Building Information Modelling (BIM) and Virtual/Augmented Reality (VR/AR) for Advanced Training Tools: An Industry 5.0 Application - A Review

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Abstract: In recent years game engines, augmented reality (AR), virtual reality (VR), and mobile devices are the trending technologies used in the field of personnel training. The combination of these technologies allows to provide highly effective and immersive training experiences for operators to develop their skills. In today's evolving industrial landscape, the ability of workforce to manage complex and unforeseen scenarios, is essential. In this paper we categorize the applications of these platforms and provide information on how these technologies have been implemented. In particular, we study the implementations of Building Information Modelling (BIM) combined to Virtual and Augmented Reality (VR/AR) to provide highly effective training experiences, by analysing in detail with 75 papers. Results show that the interoperability among different software is crucial for achieving high level of realism in virtual training environments. In addition, as the level of detail (LOD) increases, additional software is needed, increasing the effort to develop the simulation environment.

1 INTRODUCTION

In the industrial business, to ensure high levels of efficiency, workforce training is crucial. Operator performance depends on their ability to respond to the complex operating contexts and unexpected events they face on daily basis. The demand for skilled operators is always increasing, this led to foster the introduction and development of advanced training processes and technologies. This concept leads to the human-centric approach of Industry 5.0. It promotes the collaboration of humans with advanced technologies such as artificial intelligence and automation putting the well-being of workers at its centre. Given this context, this paper aims to investigate the applications of Building Information Modelling (BIM) combined to Virtual/Augmented Reality (VR/AR) to provide highly effective training experiences, connecting digital and physical environments, offering a safe, faithful and immersive platform for operators to develop their skills. Through a preliminary literature review, we propose a systematic analysis of the characteristics and software architectures of these solutions, the sectors involved and the opportunity for adopting them in industrial business. Many virtual design technologies, such as BIM (Kiviniemi et al., 2011), game technologies (Guo et al., 2011), VR (Hadikusumo and Rowlinson, 2002), AR (Mizuno et al., 2004), radio-frequency identification devices, and Geographic Information System were proposed for site hazard prevention and safety management training. For example, by using the virtual reality, the worker could learn the exact risk in their job site. In this study the objective is to evaluate the application of the BIM technology for the definition of training scenarios by using VR model.

The paper is organized as follows: in Section 1 we introduce the definition of BIM and VR/AR, while Section 2 presents the research process and method. Section 3 offers the List of BIM-VR applications. In section 4 we discuss about the research topic and

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finally, Section 5 covers conclusions and suggestions for discussion.

1.1 Introduction to Building Information Modelling (BIM)

Associated General Contractors of America (AGC, 2005) defines BIM as "the development and use of a computer software model to simulate the construction and operation of a facility. The resulting model, a Building Information Model, is a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users' needs can be extracted and analysed to generate information that can be used to make decisions and improve the process of delivering the facility". BIM is a remarkable technology regularly employed in the Architecture / Engineering / Construction (AEC) industry (Yan et al., 2013). It was developed as a tool for engineers to generate and manage building information and facilitate three-dimensional design (Lee et al. 2006). Nowadays, Building Information Modelling (BIM) has been widely used to house a broad spectrum of data relating to the lifecycle activities of buildings including two more dimensions such as planning (BIM 4D) and costs (BIM 5D). The revised bibliography attributes the sixth BIM 6D dimension to the model information in relation to the energy efficiency and sustainability of the building model in accordance with current legislation, NZEB (Nearly Zero-Energy Building) but also for the rehabilitation of existing buildings (Volk et al, 2014).

In early XXI the first historical building information model (HBIM) was developed (Murphy et al, 2009) like a new prototype-system of BIM, a modelling of historic structures as parametric objects in a database "library". Specific HBIM made up on existing historical buildings are able today to encapsulate into their own database a high level of multiple information, not only geometric but also the ones about historic evolution, material composition, stratigraphy, state of conservation, technological and structural behaviour of elements. BIM platforms and algorithms to organize a 3D database can be classified generally according to their tools, the commercial ones are: GraphiSoft ArchiCAD®, Autodesk Revit®, Bentley MicroStation V8i® and Tekla Structures®. Anyway, methods and tools of object recognition differ due to geometric complexity of the building, and applied capturing technique, data format, or processing time (Volk et al. 2014). Processing and recognition methods influence the data quality through the deployed technique and the provided Level of Development (LOD) related to interoperability issue. (Volk et al. 2014). The acronym LOD in the BIM context has different interpretations in literature. The AEC (CAN) BIM Protocol (2014) and AIA (2015) describe LOD as Level of Development referred to the different phases of construction. Consequently, the LOG (Level of Geometry) and LOI (Level of Information) describe each LOD, specifying the different details, progressively required at the given phase of the construction process. Establishing the level of detail necessary for the representation of complex architectural elements is one of the fundamental steps in developing and optimizing procedural methods. Potentially procedural modelling could significantly reduce the investment normally required in digital content modelling operations. One of the most common solutions is therefore the recourse to modelling tools external to BIM, in particular, the use of Visual Programming Languages (VPL) tools, has proven to be particularly effective in overcoming the limitations imposed by standard modelling tools when applied to complex elements that are not native to BIM.

1.2 Introduction to Virtual and Augmented Reality (VR/AR)

Virtual reality (VR) is a computer-generated scenario that simulates a realistic experience through which one interacts in a seemingly real or physical way (immersion) using special electronic equipment (Rheingold, 1991). VR has mainly been based on interactive 3D graphics, user interfaces, and Visual Simulation (VS) to display relevant data and analyses on immersive spaces. Nowadays, Virtual Reality (VR) allows the creation of large and complex training environments; hence high-risk training can be conducted in a safe and cost-effective way (De Gloria et al., 2014). Through VR training (Vahdatikhaki et al. , 2019), on-site safety awareness can be remarkably improved. Statistics show that labour trained via VR performs better in identifying risks, with 20% more than those trained traditionally during the training time (Rubio-Tamayo et al. 2017, Ramsey, 2017). There are many differences between virtual reality (VR), augmented reality (AR) and mixed reality (XR). In VR, a complete imaginary 3D environment can be created, while AR superimposes the 3D digital information over the existing 3D environment (Massimiliano et al., 2021). XR involves the real world and inserts computer-generated content in order to communicate a real-world experience. Furthermore, this holds the ability to capture as well as link fully generated virtual worlds over real-world objects. To integrate BIM with AR/VR, models have to be converted into a particular file format (.IFC, .FBX) and imported into an AR/VR engine. However, the data transfer in this process is not efficient. Because of their size and complexity, models take a lot of time to transfer and much computation effort to render. The transfer of BIM to AR/VR engines leads to inefficiency while representing 3D models with polygonal meshes (Chen et al., 2020). Some building components generated by BIM software have large numbers of redundant polygons that can be merged while keeping the original shape exactly identical. Autodesk Revit 3DS Max, Mc Neel Rhinoceros 3D and Dynamo are the most common softwars used to optimize integration between BIM and AR/VR engines.

2 RESEARCH PROCESS AND METHOD

The efficacy of VR-based training has been largely proven, but implementing VR training requires overcoming technological barriers among trainers and trainees, that ensures the VR content accurately reflects industrial tasks (Pedram et al., 2021). Maintaining an acceptable trade-off between cost and realism of virtual training environments is an open challenge, integration of BIM software and game engines allows to obtain a holistic and dynamic training environment. Overall, a systemic categorisation of the BIM-VR applications has not been proposed yet in the literature. Thus, this paper aims to fill this gap, identifying them and analysing the kind of proposed solutions, results and main aspects for training industrial personnel. To achieve these objectives, the scientific literature was scrutinised in a systematic way (Tranfield et al., 2003). The literature review was conducted on the Scopus database, while the selection procedure was designed following the guidelines drafted by (Seuring and Gold, 2012). A structured search was carried out, combining the keywords 'building information modelling and simulation', 'building information modelling and virtual reality', 'building information modelling and virtual environment', 'building information modelling and augmented reality', 'building information modelling and immersive technology', 'building information modelling and serious game' and 'building information modelling and training'. The list of papers obtained from the searches was refined following the process shown in Figure 1. The keywords search led to an initial set of 3,684 entries, excluding subject areas not relevant to this search the number of documents originally written in English is 1,453. By duplicate removal the total number is 1,238. From this set, only papers with a good Citation Index have been selected, to ensure the quality and relevance of the analysed studies. Thus, the papers were scrutinised by initially reading the title and the abstract. When title and abstract evaluations were unclear, the full paper contents were scrutinised. The following criteria were defined to select papers for the literature review:

- The paper addresses and discusses the application of BIM-VR solutions;
- The paper focuses on design process for construction industry were therefore discarded.

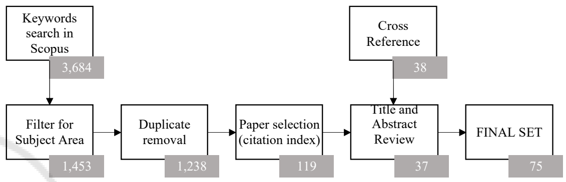

Figure 1: Systematic literature review process.

37 papers were selected based on these criteria. Lastly, in order to overcome possible limitations of keywords search, the set of papers has been complemented by cross-referencing (Seuring and Gold 2012). This step led to the inclusion of 38 additional papers. Consequently, 75 papers have been selected and analysed in detail.

3 BIM-VR APPLICATIONS

By the literature review has emerged that the implementation and integration of BIM-VR technologies has been mainly adopted in the different usage categories: safety training, machines operation training, facility maintenance, heritage conservation/cultural diffusion and others.

The publication of papers about these topics increased in last decade, when BIM technology has begun to develop. The table 1, shows the number of references of analysed papers in relation with the technology and their utilization. We consider the references repeated if it considers more categories. As it can be seen from table 1, the categories that have mostly used this type of technologies are safety training and heritage and cultural diffusion, while in the industrial sector (Machine operations training and Facility Maintenance) there are not many applications. Furthermore, the simulation part is almost exclusively linked to training for activities in dangerous environments such as fire rescue and evacuation procedures. In the following sections we analyse in detail the implementation and integration of BIM-VR technologies in these different categories.

Table 1: Category of utilization and technology used.

Category of utilization	BIM	AR/VR	Game Engine	Simulation	LOD	Tot.
Safety training	11	10	10	8	2	**41**
Machines operations training	2	2	2	0	1	**7**
Facility maintenance	1	1	1	0	0	**3**
Heritage conservation/ cultural diffusion	17	17	15	0	8	**57**
Other utilizations	4	2	2	2	1	**11**
Tot.	**35**	**32**	**30**	**10**	**12**	

3.1 Safety Training

One desired goal of a training platform is to generate expected training outcomes most cost-effectively. The powerful value of BIM-based game engines in creating a low-cost and realistic game environment has been widely recognized. Furthermore, exposing personnel to hazardous situation in a risk-free virtual environment is a viable solution for preparing them for unforeseen harmful situations on site before entering the actual worksite. Afzal and Shafiq (2021) demonstrated that a combination of digital tools such as BIM and VR can help reduce job-site safety threats and increase knowledge sharing by predetermining safety hazards and training on-site workers. They applied different the level of detail (LOD), LOD 300 was applied for the concrete floors and walls, whereas LOD 250 was applied for the other building components. Yu et al. (2022) demonstrated successful integration of VR and BIM to access the information and improve the fire evacuation training. The interdependencies between rescue tasks can be more explicit in the BIM + VR platform than in traditional training modes. Visibility has a great impact on escape chances and single BIM technology cannot simulate the effect of smoke/ temperature/cracking sounds in real fires on emergency procedures (Chen at al., 2021). Their research is focused on the realization of data exchange between BIM, IoT, AR/VR system, game engine and preliminary exploration of whether a training system can improve situational awareness of humans in the virtual environment. In order to implement BIM as a strong base for fire safety management, the model was built in LOD300. Rüppel and Schatz (2011) utilized a physics engine to develop immerse scenarios in a BIM-based serious game for fire safety evacuation simulations. The integrated physics engine, such as Nvidia-PhysX, can qualitatively simulate fire and smoke as well as structural damage after explosions. They found that the more accurate and richly detailed the real-world is mapped in the virtual-world as well as senses can be stimulated, the more the immersion effect in a virtual environment will increaseLiu et al. (2014) adopted the integration of BIM, immersive games, online games, and socio-psychology and physics models to solicit and collect real human behaviours in different emergency scenarios. The advantage of having used this methodology lies in the interoperability of the model that can be exported into more accurate software for smoke and fire propagation simulations, exodus and structural analysis. Park and Kim (2013) developed a safety management and visualization system (SMVS) that integrates BIM, location tracking, AR, and game technologies. BIM is used to create the virtual site model that is converted and stored in the visualization engine for importing and exporting external information such as safety information data and sensor signal location data. If an active RFID is applied to identify worker location, an immediate warning signal can be delivered to workers and a proactive accident control would be possible in the site as well.

3.2 Machines Operations Training

Bernal et al. (2022) developed a system for power substation operational training using BIM and serious games. The model included the main structural, architectural and power equipment and control switchboards, with different levels of development to reduce model complexity, LOD 100 for foundations, basement and site-work while LOD 350 for visible and main equipment and services. Different operational missions could be carried out in the serious game, allowing several skills to be coached. Mondragón-Bernal (2020) used realistic BIM files to develop simulations and focuses on machines' operational training to instruct in the correct operation sequence of the machines, as well as the safety precautions that must be followed to avoid accidents. The user interacts with the immersive game using a Microsoft® Kinect®, tracking the user's upper arm movements (using relative skeleton joints) as well as gamepad keys.

3.3 Facility Maintenance

The use of virtual collaborative solutions such as AR/VR/XR combined with cloud computing and artificial intelligence is significant in the facility maintenance (FM) industry (Zakiyudin et al., 2013).

Agostinelli and Nastasi (2023) investigated the concept of collaborative XR in operation and maintenance tasks as well as for workers' training, exploring a possible framework architecture based on BIM an XR for different application areas of FM. The goal is to improve efficiency as workers currently have to manually get information from different sources and devices to achieve their tasks, leading to a large number of possible errors.

3.4 Heritage Conservation/Cultural Diffusion

Digitisation is becoming an effective solution in making monuments and cultural sites virtually accessible to people, the HBIM model is often used as a base model for VR/AR applications to be employed for cultural tourism purposes. These applications led to the development of immersive environments oriented to the built heritage, thus facilitating a direct interaction of historical models with specific contents of historical-cultural interest.

Meegan et al. (2021) examined the process for developing Virtual Learning Environments (VLEs) using digital recording and modelling of architectural heritage and archaeology. Osello et al. (2018) developed an HBIM model where the architectural elements are simplified, but ensuring the accuracy of values related to space management and component conservation, leaving aside the geometrical correspondence with reality. For this reason, each BIM object was described to a proper LOD, depending on the specific strategy of modelling. Stanga et al. (2023) analysed the application of UAV (Unmanned Aerial Vehicle) photogrammetry in archaeological sites and monuments, highlighting the potential benefits of integrating drones into a comprehensive survey strategy that integrates topographic networking, laser scanning, terrestrial photogrammetry with HBIM and extended reality (XR). Chiabrando et al. (2016) focused on documentation derived from 3D point clouds survey techniques as a significant knowledge base for the HBIM conception and modelling, and on 3D reconstruction of buildings aggregates from a LiDAR (Light Detection And Ranging) and UAV survey by optimizing processes of segmentation, recognition and modelling of historical shapes of complex structures. Banfi (2021) highlighted pros and cons of HBIM projects carried out with different 3D survey methodology for scan to BIM (laser scanning, photogrammetry and UAV) and tries to define a process that can support professionals and not BIM users in creating new digital experiences such as virtual museums and serious games through a methodological approach based on the latest generation of tools in the field of VR and AR. Banfi (2020), thanks to the direct application of novel grades of generation (GOG), went beyond the creation of complex models for HBIM and explored the creation of informative 3D generation of unique elements characterized by high grade of accuracy (GOA) and level of information (LOI) based on the required representation scales. He defined a digital workflow capable of communicating with different types of devices such as Oculus Rift, mobile phone and personal computer. Antuono et al. (2024) developed a BIM-oriented information repository to enrich augmented fruition with virtual tools for real-time information querying on the parametric models.

3.5 Other Applications

Shen et al. (2012) aimed to create a training environment to conduct energy re-commissioning trainings for hospital facility management staff by adopting an interactive web-based 3D BIM game environment (Unity 3D) to allow users to fix and enhance the performance of HVAC systems in Windows, Mac, and iOS and Android devices. Instructors can create scenarios with single or multiple faulty symptoms that are visible to the users in the 3D model, and then challenge the users by asking them to come up with corrective action.

From the point of view of energy efficiency and sustainability, Montiel-Santiago et al. (2020) realized a building energy model (BEM) using BIM Revit software, with the plugin Insight 360 Lighting, and EnergyPlus simulation engines. They performed an analysis of lighting and natural light of the BIM model through automatic and customizable configurations, furthermore, after importing HVAC system in Revit, they carried out simulation and energy analysis of the modelled building. Natephra et al. (2017) developed a BIM-based lighting design feedback (BLDF) for realistic visualization of lighting conditions and calculation of lighting energy consumption using an interactive and immersive VR environment providing qualitative and quantitative outputs related to lighting design. Autodesk Revit, Autodesk 3ds Max, Unreal Engine and the visual programming in Dynamo are used to develop the

BLDF system. Exchanging information between BIM and the chosen game engine is limited to only 3D non-complex geometries (LOD 100–300).

For Architecture, Engineering & Construction, (AEC) business Jeong et al. (2016), through a BIM-integrated simulation, developed a dynamic building construction productivity plan and calculate the project's per-hour rate of production. By executing the process, they extracted the simulation input data from the BIM model, translated it into the simulation data format and imported it in Anylogic® simulation application.

4 DISCUSSION

As result of literature review, the applications of Building Information Modelling (BIM) combined to Virtual or Augmented Reality (VR/AR) and serious games are mainly used in safety training and heritage conservation/cultural diffusion sectors while for training in industrial business it is not very widespread yet. For creating a realistic built environment in 3D game engine, data interoperability between design software and game engine is a significant issue (Shen et al., 2012). In industrial business the use of the BIM-based VR module may be suitable for one dedicated project, however, modelling and developing 4D simulation in a gaming engine for a new project will be time-consuming (Afzal and Shafiq, 2021). Hence, a repeatable workflow is recommended to make this process more efficient. Liu et al. (2016) developed a workflow that illustrates an effective way to link BIM models on Unity game engine, the file is pre-processed using 3DSMax from Autodesk Revit to optimize image smoothness and increase resolution. Once the .FBX file (BIM) has been imported as a new asset on the game engine, it can be edited in order to define animations and interaction properties on the serious game world. When the BIM model is not available, it can be created in two ways: starting with a 3D project file otherwise with a structure scan process to generate point cloud data to be transferred and subsequently modelled in BIM Platform. Also, in "scan-to-BIM" process Autodesk Revit is the most used software to produce the 3D BIM model due to its speed in terms of modelling time and transferring the point cloud model into "3D BIM". This step took 20 working days to model in BIM with LoD 3 (level of detail) over elements like the windows, doors, and plaster, among others (Baik, 2021). The requested effort to develop a virtual environment that meets the realism requirements necessary for the training purpose becomes a crucial factor in choosing this type of solution in industrial business. First of all, it has to be considered whether the 3D BIM is already available or not in the design phase. Obviously, in the second case, the creation of the simulation environment is much faster because the BIM development phase is skipped, or at least integrated. The second important issue is the level of detail (LOD) that has to be reached in the 3D BIM model for obtain the requested realism in virtual training environment. LOD higher than 300 lead to a greater complexity of the model both in terms of development and interoperability with the virtual engine (see figure [2]), this involves the introduction of additional software as a bridge between BIM and the virtual engine (e.g. 3Ds Max) that require further effort both in the design and connection phases. Further integrations of the virtual model with IoT, RFID or other position sensors or simulation supplements for the creation of increasingly realistic training scenarios require further development, increasing the complexity of the solution.

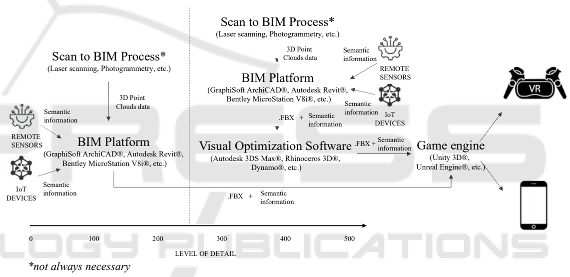

Figure 2: Simulation Model and File Exchange within Software for different LOD level.

5 CONCLUSIONS

In this paper, we presented a literature review to analyse the implementation and the applications of Building Information Modelling (BIM) combined to Virtual or Augmented Reality (VR/AR) and serious games with focus on the characteristics and software architectures of those solutions, the sectors involved and the opportunity for adopting it in industrial business with the scope of creating automatic BIM/VR personnel training environments. Except for Architecture and Construction industries, most of the uses of the combination of these technologies occur in Safety Training, Heritage conservation/cultural diffusion, Facility Maintenance and Machines Operations Training businesses. Interoperability between game engines and BIM models brings the possibility of using real world-based training scenarios able to take advantage of all the information contained in them and the use of AR and VR technologies with game engines helps achieving immersion in the training environment. When a high level of realism of the simulation environment is required, the effort for developing a training scenario increases accordingly and the use of additional software is necessary to optimize the fluidity and sharpness of the images. Although several authors demonstrated the validity of these training tools compared to traditional training methods, their implementation in the industrial sector is still not very widespread since, as a BIM model is not always available, the effort required for the development of a dedicated training scenario could exceed the expected benefits.

Future research can then be directed towards the evaluation of the effort required to develop training plans based on BIM in function of the different levels of LOD required.

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