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Article

Connecting the knowhow of design, production and construction professionals through Mixed Reality

Rizal Sebastian [1,*], Rosamaria Olivadese [1], Emanuele Piaia [2], Roberto Di Giulio [2], Peter Bonsma [3], Jan-Derrick Braun [4] and Günther Riexinger [5]

[1] DEMO Consultants BV, Delftechpark 10, 2628XH, Delft, The Netherlands; rizal@demobv.nl; anna@demobv.nl; rosamaria@demobv.nl
[2] University of Ferrara – Department of Architecture, Via della Ghiara 36, Ferrara 44121, Italy; emanuele.piaia@unife.it; roberto.digiulio@unife.it
[3] RDF Ltd., P.O. Box 32, 1320 Bankya, Bulgaria; peter.bonsma@rdf.bg
[4] HOCHTIEF ViCon GmbH, Alfredstraße 236, 45133 Essen, Germany; Jan-Derrick.Braun@hochtief.de
[5] Fraunhofer IPA, Nobelstraße 12, 70569 Stuttgart, Germany; Guenther.Riexinger@ipa.fraunhofer.de
* Correspondence: rizal@demobv.nl; Tel.: +31-15-750-2520

Abstract: At present European buildings typically consume two to five times more energy than predicted at the design stage. An important cause of this performance gap is the discrepancies between the design specification and the As-Built condition. Such discrepancies are mainly due to the gaps in knowhow between design, production and construction professionals. Design is more and more contained into a virtual environment and loses touch with the physical production and construction sites. As the construction sector enters the Industry 4.0 era, Building Information Modelling (BIM) based Mixed Reality can intertwine virtual and real worlds to bridge the knowhow gaps.

Keywords: Building Information Modelling (BIM); Mixed Reality; energy performance gap; knowhow gap; prefab buildings

1. Introduction

Buildings in Europe typically consume two to five times more energy than predicted at the design stage [1, 2]. With the increasing demand for more energy-efficient buildings, the construction industry is faced with the challenge to ensure that the energy performance predicted during the design stage is achieved once a building is in use. Unfortunately, there is extensive evidence to suggest that buildings usually do not perform as well as predicted.

Previous studies sought and examined the main causes of such a discrepancy. IEA EBC Annex 53 [3] argued that the energy performance gaps were caused by suboptimal operation and building occupant's behaviors, climate changes, and low quality of building materials or components. Menezes et al. [1] pointed out to similar causes, and added several others related to energy performance prediction, in particular: inaccuracies of design assumptions, inadequacies of energy modelling/simulation tools, and lack of feedback to designers after handover that inhibits improvements both to the existing buildings and for future designs.

These causes may justify the energy performance gap over a longer period of time; however, often the performance gap is already detected at the delivery of newly constructed or refurbished buildings before Post-Occupancy Evaluation (POE) is performed [4]. It means that the discrepancies are present even before the effects of occupants' behaviors, building operation or climate change take place. In such a situation, the remaining possible causes of discrepancies are: inaccuracy of energy calculation and lower quality of building materials/components. Nevertheless, neither of these causes can explain large performance gaps, especially when state-of-the-art energy calculation

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norms and tools are considered since they have a much improved accuracy to include dynamic/unregulated energy loads from building occupants and climate changes. Moreover, modern buildings are largely composed of prefabricated components with certified quality and performance level.

Therefore, this paper looks beyond the causes indicated by the aforementioned studies. It investigates the cause of performance gap with regards to the gaps in knowhow between different design, production and construction professionals. These knowhow gaps lead to suboptimal processes and human errors. Several previous studies have put attention on these human factors. Baiburin [5] found that 48% of defects occurred during construction stage and Atkinson [6] highlighted managerial errors in construction processes. Construction workers often do not implement the design properly and make ad hoc changes, and designers do not take full account of the production and construction implications in their design solutions. Josephson & Larsson [7] claimed that more than 72% of such errors could have been detected earlier by a proper judgment; hence, this paper focuses on methods and instruments to bridge the existing knowhow gaps.

The scope of research presented in this paper is concerned with Building Information Modelling (BIM) in combination with Mixed Reality technologies in order to bridge the knowhow gaps between design, production and construction professionals. BIM has been maturing and growing rapidly in building and civil infrastructure sectors. The use of BIM on the construction sites –further than in design and engineering offices– is becoming more and more important [8, 9]. A conceptual framework to investigate how BIM use can be extended to the construction site via Mixed Reality has been presented by Wang et al. [10]. Human factors are addressed as the core principle in this framework, considering that Mixed Reality, by nature, involves the human sensations with both real and virtual information sources.

In the next section of this paper, a brief theoretical review is presented on industrial revolutions and their implications on the evolution of knowhow gaps in construction. BIM and Mixed Reality technologies as part of the Fourth Industrial Revolution (Industry 4.0) are highlighted. In the subsequent section, a research methodology that refers to the on-going EU collaborative research project titled INSITER is described. This section is followed by an analysis of the actual research findings. Finally, conclusions on the current research are drawn along with recommendations for follow-up research.

2. Theoretical review

Professional roles and knowhow in the construction industry evolve along with the industrial revolution. The last half of the 18th century saw the unfolding of a series of events, primarily in England, which historians called as the first Industrial Revolution. This revolution had a profound influence on society as a whole as well as on building technologies [11]. The coming of the industrial age marked a major change in the role of architects. In pre-industrial era, architects were fully involved and responsible for the whole building process, from design until on-site realization. Responding to the industrial revolution, architects developed a new role of licensed design professionals. In addition, with the coming of building science, there was a further division of labor. Structural engineering appeared as a separate discipline specializing in the application of mathematical models in building. More and more specializations were introduced while the gap between white and blue collar workers grew larger.

The second industrial revolution, which began around 1880, was characterized by mass production of steel, the introduction of reinforced concrete, and a new form of electric energy that transformed building technologies [11]. As steel components were produced in factories before brought to the construction sites, the concept of prefabrication was introduced. In this second industrial age, building services and support systems began to develop. Buildings were equipped with elevators, lighting, heating and cooling systems. New professional specializations of Mechanical Electrical and Plumbing (MEP) and Heating Ventilation and Air Conditioning (HVAC) engineers became widely accepted.

The third industrial revolution was commonly known as the Digital Revolution, refers to the advancement of technology from analog electronic and mechanical devices to the digital technology available today. This era started during the 1980s [12]. The advancements during the third industrial age included personal computer, the internet, and Information and Communication Technology (ICT). The discipline of architecture was a protagonist of this revolution. The imminent diffusion of new productive systems, along with the development of advanced software, allowed new possibilities to connect the domains of design and construction, to design building components with certain (algorithmic) descriptions, and to synthetically describe the physical environment and its behaviors within the digital environment [13]. In this industrial age, architects started using diffused Computer-Aided Design (CAD) software as a representational tool to improve precision and expand the limits of their creations. Consequently, computer and automation began to contain design into a virtual environment.

Throughout the first, second and third industrial revolutions, segmentation (i.e. narrowed down due to specialization) and fragmentation (i.e. breaking apart and isolated) have taken place between different disciplines and professions in the construction industry. This has contributed to the growing gaps of knowhow between design, production and construction professionals.

The fourth industrial revolution is fundamentally different from the previous three ones that were mainly characterized by advances in technology [14]. The fourth industrial revolution is characterized by a range of new technologies that are merging the physical, digital and biological worlds; impacting all disciplines, economies and industries; and even challenging ideas about what it means to be human. The term "Industry 4.0" was coined in 2011 at the Hannover Fair, originated from a project in the high-tech strategy by the German government [15]. Mixed Reality and simulation of production processes, especially the creation of 'digital twins' are among the key technologies in Industry 4.0 [16].

The actual manifestations of Industry 4.0 in construction are found in the disruptive impact of Building Information Modeling (BIM) and the development of smart buildings [17, 18]. A positive implications of Industry 4.0 technologies is the integration of design, off-site production, and on-site assembly [19]. There is an awareness that even on the building site, construction needs to catch up with Industry 4.0 [20]. This encourages new partnerships to bridge the knowhow gaps through a future ecosystem of partners, suppliers and customers in order to achieve an optimal building performance.

3. Research methodology

This paper presents technical research within an on-going EU project titled INSITER (Intuitive Self-Inspection Techniques using Augmented Reality for construction, refurbishment and maintenance of energy-efficient buildings made of prefabricated components; www.insiter-project.eu). INSITER focuses on Mixed Reality technologies to bridge the knowhow gap between design and construction. Mixed Reality encompasses the continuum of possible combinations of elements from both virtual and real environments. The continuum between fully-real and fully-virtual worlds comprises: Real Environment – Augmented Reality – Augmented Virtuality – Virtual Environment [21]. For its applications in the Architecture, Engineering, and Construction (AEC), Augmented Reality (AR) is highly relevant as a technology or an environment where the additional information generated by a computer is inserted into the user's view of a real world scene. AR thus allows a user to work in a real world environment while visually receiving additional computer-generated or modeled information to support the task at hand [22]. With this consideration, AR development is prioritized in the INSITER project.

The methodology adopted in INSITER can be summarized in four main stages. The first stage is focused on digitalizing the building, including its components and construction processes, in BIM where information is structured to be eligible for deployment during the construction stage. As time-related information about construction/assembly sequences is included in the 3D model, a four-dimensional (4D) BIM is developed. The BIM approach in the INSITER project relies on IFC open-standard for interoperability. Static IFC BIM models are enhanced with process simulations to include dynamic 4D information, handed from design team to on-site workers. The 4D simulations then become available for self-instruction for construction workers (Riexinger et al., 2018).

The second research stage deals with laser, thermal and acoustic/ultrasound scans on the existing building in a refurbishment project, or on a full-scale mock-up with crucial building components in a new construction project. Laser scans are meant for geometry and texture checks; thermal scans for detecting thermal bridge, insulation performance (U-value) and humidity issues; and acoustic/ultrasonic scans for detecting air tightness and material integrity issues. Subsequently, the scan results are integrated in / superimposed to BIM for showing critical points where defects exist or potentially occur. Virtual clash detections are performed off-site using relevant BIM tools. Two approaches to clash detection are used: the first one is concerned with detecting and eliminating clashes due to design errors; and the second one is analyzing possible clashes when the design solutions are compared against the actual conditions showed by the scan results that are integrated in BIM. The outcomes of the BIM clash detections are consolidated in the so-called '3D clash cubes', which are isolated/highlighted areas of the BIM model to be further examined on-site either to fix the detected errors or to prevent the potential ones.

In third research stage, Augmented Reality (AR) using the 4D BIM is prepared. Self-instruction models and identified or potential construction errors highlighted in the '3D clash cubes' are visualized and examined in the AR environment. In the INSITER project, knowledge and experience of AR development and deployment in manufacturing (for a factory environment) is transferred to construction (for a building site environment). An important aspect of the AR for construction is the further development and application of tracking solutions and methods for positioning of digital objects within the real work environment at construction site [23].

The fourth and final research stage is dedicated to organizing trainings for the professionals in a building project in an interactive and iterative way. Three training modules are designed, namely: 1) awareness training on self-instruction and self-inspection to prevent building's energy performance gaps; 2) skill training to utilize the INSITER AR systems on the building site; and 3) collaboration training for design, production and professionals to ensure the buildability of the design solutions and to avoid misinterpretations of the design specifications by on-site workers.

4. Actual research findings

In this section, actual findings from laboratory and field tests in the INSITER project are reported. For lab testing purposes, a real-scale mock-up of a room unit made of prefabricated panels was erected. A BIM model of this real mock-up was created. The lab facility of the Università Politecnica delle Marche in Ancona, Italy was used. The lab testing was dedicated to: 1) optimizing the procedures for thermal and acoustic scanning; 2) enhancing the data interoperability between 3D scan images and IFC BIM; and 3) developing a BIM-based AR solution, including the visualization of scan results and self-instruction simulations for on-site workers. For the field testing, a real refurbishment project was used. This project comprised a 9-storey university building on the campus of the University of Twente in Enschede, the Netherlands. The field testing was dedicated to: 1) performing time-efficient and cost-effective 3D thermal scans of the exterior and interior of the building; 2) checking the BIM model of the MEP systems by virtual clash detection and deploying BIM-based AR for visual comparisons between the BIM model and the installed parts of the MEP systems; 3) demonstrating the guidelines for self-instruction and self-inspection using a mobile device; and 4) collecting direct feedback from practitioners during a live demonstration.

The results from lab testing regarding thermal scans, as shown in Figure 1, were: 3D thermal maps, thermal bridge evaluation, thermal imaging for U-value distribution assessment, and image post-processing for Signal-to-Noise Ratio (SNR) improvement. The results from 3D acoustic scans on the lab mock-up were: optimized setup for sound intensity measurement using SoundBrush, a solution to export SoundBrush data as a 3D model, sound source localization for detecting air tightness issues at the edge of the panels, and sound intensity analysis for determining air tightness issues at the junctions of the room unit [24].

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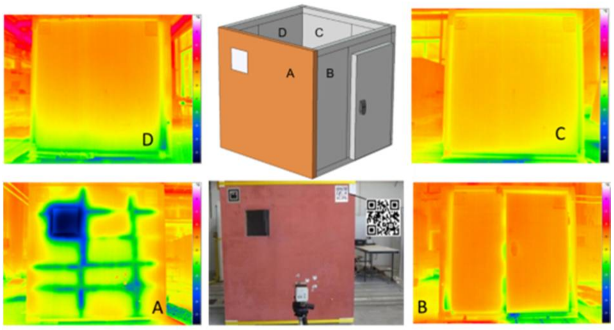

Figure 1. 3D thermal scan results from lab testing [24].

Furthermore, BIM-based AR lab testing resulted in a prototype AR solution through which 3D models, thermal images, sound intensity vectors, and self-instruction simulations for an assembly process can be visualized. The AR solution for lab testing was deployed on a mobile device (tablet), as shown in Figure 2. When creating 4D simulations, all relevant BIM objects were be linked to the process data of a time schedule. This enabled specific objects of the BIM model to be highlighted depending on the progressing activities in the schedule. By doing so, the assembly process could be visualized in a way that is easy to understand for on-site workers [23].

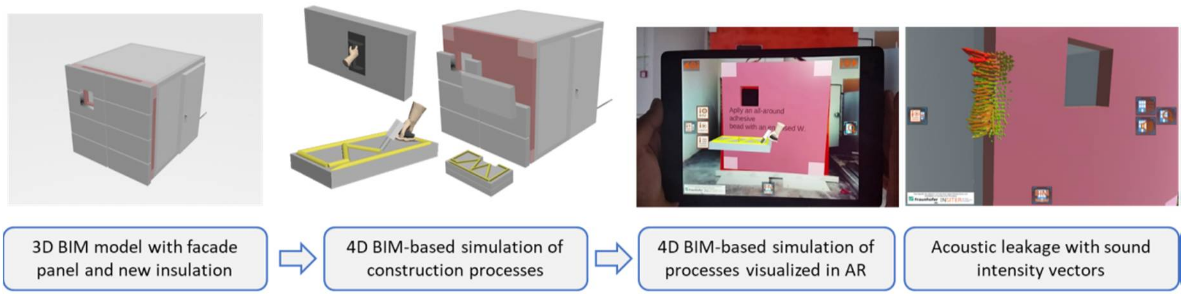

Figure 2. AR prototype in lab testing [25].

The field testing started with parallel activities on-site and off-site. On the building site, thermal scanning of the building envelopes was performed while off-site the architectural and MEP BIM models were processed for the purpose of self-instruction simulation, clash detection, and AR deployment [25]. Figure 3 shows the results of the thermal scans of the building exterior and interior after post-processing of scan images to present thermal-indexed images.

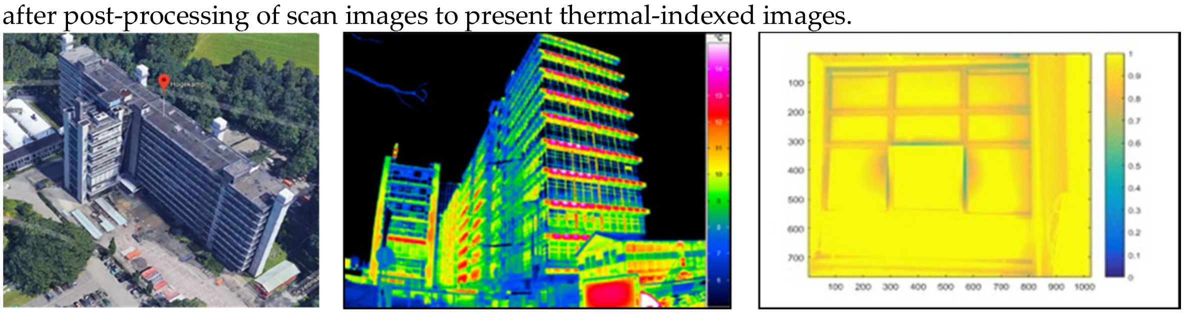

Figure 3. Thermal images from field testing [25].

By superimposing the thermal image to the BIM model and examining the result in AR, thermal related issues were detected (Figure 4). The BIM model of the MEP system, including indications of clashes and assembly or inspection instructions, was then deployed in AR (Figure 5). Microsoft HoloLens smart glasses were the selected as the hardware for this field testing among other possible smart mobile devices.

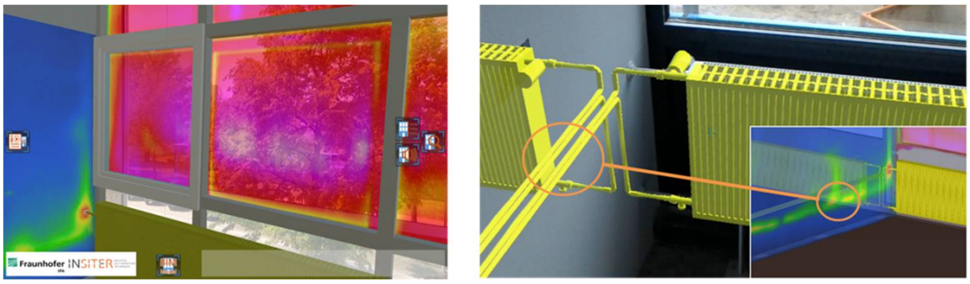

Figure 4. BIM-based AR showing possible thermal-related issues [25].

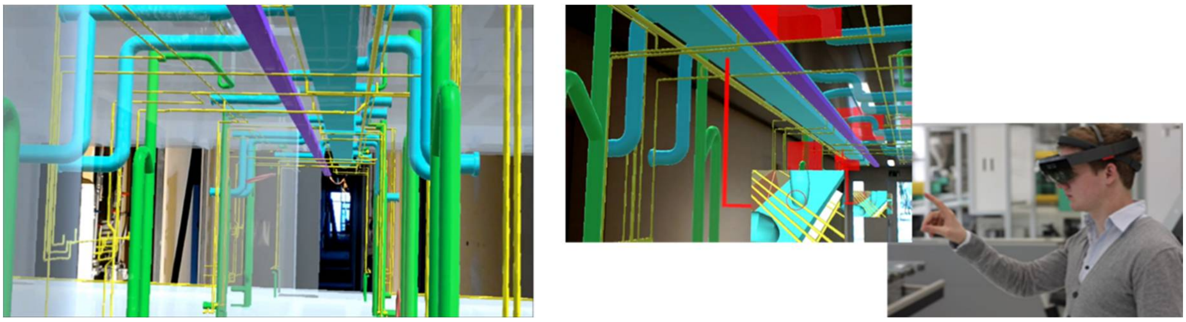

Figure 5. AR deployment to examine MEP systems using smart glasses [24, 25].

5. Conclusions and discussions

Based on the research findings and the feedback received from the practitioners during field testing, this paper concludes that it is viable to develop and implement BIM-based AR to prevent and resolve building's energy performance gaps. BIM and AR technologies, which have emerged as part of Industry 4.0, play an important role in connecting the virtual design environment and the physical production and construction sites. By utilizing these technologies, design, production and construction professionals can get an insight both into the conceptual as well as the practical considerations behind the design solutions and their buildability in the factory and on the construction site. By bridging the knowhow gaps between the different professionals, suboptimal processes and human errors during the construction stage can be minimized, and the targeted performance can be achieved. This approach will also contribute to resolve the existing fragmentation in the building value-chain, especially between white and blue collar labors.

The current results from the INSITER project are on Technology Readiness Level (TRL) 6, which means that the technology has been demonstrated in a relevant industrial environment / in practice. Although certain technical barriers still exist related to hardware, software and data interoperability, the most important challenges for the further TRL enhancement towards 8-9 (i.e. the technology is qualified and market-ready) and for a large-scale implementation of the innovative solutions are found in the acceptance of the construction professionals, the cost-effectiveness of the methods and tools, and the standardization of collaboration processes to facilitate self-instruction and self-inspection. These aspects should be addressed in follow-up research and exploitation.

Attention should also be given to further scientific research on BIM, which is often recognized as the 'digital twin' of a real building or a building process [26]. AR can bring the two different worlds where these 'twins' live in closer to each other, for instance AR can give back the real of sense of space and dimension to designers beyond virtual design models. Particularly for buildings based on prefabricated elements, these technologies will significantly enhance the concept of Design for Manufacturing and Assembly (DFMA), Lean Construction and Circular Economy. As design, production and construction become well aligned, process and material wastes can be eliminated. Production, construction and recycling implications can be anticipated during the design stage.

On BIM-based clash detection, attention should be given to future research on Machine Learning and Artificial Intelligence within the framework of Industry 4.0 for construction.

Particularly for typical prefab-based buildings, Machine Learning can speed up and improve the accuracy of defect identification and performance validation using BIM in which 3D scan results are incorporated.

Acknowledgments: The INSITER research project has received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement no. 636063.

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