A BIM-based Framework for User-centered Evaluation of Complex Buildings in Virtual Environments

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The design of buildings requires architects to anticipate how their future users will experience and behave in them. In order to do this objectively and systematically user studies in Virtual Environments (VEs) are a valuable method. In this paper, we present a framework for setting up, conducting and analysing user studies in VEs. The framework is integrated in the architectural design process by using BIM as a common modeling and visualisation platform. In order to define the user studies simple and flexible for the individual purposes we followed a modular concept. Modules thereby refer to different kinds of user study methods. Currently we developed three modules (Wayfinding, Spatial Experience and Qualitative Annotations), each having their individual requirements regarding their setup, interaction method and visualisation of results. In the course of a architectural design studio, students applied this framework to evaluate their building designs from a user perspective.

Keywords: Pre-Occupancy Evaluation, Virtual Reality, User-centered Design, Building Information Modeling, Architectural Education

INTRODUCTION
Buildings are in the first place created for their users (Gropius 1962). Consequently, the design of a building requires architects to anticipate how its future users move and find their way through the building, how they experience the spaces or how well they can conduct certain activities in the building. However, this is not an easy task, due to the numerous influencing factors both from the side of the physical environment (such as geometry, light, color) as well as from the side of the user (different social backgrounds, expectations, age, etc.). This challenges the design of buildings. Even architecturally renowned buildings are, consequently, sometimes hard to understand for their actual users (cf. Hölscher & Dalton 2016).

Basically, there are two distinct approaches to anticipate user behaviour in the design stage. Both of them can be referred to collectively as “pre-occupancy evaluation” methods. The first approach is the use of analytic models, that to some extent
are able to simulate or evaluate certain aspects of user-behaviour. Examples are agent-based models for simulating crowding/evacuation (Bandini et al. 2006), space syntax techniques for analysing cognitively/behaviorally relationships between spaces (Hillier 1996), or activity scheduling (Shen et al. 2013). The second approach is to actually ask future users how they evaluate the building design, or to observe their behavior (see e.g. Kuliga 2016; Hölscher et al. 2006). In the following, we focus on this second approach; to which we will refer as “user study”.

To conduct a user study, a representation of the future building is needed. However, unlike to product or web design, in architectural design the creation of real-world prototypes would be too costly and time-consuming. Therefore architectural representations are scaled and reduced in their dimensionality and level of detail (e.g. such as floor plans, elevations, sections and perspective drawings). However, these representations need additional skills/education for correctly reading them and are limited in reflecting the real future spatial situation (e.g. regarding the actual scale and possibilities for interaction, such as moving). Thus, virtual environments (VEs), where users are placed in the building on eye-level perspective are most suitable to conduct user studies (e.g., Kuliga et al. 2015; Westerdahl 2006). Current Virtual reality (VR) technology (such as the nowadays widespread and affordable head mounted displays, HMD) allow to experience the future building stereoscopically (real 3D) with a high resolution, high level of detail and in real scale. In a recent study with latest technology, Chamilothori et al. (2018) compared the subjective spatial impression of virtual and real environments and discovered almost no difference in the ratings.

These recent technological advancements help designers (and future users) in acquiring a “feeling” for the spatial impression of spaces, as well as for the relation between spaces (by moving through the VE). Today, numerous commercial tools exist to quickly and easily view and even change design models in virtual reality. However, methods for systematically and efficiently investigating in the design phase how potential future users behave and feel in the designed buildings, to our knowledge, need further development. In the following, we give a short overview about methods for conducting user tests in VE. Afterwards, we are presenting our newly developed toolbox for setting up, conducting and analysing user studies in VEs (VREVAL). Finally, we show a case study using this toolbox.

**RELATED WORK**
Since the VR was first developed and throughout the years, numerous approaches to support architectural designing in VE were undertaken (e.g., Schulz et al. 2014; Donath & Regenbrecht 1996). Regarding the evaluation of buildings in VR, many tools for visualising buildings in VR exist (such as *Enscape3D* [1], *Oneiros* [2], *IrisVR* [3]). However, tools to systematically evaluate buildings with / or inside VR from the user perspective are rare.

Palmon et al. (2006) introduced a tool called Habitest for evaluating the accessibility for disabled building users. In a desktop based VE, users navigated through a dwelling on wheel-chair eye-level, while for collision detection the dimensions of the wheel-chair were set. While moving, the trajectories were tracked; and participants identified deficits with the dwelling, from a user-perspective, during or after the study.

Dunston et al. (2007) used a CAVE for evaluating the usability of hospital rooms. They implemented interaction techniques for manipulating the environment (e.g. opening shelves and doors). Due to the small and simple VE (one room) and the possibility to directly interact with the participant in the CAVE (seeing / hearing each other), no methods for collecting user feedback were developed in this project.

Williams, Sailer and Priest (2015) developed an online tool for assessing the perception of school buildings. Their Interactive Space Analysis Tool (ISAT) used a series of 360° photos of a built building (however, the tool can principally also be used for future buildings) for experiencing and navigating through
the building (similar to Google Street View). The setting also allowed to mark parts of the image and to add comments to them (these comments were categorized as “good”, “bad” or “for information”).

Angulo (2015) applied VR for architectural design education; and in particular to systematically evaluate the spatial experience of student designs. She used questionnaires for rating the designed environment (e.g. how open/closed, pleasant/unpleasant the spaces were experienced, or how effective the circulation was). Participants filled out the questionnaires after the actual VR-experience.

Grübel et al. (2017) presented a framework EVE (Experiments in Virtual Environment) for conducting scientific studies inside VEs. They stressed the importance of integrating the questionnaires directly into the VE, because switching between the virtual and real world would impede immersion. The target group of this framework were environment-behaviour researchers with only little programming knowledge. EVE facilitated creating VE-based questionnaires and the organization of data (e.g. synchronizing data, movement trajectories and physiological sensor data), as well as their analysis.

VREVAL FRAMEWORK
In the following, we present a toolbox (VREVAL) that we developed for architects in order to conduct user studies for evaluating their designs from a human-centered point of view. Thus, our focus lays on the simplicity and flexibility of its usage as well as its convenient integration in the design process.

The toolbox was implemented using the Game Engine Unreal [4] and its internal scripting language Blueprint and C++. Regarding the hardware, VREVAL can be used in desktop-mode (using screen, keyboard and mouse) as well as in VR-mode. For the latter, HMD’s (such as Oculus [5] or HTC Vive [6]) with controllers (for navigation and answering questionnaires) are required.

Fig. 1 shows how VREVAL is integrated in the design process. After creating a model of the designed building (BIM based), the model is imported to Unreal. In Unreal the questionnaire can be created by dragging questionnaire modules into the VE and configuring them there. After finishing the set up an executable file is created, which can be run on any (VR-ready) computer. For this reason, studies can be not only conducted in the laboratory, but also at home, e.g. for crowdsourcing purposes. After the study, the data can be visualised and analysed and finally changes to the design can be made based on the findings.

In order to set up a study, we chose a modular approach. Thereby each module represents a certain type of study method for systematically evaluating spatial environments. Typical methods for environment behaviour studies can be found in Zeisel (2006). They can have both quantitative and qualitative character. Each module offers graphical user interfaces that are displayed inside the VE (dialogue boxes for each type of study method) and manages the storage of the user responses. The modules can be adapted to the needs of the designer and be combined to create a complete questionnaire. So far, we developed three different modules, namely Wayfinding, Spatial Experience and Qualitative Annotations. In the following these three modules are described briefly.

Wayfinding Module
The “Wayfinding Module” (WFM) serves for creating studies for identifying navigation problems in a building. Therefore, one can define several destinations as wayfinding tasks in a building. For each destination one can define a task-description that the participants read in order to understand what they have to do (e.g. “Imagine you come to this library for the first time. Please first go to the locker to put away your bag,” see Fig. 2, center-top). Such descriptions are important in order to help the study-participant taking the perspective of the future user.

Spatial Experience Module
The “Spatial Experience Module” (SEM) offers a questionnaire to ask participants about their subjective impressions of a certain places in a building. Therefore, the study-designer has to define the locations
(including the initial viewing direction) and define the text for questions as well as the possible answers (from which the user later can chose). An often used method to assess the spatial experience is the semantic differential (Osgood et al. 1957). In this method, two opposite word pairs are presented (e.g. public/private or beautiful/ugly) and the participant has to choose between the opposites using, e.g. a Likert-Scale (e.g. between 1 to 5, meaning e.g. from “very public” to “very private”). In this study module, the participants are “beamed” to the defined locations. There they see the questionnaire box in front of them, can have a look around and then answer (Fig. 2, center-center).

**Qualitative Annotations Module**

Since not all aspects of a building can be covered by pre-defined questionnaires, the “Qualitative Annotation Module” (QAM) allows collecting free comments about places in the building. For this aim, the participants can walk around in the building, point at places and describe what they wants to say about them. Here, however, a work-around is necessary, since typing text while wearing a HMD is hardly possible. We decided to display a dialogue, where the user can select multiple tags that describe the value (positive, negative, neutral) and the categories of the comment (Fig. 2, center-bottom). These categories can be freely defined by the researcher (e.g. aesthetics, functionality, privacy, circulation, spatial impression, daylight, exterior view). After the participant finished this task (by selecting the tags for several locations), a list of all locations the participant tagged is shown; including screenshots and tags to visually and verbally remember the locations/comments. In this list, the participant can add text to describe thoughts about the place in more detail.

**Setting up the study**

After the model has been imported to Unreal, the study designer defines the modules using Unreal. Each module is designed in such a way that it can be added to the scene using “drag & drop”. Each instance of the module can be edited independently, using specialized input fields. The wayfinding-module, for example, only needs three input fields: title, task description and the location of the target destination. Additional questions to e.g. collect demographic information (such as gender, age, expertise) can be defined in a separate module. These questions are be shown on without showing the VE (e.g. on the screen before the real study starts). Once these steps are completed, an executable file is created and is given to the study participants. While conducting the study, all information (e.g. the trajectories that the participant is walking, the answers to the questionnaire, annotations, participant-ID) is stored in a separate file (JSON-format).

**Visualising Analysis Results**

For data analysis, we developed methods to directly (and thus conveniently for the designer) display the data in the building information modeling software;
in our case Autodesk Revit. For processing the result data, we developed a set of custom Dynamo nodes in C sharp using the Zero Touch interface. All the data is mapped into the Revit model properties and special marker family objects with desired attributes (e.g. Start/End Time, Participant information, Comments etc.). Additionally, a functionality to display the study results through a tooltip interface was implemented.

For the WFM, the trajectories of each participant are displayed as polylines. The lines are labelled with the participant-ID, and can be colored in order to better differentiate between different participants (see Fig. 2, top-right). Furthermore, we implemented the functionality to connect the Revit camera to the imported paths in order to move along them. For the SEM, the results are displayed in a tooltip window, while one hovers with the mouse over the respective locations. Thereby, the results can be shown for each participant as well as the average (see Fig. 2, middle-right). For the QAM all locations, where an annotation was made, are marked with a circle. The color of the circle thus represents if the annotation was positive (green), negative (red) or neutral (blue). Next to the circle the participant-ID, the tags and the detailed description are displayed (see Fig. 2, bottom-right). Furthermore, all data can be imported to any statistical analysis software for further processing (e.g. to identify the most often used words in the annotation).

APPLICATION IN A DESIGN STUDIO
VREVAL was tested in an architectural design studio (master level) with 20 students. The students designed a complex building (centre for academic ex-
change, CAE). The design task stemmed from the competition “Designing buildings from the inside out” that was initiated in 2011 by the SFB “Spatial Cognition” (Dalton et al. 2012) and already used in an architectural design studio in 2012/13 (Schneider et al. 2013). This time, after the students created their designs, they had to create a user-study by using the above mentioned VREVAL-modules and mutually participate in their studies (peer review). The results of the studies were analysed and served as input for redesigning the building.

The programme of the CAE included lecture halls, a cafeteria, seminar rooms, workspaces and short-time residences (see Fig. 3, right). The building requires to consider different types of users (researchers, students, administration staff and people from outside academia interested in a certain topic of a symposium, or just wanting to drink a coffee). The site for the CAE was artificially created with the intention to focus the design task only on the interior spatial organisation rather than on the shape and appearance of the building from the outside. For this reason, we chose a plot which was completely closed to three sides and open to the street (see Fig. 3, left). The dimensions of the plot were chosen to be large enough to flexibly arrange the demanded spaces.

For the design of the building, the students were asked to mainly focus on the arrangement of spaces with respect to the expected user behaviour. For this reason, they were allowed to ignore all other aspects (costs, statics, energy). After the input on scientific methods on measuring/testing building usability, the students had three weeks to create an initial design, two weeks for user evaluation tests and further three weeks for analysing the feedback and redesign the building. The building designs had to be modeled in Revit in order to have complete and detailed models for the VR-Studies. In order to ensure comparability among the projects and to emphasise the focus on building geometry, we set few standard materials for walls, doors, ceilings and defined standard lighting. In the following we will less focus on the design of the building, rather than the use of VREVAL in the evaluation process.

Fig. 4 shows typical examples of how students visualized the user study results. The trajectories from the WFM for a four-storey building of one student group are displayed on the left. Students identified for some participants deviations from the routes that they originally expected the users would take. The second image (Fig. 4, center), shows a typical visualisation of the spatial experience questionnaires. This helped students to identify unpleasant or dark rooms or if privacy, where necessary, was achieved. The last image (Fig. 4, right) shows an example for visualizing the annotations, that their classmates made, when exploring their building. Thereby positive and negative comments were differentiated, such as “I can feel the entrance like welcoming you to the building” or “Narrow passage, imagine many people passing there at the same time”.

From a teacher’s perspective, the most challenging task during this project was to get the students to take in an analytic view on their designs. Almost all students had difficulties in critically analysing the potential weaknesses of their buildings. On the one hand, these difficulties arose from the fact that they never systematically thought about “user performance” and thus were lacking the vocabulary for defining what this actually means. On the other hand, it might be due to the fact that during their whole previous study time they were always demanded to defend their designs in the best possible manner (there seems to be a trained behaviour among architecture students to not confess failures). Thus, among some students there was noticeable reluctance in conducting this step. After having completed the whole course, most students (12 out of 13 responses) were very satisfied with the course and glad about the experience (one student rated the entire course highly negative, and 7 did not participate in the course evaluation). Finally, we conducted a survey among the students to assess the potentials and limits of the current state of the tool and its application in their design process. In the following, the main findings of this survey are reported briefly.
Feedback from students
Regarding the use of VR, we can summarize, that students felt that they could experience spatial dimensions more “realistically”. They also stated that they noticed problems much better in the first-person virtual reality simulation, than in the “traditional” representations (“In VR I saw some details and mistakes I did which were hard to see in plans, sections, and views”). Some students reported that they felt “more emotional” in VR; e.g. when they suddenly “felt” the narrowness or darkness of certain hallways.

Regarding the evaluation of their designs with VREVAL, students stated that it helped them to better “understand the personal feelings of the users when they were in [their] design” and to “see failures that go unnoticed, to see how users perceive [their] design and to understand how they circulate in the building.” The visualisations helped to identify problematic “hotspots” that they further focused on in their redesign. Furthermore, they stated that the QAM was particularly useful, because it enabled them to freely leave comments to any place and any issue. The SEM on the other hand was seen as too restricting and for most students hard to draw conclusions from the results it provided.

The students argued that virtual reality needs further technical development and ambient experience. For instance, they criticized the steering mechanism for walking: they got bored when walking long distances (which was necessary for the trajectory calculations) or could not handle the devices well enough. Some students experienced occasional cybersickness. Furthermore, students did not like low level of detail / grey-scale / standardized lighting of their models (that we demanded for the sake of comparability). Regarding the modeling of their designs with BIM-Software in the very early stages (there was only three weeks time from the announcement of the design task to a model that can be used for the VR-Study), they argued, that, although BIM is “really useful for designing the model in detail” it is “quite hard to do the concept phase.”

CONCLUSION AND OUTLOOK
With VREVAL, we introduced a framework for creating, conducting and analysing user studies for evaluating buildings from a human-centered perspective. The framework follows a modular approach making it flexible to create studies that are customized for individual purposes. Furthermore, it is conceptual-
ized as an integrated part of the architectural design process, by connecting the study setup and the visualisation of the study results to BIM. From testing the framework in a student design studio, we experienced general difficulties among architecture students in critically analysing designs from the user perspective. However, after conducting user studies with VREVAL, students reported very positively on the usefulness of this method for identifying problems that we were not able to see otherwise.

Currently, we are planning to publish the framework as open source, allowing other researchers and architects to participate in the development and add additional modules or to enhance the existing ones. For example, the annotation module could be complemented by a voice recording (and voice to text transcription) feature, allowing to conduct “think aloud”-method, typically used in usability testing). Furthermore, the interface of VREVAL to architectural modeling software needs to be improved. Until now the building model is imported as a FBX-file via 3D Studio Max. Herefore, we envision an IFC-based import/export, whereby also the definition of the questionnaire module parameters might be included in IFC, making it possible to directly prepare the questionnaire in BIM.

In the future, we are interested in testing VREVAL on real architectural projects with real clients and real users (a first pilot test on the case of a railway station was reported in Kuliga et al. 2018). Thereby, for sure further questions on the usability of VREVAL will arise, as well as new aspects of user testing might occur. Furthermore, such scenarios might call up the idea of using crowd sourcing as the methods for data collection.

ACKNOWLEDGEMENTS
We thank Martin Brösamle and Christoph Hölscher for providing us with the (no more online available) information on the design competition from 2012.
and Florian Geddart and Dr. Kerstin Sailer for joining the final critique of the design studio and giving valuable comments on the tool.

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