilion (e.g. technical operators, healthcare personnel, administrative staff, medical staff, patients and external users); (2) have occupancy data on narrower time ranges than the ones provided by the CE with the POE. A mobile application was used to collect the number of end-users moving in the pavilion in the critical time-slot according to users profiles; these data, elaborated in percentages, was used as input for simulating the current building use scenario within a BIM-based crowd simulation tool.

Available as-built documents have been reviewed and translated into a BIModel in Autodesk Revit. The level of definition of the BIModel was established according to the model use defined for this case study, which is the translation of POE data into a dynamic simulation able to support the communication and analysis of existing occupancy conditions. Spaces, circulation paths, external and internal walls have been modelled to simulate the flows of end-users. Other elements (e.g. ceilings, windows, furniture) and attention to the lighting of the spaces guarantee a greater sense of presence during the immersive experience, which will be described in the next paragraphs.

The existing building use scenario of the pavilion, related to the critical time-slot (i.e. activities, end-users, circulation paths, spaces), has been formalised by the BPMN graphical modelling approach for processes [13] to be organised and used as a reference framework for the simulation.

3.2 Occupancy data as input for the crowd simulation

Occupancy data have been used as input to a crowd simulation tool (i.e. Oasys MassMotion), where the agents have been customised based on the profiles of end-users acting in the analysed pavilion. Various agents have been created to represent technical operators, healthcare personnel, administrative staff, medical staff, patients and external users (Figure 3). Their profiles have been parametrised considering geometrical data (e.g. range of action) and behavioural data (e.g. circulation paths, speed of movement). The number of agents for each type of profiles of end-users have been set according to the POE data integrated with on-site surveys and measurements organised in 15-minute time ranges during the critical slot.

The BIModel has been imported into MassMotion, which is able to parse the Industry Foundation Classes (IFC) data format and automatically recognise the elements that hinder the movement of people (e.g. doors, walls).

Finally, the simulation has been run according to the scenario described in the BPMN (i.e. critical time-slot), with the collected data used as simulation parameters and the geometrical constraints of the BIModel.

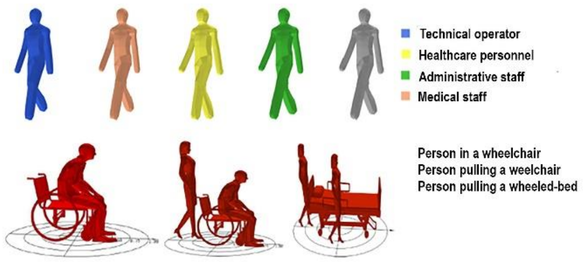

Figure 3 Agents set for the simulation

3.3 The BIM-based crowd simulation as communication tool

The result of the crowd simulation has been optimised by an iterative review process with additional on-site surveys and focus groups with the CE. Such an optimisation has allowed the simulation to be representative for the current in-use condition and related critical issues in the access of the end-users to the services offered in the analysed hospital pavilion. For example, the simulation has highlighted the problem of clashes between the two flows of end-users (i.e. users of the hospital canteen and users entering the building and going towards the elevator) in the hall of the pavilion in the critical time-slot (lunch time). Based on that, it has been possible to share with the CE and a representative group of stakeholders:

- a clear visualisation of the problem and communication of the issue to people that usually do not experience the critical time-slot in the pavilion, but that may be required to take decisions and develop strategies about it (e.g. define the available budget for the reconfiguration of the internal layout) (Figure 4);
- a definition of the profiles of end-users that access the services provided in the analysed pavilion (e.g. personnel, visitors, patients, disabled people using wheelchairs, patients transported on hospital beds) (Figure 5);
- a density map of the pavilion at the critical time-slot, useful to understand which services are the most used ones during the critical time-slot and support future design and decision processes regarding the

reconfiguration of the internal spatial layout (Figure 6).

Figure 4 Results from the crowd simulation have been used to support focus groups with the client

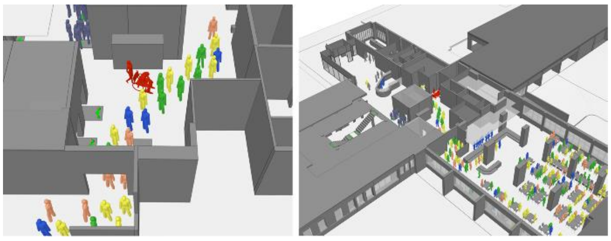

Figure 5 Crowd simulation of the current condition

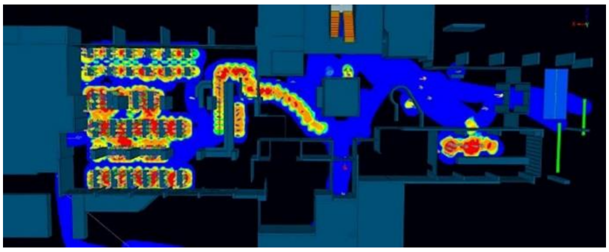

Figure 6 Density map of the pavilion at the critical time-slot

3.4 The BIM-based crowd simulation as Pre-Occupancy Evaluation tool

Occupancy data, collected during the POE and organised in traditional paper-based documents by the CE have been digitised. Once integrated with on-site surveys, they have been used as input for the simulation, becoming a dynamic representation of the current building use scenario and critical issues. The possibility to use the same simulation data and formalised building use scenario for evaluating design options for the layout reconfiguration of internal spaces has been discussed with the CE. In this way, the simulation would not be just the result of the Post Occupancy Evaluation and the picture of the current asset performance, but it would become the tool for an effective Pre Occupancy Evaluation of design proposals [14]. This hypothesis has been tested by proposing low-budget internal layout reconfigurations. The related BIModels have been imported in MassMotion, where the simulation, based on the same data as the existing in-use condition, has been executed again (Figure 7). In this way, it is possible to evaluate how, without changing the current building use scenario, it would be possible to (1) create a pre-occupancy simulation of access, space and use performance of the building according to various design proposals and (2) eventually select one of those options based on the results of this simulation.

Figure 7 Crowd simulation of the current in-use scenario applied to low-budget reconfigurations

4 Immersive Virtual Environment

Subsequently, both the BIModel and the crowd simulation have been imported into a game engine (i.e. Unity3D) to be visualised and experienced in an immersive VR headset (i.e. HTC Vive), with communication and analysis purposes in mind. The aim of this second part of the case study consists of the possibility to switch from the analysis of flows to the perspective of the end-users, who are part of those flows. Immersive VR has been used to evaluate the building spaces from various points of view, simulating four different scenarios:

- able-bodied users (scenario 0 and 1);
- person in a wheelchair (scenario 2);
- person pulling a wheelchair (scenario 3);
- visually-impaired person (scenario 4).

Unity3D was used to build the immersive environment with accurate lighting, a locomotion system and creation of various profiles of end-users to be simulated (e.g. viewpoint height), supporting the VR-headset natively. Moreover, the game engine was first used to import and visualise in the immersive VR both geometrical and non-geometrical attributes of BIM objects: this was necessary to be able to select and visualise information related to building objects while navigating the virtual scene. An interoperable data flow is not possible between Unity3D and a BIM authoring platform by default. The BIModel has been imported in Unity3D through the *.fbx data format and C# scripts have been used to import the non-geometric attributes embedded in BIM objects to be visualised when selecting them with one of the controllers. A teleporting system has been also integrated to navigate the BIModel.

In order to add the “occupancy” variable in the interaction with the building, while navigating in the virtual environment and experiencing the spaces as crowded as in the current building use scenario of the hospital pavilion, the crowd simulation developed in MassMotion has been also imported into Unity3D. This data flow has been managed by an Alembic (ABC) file exported from MassMotion to Autodesk 3ds Max, where an *.fbx file has been then created to be used in Unity3D (Figure 8). Once imported into the game engine, the crowd simulation maintains the number of agents and their speed of movement as defined in MassMotion and compliant to the POE data.

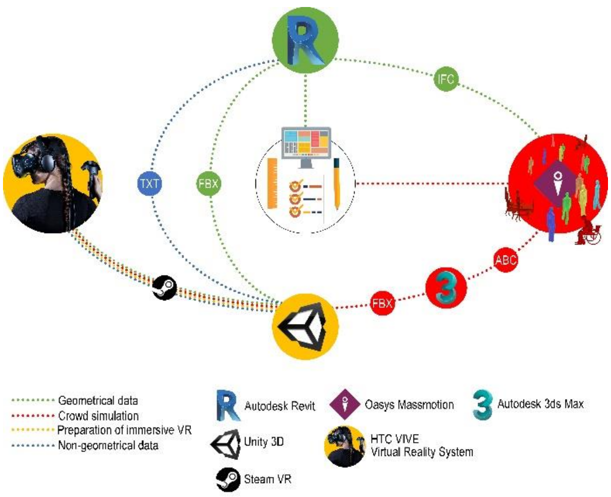

Figure 8 Data flow from the BIM authoring platform to crowd simulation and the immersive virtual environment

4.1 Simulation from the prospective of various end-users

Four scenarios have been created to experience the hospital pavilion and the crowd simulation from the perspective of as many profiles of end-users. The benefits of VR have been evaluated, highlighting its role as occupancy evaluation tool, its use for training purposes and to better understand how various profiles of end-users perceive the space. A modified first-person camera in Unity3D supports changing the perspective of the end-users according to the various scenarios.

4.1.1 Scenario 0: able-bodied users

Scenario 0 represents the point of view of an able-bodied user, a person of average height without disabilities and able to walk within the building spaces. The crowd simulation was not enabled in this scenario (Figure 9).

Figure 9 Internal spaces as visualised in the immersive virtual environment

4.1.2 Scenario 1: able-bodied users with the crowd simulation

Scenario 1 differs from the previous one because the crowd simulation has been imported in the immersive virtual environment and the user can evaluate how the feeling in using the building spaces changes when a crowded situation occurs (Figure 10).

Figure 10 Internal spaces as visualised by an able-bodied person, including the crowd simulation based on POE data

4.1.3 Scenario 2: person in a wheelchair

Scenario 2 represents the perspective of a person in a wheelchair: the movement of an electric wheelchair has been programmed in Unity3D to be controlled in VR by using the HTC Vive 3D-joysticks. The wheelchair user may represent either an employee on a wheelchair or an external visitor. A script has been created to visualise the walking (simulated) end-users via a red highlight when they are within the range of action of the wheelchair user. According to the CE, hospital employees with disabilities do not use the canteen service because of the current issue, optioning for other food services. This scenario aims to allow the CE to better understand the perspective of a person in a wheelchair using the building spaces and the problem that he/she must face in a day-to-day situation (Figure 11).

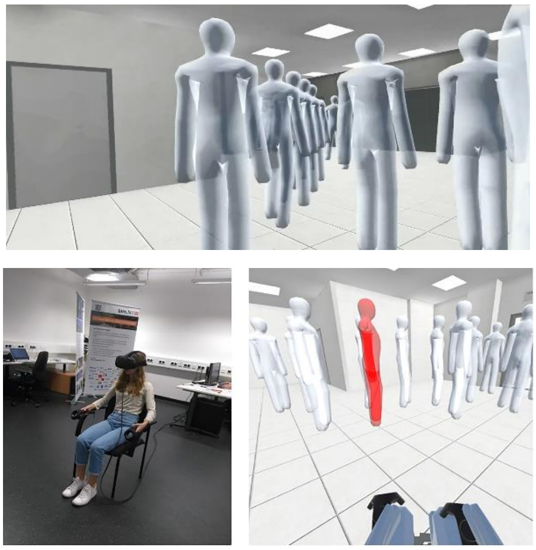

Figure 11 Simulation of a wheelchair user experiencing a crowded situation based on POE data. The accessibility of internal spaces can be tested and evaluated

4.1.4 Scenario 3: person pulling a wheelchair

Scenario 3 has been created to simulate an end-user pushing a wheelchair, which may be the case for medical staff that accompanies a patient from the ambulance parking to the hospital wards by the emergency entrance (Figure 12). In the current building use scenario, this situation is the one that causes major issues during the critical time-slot, because end-users entering from the emergency entrance and going to the elevator must cross the queue of end-users waiting to enter to the hospital canteen. The immersive simulation allows who usually do not experience that scenario to feel the actual discomfort of this implication.

Figure 12 Circulation path from the emergency entrance and the elevators is simulated from the perspective of a person pushing a wheelchair

4.1.5 Scenario 4: visually-impaired person

Scenario 4 simulates the viewpoint of a visually-impaired person. The rendered view in the HTC Vive has been partially obscured to reproduce the view of a visually impaired person (Figure 13). Sensitive paths have been modelled in the BIM authoring platform. A virtual cane, attached to the HTC Vive controller, enables users to follow the paths, while walking in the displayed building spaces. The cane/controller has been programmed to vibrate when touching sensitive paths during the navigation in VR. For example, such a scenario could be used (1) to validate the design of sensitive paths and internal spaces also in new design proposals acting as a Pre Occupancy Evaluation tool; (2) with training purposes; (3) to better understand how visually-impaired person perceive the space.

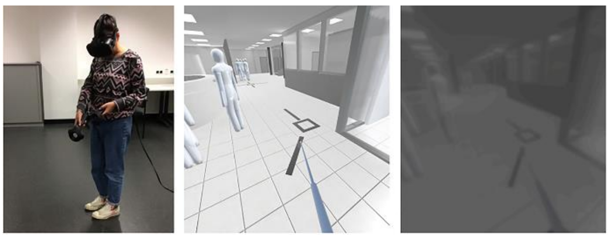

Figure 13 How a visually impaired user follows the sensitive paths with a simulated cane

4.2 Feedback collection

Feedbacks on the VR-aided scenarios previously described have been collected from people with various backgrounds and experience in the use of VR (i.e.

computer science, civil engineering, humanist disciplines, architecture, building accessibility, CEs). Fifteen users have been asked to navigate within the model, testing the proposed scenarios. It has been required for them to move through the spaces according to the actual circulation paths of employees, visitors and patients to experience the same crowded situation as detected during the POE and simulated in MassMotion. Despite the various backgrounds and experience in VR technology, users provided similar comments (excerpt):

- when switching from scenario 0 to scenario 1 it has been noted that spatial dimensions, even if compliant to building codes, may not be sufficient in a crowded situation as the experienced one
- the perception of the actual discomfort due to the occupancy simulation is realistic
- the crowd simulation, which is compliant with POE data, provides an added value to the implementation of immersive virtual environments as evaluation tools
- CEs have highlighted the possibility to experience building spaces from the perspective of the end-users as positive input in the decision-making process
- the possibility to support user-centred design processes and stakeholder engagement by immersive technology has been considered
- immersive VR could be an effective tool to analyse the accessibility of building spaces, going beyond codes, regulations and computable parameters and implementing the dynamic simulation of how the building is/will be used
- immersive VR could be used as a training tool to learn how a person with disabilities moves and acts within the space

5 Results

The paper describes the implementation of crowd simulation and immersive VR in the communication and analysis of access, space and use performance of an existing building. A case study has been developed testing VR implementation in an hospital pavilion where both medical and food spaces are located, causing a clash between flows of end-users in critical time-slots.

Crowd simulation has been used to integrate a multitude of paper-based POE data and translate them into a dynamic representation of the critical in-use condition; the case study has allowed the research team and the CE to understand which type of POE data are needed to create a reliable simulation of the in-use condition. Such a simulation allowed a clear visualisation and communication of current issues to people that usually do not experience them but who are involved in taking decisions related to the asset management. Moreover, POE data digitally simulated have been also applied to the pre-occupancy evaluation of design proposals for the low-budget reconfiguration of the internal layout.

Immersive VR shown the possibility to switch from the analysis of flows to the evaluation of the perspective of the end-users, simulating their point of view in a day-to-day situation. The combined use of crowd simulation and immersive VR, in fact, enables the users to perceive crowding in the occupancy evaluation and adds the user experience as a design input, representing an innovative approach that goes beyond traditional resources such as personal experience and regulations. This application may support the validation of design proposals, the evaluation of current in-use scenarios and a better understanding of how end-users perceive the space and its performance in meeting their needs.

A data flow has been proposed and tested to connect the BIM authoring platform, the crowd simulation tool and the immersive virtual environment. Moreover, the CE has started to consider the possibility to attach the outputs of a similar simulation (e.g. a video) to the traditional paper-based documents for better communicating needs and requirements to the suppliers.

6 Conclusion

The case study described in this paper aims to evaluate how VR technologies may be used to communicate and analyse the current in-use condition of an existing building as far as access, space and use performance are concerned. It conceptually connects the iterative review and feedback process (e.g. Post Occupancy Evaluation) to the briefing one (e.g. restate a need for action, evaluate lessons learnt, needs and expectations).

Some aspects should be further considered and researched about the implementation of VR in AEC/FM processes: technological, procedural and contractual aspects should be integrated into a single implementation framework. In particular:

- the suitability of various VR technologies should be considered according to different processes (e.g. collaborative design review, user involvement, building code checking) [11]
- process phases, users to be involved, related responsibilities and requirements to be analysed should be deeply evaluated before implementing VR
- contractual aspects related to the implementation of VR-aided simulations in AEC/FM processes should be investigated (e.g. consequences if a gap between simulated and actual performance occurs)

Moreover, the novelty effect of VR technologies in the AEC/FM industry should be considered: the case study described in this paper lasted for five months during which the CE has been iteratively involved to validate the simulation and evaluate the possible benefits of such an approach. The CE took a considerable amount of time before switching from considering the simulation as a fancy video to deeper understand its communication and analysis benefits. As a first attempt, this case study has been affected by the novelty effect, but final results suggest for a possible effective implementation of VR technologies, as well as BIM methodology, in future actions.

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