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Virtual Tours as Effective Complement to Building Information Models in Computer-Aided Facility Management Using Internet of Things

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Featured Application: using Virtual Tours (VTs) to complement Building Information Models (BIMs) and Internet of Things (IoT) systems as a solution for remote control, building automation systems, and other tasks involved in Computer-Aided Facility Management (CAFM). The aim is to provide contextual access to information and opportunities for interaction, simplifying the task of those responsible for managing and maintaining building assets.

Abstract: This study investigates the integration of Building Information Models (BIMs) and Virtual Tour (VT) environments in the Architecture, Engineering and Construction (AEC) industry, focusing on Computer-Aided Facility Management (CAFM), Computerized Maintenance Management Systems (CMMSs), and data Life-Cycle Assessment (LCA). The interconnected nature of tasks throughout a building's life cycle increasingly demands a seamless integration of real-time monitoring, 3D models, and building data technologies. While there are numerous examples of effective links between IoT and BIMs, as well as IoT and VTs, a research gap exists concerning VT-BIM integration. This article presents a technical solution that connects BIMs and IoT data using VTs to enhance workflow efficiency and information transfer. The VT is developed upon a pilot based on the Controlled Environments for Living Lab Studies (CELLS), a unique facility designed for flexible monitoring and remote-control processes that incorporate BIMs and IoT technologies. The findings offer valuable insights into the potential of VTs to complement and connect to BIMs from a life-cycle perspective, improving the usability of digital twins for beginner users and contributing to the advancement of the AEC and CAFM industries. Our technical solution helps complete the connectivity of BIMs-VT-IoT, providing an intuitive interface (VT) for rapid data visualisation and access to dashboards, models and building databases. The practical field of application is facility management, enhancing monitoring and asset management tasks. This includes (a) sensor data monitoring, (b) remote control of connected equipment, and (c) centralised access to asset-space information bridging BIM and visual (photographic/video) data.

Keywords: internet of things; building information modelling; virtual tours; computerized maintenance management system; computer-aided facility management; life-cycle assessment

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1. Introduction

The Architecture, Engineering and Construction (AEC) industry increasingly integrates digital modelling and navigation technologies, such as Building Information Models (BIMs), Virtual Reality (VR), Augmented Reality (AR), and Extended Reality (XR), into its practice [1–6]. These advanced technologies are transforming the AEC industry by enhancing collaboration, productivity and quality during the conception and construction phases, as well as subsequent tasks throughout the building's life cycle, such as Computer-Aided Facility Management (CAFM). The latter is enabled through the use of Computerized Maintenance Management Systems (CMMSs) and other digital tools, including the Internet of Things (IoT) and Virtual Tours (VTs) [7,8]. Although these technologies emerged for different purposes, the natural workflow connecting tasks along the building life cycle increasingly demands their integration. This article describes a technical solution connecting BIMs and IoT data using VT environments and tools. To explain the need and framework of the present technical solution, below is a brief description of the different technologies and their current use throughout the building life cycle concerning the exploitation phase (i.e., facility management and CAFM).

BIMs and visualisation tools. The purpose of Building Information Modelling (BIM) and the resulting Building Information Models (BIMs) is to link 3D virtual geometry and alpha-numeric information related to building and construction. The AEC industry increasingly adopts BIMs as a means of communication among the disciplines implicated (i.e., architects and engineers). In turn, BIM methodologies provide these disciplines with protocols and tools aiming at the effective transfer of information along the design and construction phases. This includes uses such as budget control, construction planning and quality control [1,9–11]. Standards have been implemented in most AEC associations, helping define professional frameworks [12], the classification of construction elements into digital entities (i.e., Industry Foundations Classifications (IFC)) [13], and the definition of levels of detail each model must provide according to the required usage and development phases [14]. These standards define Levels of Detail (LOD), which result from the combination of the Level of Geometry (LOG) or the level of detail of the model's 3D objects, ranging from LOD 100 (global volumes) to LOD 500 (including specific constructive elements like screws or door handles). Similarly, standards define the Level of Information (LOI) attached to these geometries, which augment in complexity from LOI 100 (limited to the object's name and category wall, window, etc.) to LOI 500 (including detailed information such as material composition, manufacturer guarantee, or electricity consumption, according to the type of element). As will be detailed further in this document, high-resolution LOG may be particularly problematic when BIMs are used for CAFM purposes.

VR, AR, XR. Besides 3D data, BIMs provide virtual versions of real or future buildings, helping anticipate aesthetic, construction, or logistic problems before and during construction. Digital tools such as VR and AR, initially developed for the gaming industry [15,16], are increasingly adopted by the AEC industry to help visualise their 3D models, serving different purposes [17]. VR is commonly used to showcase projects to clients and investors, exploding the immersive and realistic possibilities of VR to provide vivid, immersive experiences. For instance, how spaces and materials will look in future new or retrofitted buildings [18]. Some examples have even gone further to explore the possibilities of linking BIMs and IoT technologies via VR environments [19–22]. In turn, AR and XR technologies are mostly implemented as construction quality control tools, allowing the superimposing of digital models into the building-in-progress site and helping professionals anticipate future collisions or detect the misplacement of certain elements under construction [23]. Another extended use of AR and XR relates to cultural heritage buildings—improving historical site explorations [24] or guiding visitors within districts and buildings [25].

VT. Defined as image-based geolocalised 3D reconstructions of real spaces and buildings, VTs are increasingly used to showcase and visit buildings remotely. The primary sectors utilising VTs are heritage and culture, as well as tourism and hospitality [26–30]. This encompasses museums, hotels, archaeological sites, and other institutions worldwide. Additionally, Google Maps 'Street View' is a significant VT tool that allows users to explore nearly any street globally [31]. VT can also be linked to geolocalised databases. Google's street browser prompts street names, and some buildings and businesses are pinned with related information. Likewise, VT software [32] and platform providers include modules allowing users to tag and describe objects shown in the image environment, including the possibility of linking IoT data, as this research will demonstrate.

IoT. IoT technology links real-object data to the object's virtual replicas stored in the cloud or a server. Such objects are usually equipped with sensors and specialised software, enabling monitoring and remote control. IoT is already part of daily life in many households and companies. It is also becoming prominent in CAFM, integrating monitoring devices that not only track and control building performance as Building Management Systems (BMSs) [33–41] but also introduce energy-saving and space-optimisation methods based on user behaviour and other real-time measurements [42,43].

CAFM platforms. Over the past decades, the information technology (IT) industry has developed software solutions for Common Data Environment (CDE) and CAFM platforms. Some of these solutions are designed for specific building phases, such as conception to construction [44–47], fabrication [48,49], or facility management [50]. Other platforms are conceived with an LCA approach, aiming to integrate data-management tools along the entire building life cycle [51–53]. CAFM platforms enable users to integrate BIMs, 2D plans, product catalogues, and other relevant documents that gather information related to the building and its equipment. In addition, these platforms feature interfaces, such as Gantt charts and spreadsheets, to assist facility management routines, including service management, quality control protocols, or room allocation. Due to their varying levels of complexity, using these platforms can be challenging, requiring consistent training and significant time investment. Furthermore, as will be discussed further, even though these platforms allow the integration of VTs, the connection between intuitive VT navigation and BIMs remains absent.

To summarise this review, with a particular focus on CAFM practice, both literature and empirical knowledge demonstrate feasible and practical connections between IoT and BIMs [19–22,54–59], as well as between IoT and VTs [60]. In contrast, a research gap concerning the link between VTs and BIMs is evident [61,62]. These technologies can be integrated into the specialised platforms mentioned above to better assist facility management in daily tasks, such as room allocation, equipment management, maintenance scheduling, or security control. In the case of CMMS, such platforms can also integrate remote monitoring and control via IoT, including the synchronisation of BIMs and real-time monitoring data (Digital Twins) [35,39,54].

For this reason, asset owners need both detailed and not detailed BIMs. Figure 1 illustrates the benefits of BIMs (green shade) versus VT (blue shade) in relation to their usage across different building construction phases. While detailed BIMs may be almost useless for routine operational tasks, they are crucial for subsequent phases such as renovation and demolition. Hence, owners require AEC professionals to deliver BIMs with lower LOG, and often higher LOI, [63] compared to the BIMs used for construction. The need to reduce BIMs level of detail for FM purposes is translated into complex Moreover, even though detailed BIMs represent reality digitally, they still miss out on some important documentation layers, like visual information from photos, webcams, or videos. In addition, certain IoT systems for remote control and monitoring could be easier for non-trained users if they interact with photorealistic environments (VTs) rather than abstract digital models (BIMs) [26]. Upon these arguments, this article explores the potential of VTs as a complement to BIMs in IoT-based CAFM, trying to answer its main question: how can VTs complement and connect to BIMs within a life-cycle perspective?

The purpose of our work is to explore the potential of VTs for practical applications in CAFM. We propose a technical solution using VT as an intuitive access point for FM users to BIMs and IoT data. This solution aims to enhance monitoring and asset management tasks, including (a) sensor data monitoring, providing an interface for rapid data visualisation and direct access to data sources; (b) remote control of connected equipment, allowing FM users to operate certain IoT objects directly from the VT interface; and (c) centralised access to asset-space information, integrating BIMs stored in CDEs and FM platforms with the dynamic information contained in georeferenced 360° images.

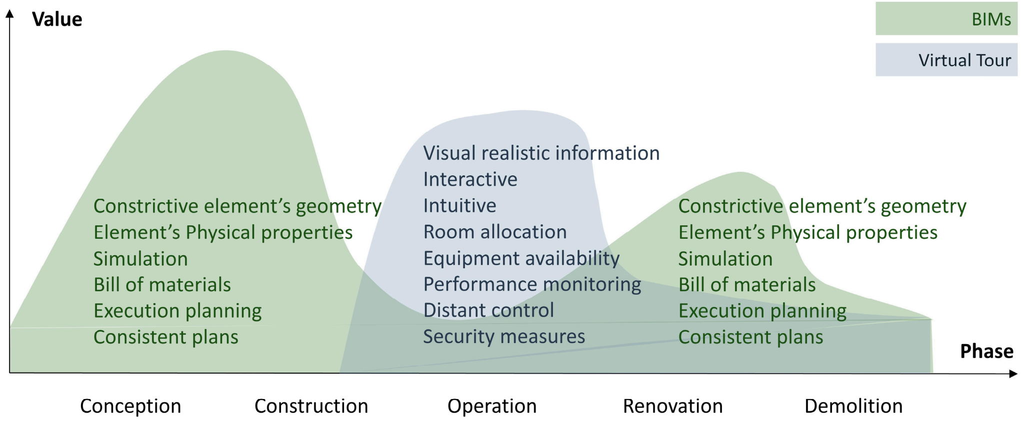

Figure 1. Added value of BIMs and VTs, in relation to the building life-cycle phase.

2. Methodology

The business problem encountered by AEC and CAFM professionals has been discussed in the preceding section. Specifically, spatially referenced building data, which are crucial for CAFM and reside within BIMs, are frequently inaccessible or overly complex for effective utilisation by facility managers. Through literature analysis and the author's empirical insights as research-driven facility managers and integrators of innovation into a research facility [64], this research determines that VT can offer a solution to the business problem. In this sense, and as illustrated in Figure 2, VT is regarded as an operational point of entry for CAFM users to access IoT and BIM data.

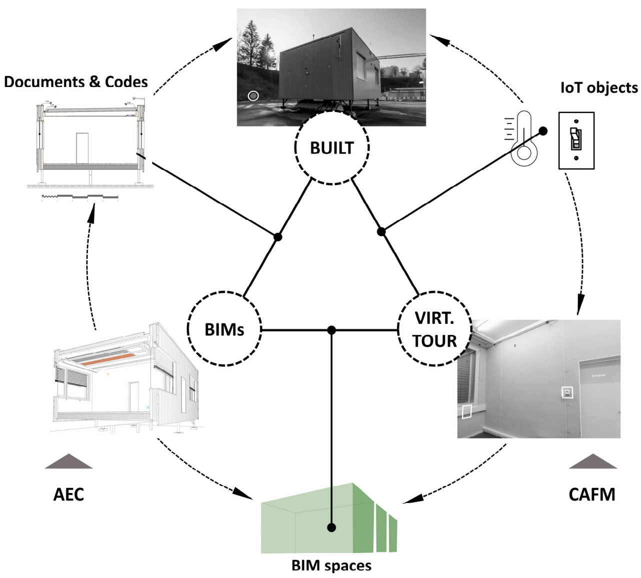

Figure 2. AEC and CAFM entry points to the Information-control loop between the build object, BIMs, and VT.

Consequently, a VT has been developed based on the methodology outlined below. This VT enables navigation through the interiors and exteriors of various assets, as well as consultation of monitoring (IoT) and BIM data. The VT is composed of georeferenced photographs captured periodically on a lapse of one year using 360° cameras and drones [65,66]. The tour also features an accreditation module providing access to building data according to user category, ranging from public to specialised scientists.

To evaluate the IoT-VT-BIMs connectivity (see Figure 2), the Controlled Environments for Living Lab Studies (CELLS) [67] has been used. CELLS is a twin-room HVAC autonomous pavilion that allows the control and monitoring of indoor comfort conditions and building management systems, including automation of certain functionalities. CELLS operates as an "incubator" to benchmark and validate systems that will be functional on real buildings, including the current [68] and future offices of the Smart Living Lab [69]. This future application is relevant to this research, as it involves CAFM at a high level of complexity, including flexible monitoring and remote-control processes. The future office building features dismantlable façade modules for testing and monitoring new envelope materials, as well as flexible partitions accommodating a range of spatial layouts and various office sizes. This future system is based on a 3 by 3 m module, where each module can be individually controlled thanks to a specialised HVAC system [64].

The case study of CELLS provides a unique perspective on this integration, offering a practical example of how these technologies can be implemented in real-world settings. The constructive characteristics of this pavilion, including its building envelope, the double-glazed windows, and the HVAC and electric systems, provide optimal and reliable conditions for the operations and measurements involved in the experiment. To create the VT and establish its connection to IoT and BIM data, the following steps have been taken:

A. System data setting
    - IoT: CELLS is equipped with a number of IoT elements, including sensors (temperature (interior and exterior), wind speed, rain, inlet power consumption, lighting fixtures, active power, lighting intensity, etc.), as well as controllers (blinds (up/down), lighting switches (on/off), among others). For the demonstrative purposes of this research, two specific system elements have been fully integrated into the IoT-VT-BIMs (see Figure 2) connection: light control (on/off) and historical temperature inquiry (interior and exterior). Remote control and inquiring of these elements using HTTP protocols and interface are set.
    - BIMs: a digital replica of the pavilion was modelled using the BIM software Autodesk Revit v.2023 [70], and according to an LOI 400 standard [14]. In previous research, this model was successfully integrated into a VR environment and linked to the related IoT data [22].
B. VT setting
    - Image capture: definition of physical spots to capture interior and exterior images of the building, combining aerial and ground photographs using a 360° camera [65] and a drone [66]. This sequence is recurrent over time, allowing to capture spatial arrangement changes.
    - Image processing: captured images are processed to develop the website VT using the website PhotoSphereViewer library [71] and the JSON configuration files to establish a chronological framework for various historical periods in a specific location and to identify associated named locations.
C. VT link to IoT: the creation of identifiable objects in the VT to establish a request to the real-time IoT database. This allows the identification of certain elements corresponding to controllers or actuators in the real space. As a case study, a temperature reader has been used to display the historical values of temperature in a specific room in relation to the global external temperature.
D. VT link to BIMs: the upload of BIMs into a Common Data Environment (CDE) and establishment of a connection between the photo location in the VT—'*the room*'—and the related room object in the BIMs (i.e., IfcSpace). All information associated with the room should be accessible from the VT.
E. Accreditation: the implementation of a module to manage user accreditation to access certain spaces and data. Accreditation takes place at four levels: (a) public (can visit only non-confidential spaces); (b) building users (+ access to certain confidential spaces and data); (c) group leaders (+ access to sensible confidential data); and (d) managers (access to the entire system).
F. Evaluation: testing connectivity and evaluating system implementation and replicability.

G. Scalability: the development is implemented in the building currently housing the Smart Living Lab, which includes 34 offices and 3 meeting rooms and large communal spaces [68]. The use of this ongoing process allows us to evaluate the tasks, effort, and operability problems encountered in the transition from the test bed to a real-life building.

3. Results

Below is a succinct overview of the key steps involved in implementing the methodology and ensuring its replicability.

Step 1: Use-case definition. This step consists of answering the following questions: who will utilise this development, and how will it enhance their task performance? The use case implies researchers who will employ the new building as a scientific tool [64]. Each user group—professors, scientific collaborators, doctoral students, and the facility maintenance team—must have effective access to information in a format that best suits their task-needs. For CELLS, which serves both teaching and research purposes and caters to individuals who may not always be on-site, an essential requirement is an online solution that is accessible remotely.

Step 2: Development strategy. This involves assessing whether existing open-source solutions can adequately address a specific use case or whether an in-house solution is necessary. Various VT software options were tested, standing out 3DVista VT Pro [32]. While the tested software provided features useful to the research, certain requirements were not attended to: (a) Authentication Component: the use case necessitates an authentication component that aligns with the IT security standards of the involved institutions (EPFL, HEIAFR, and UNIFR) [69]; (b) Flexibility for Marker Integration: the ability to seamlessly integrate markers (such as polygons or geometric elements) into 360° images, allowing connections to IoT elements; (c) Scalability: the need to accommodate both detailed construction aspects (at a small scale) and broader neighbourhood dimensions (at a larger scale); (d) Versioning: the VT needs to be evolutionary over time in relation to building life-cycle analysis and renovation updates—chronological navigation through different versions of the same location is essential; and e) JavaScript Integration: need for flexibility to integrate JavaScript scripts, whereas 3D Vista was very limited, including limited or incomplete documentation.

Step 3: Capturing devices. This step complements the development strategy by integrating the capturing devices to be used. According to the use case, the building assets at the district level (outdoor) needed to be reconstructed, including detailed information at the room level (indoor). A specific device was dedicated for each function. For the district level, a DJI Mini 3 Pro drone [66] was used, which allows 360° photo captures at various altitudes (i.e., 2, 30, and 70 m), as well as zenith views (orthophotographs). For room capturing, the Ricoh Theta Z1 [65], a 360° camera, was chosen for its simple use and linkability to standard smartphones (see Figure 3—image acquisition).

Step 4: VT technical development (see Figure 3—image acquisition and image file processing). Having defined the use case and the development strategy, development was divided into six technical modules: (1) Capturing protocol: the referential definition of capturing points, including nodes of reference and capturing frequency. (2) Storage sizing: According to image resolution and capturing frequency, the size and type of storage device was defined. The images are stored on the same server used by the VT web page. (3) Image chronological sorting: The configuration file indicates to the tour360 server that a new date has been added, including the name of the associated locations. Without this information, the server will not be able to identify new available image-paths. Consequently, the date picker would not offer the new date for a given location. The configuration file plays a crucial role in ensuring that the tour360 server can effectively manage and display new dates associated with specific locations. (4) Image polar orientation: A script defining a reference point to establish a singular orientation for each capture point. This module is important for making VT navigation more intuitive, preventing unwanted changes in the direction of observation when moving from one location to another. This also provides users with a compass and the orientation of the image in relation to the geographical north. (5) Lag prevention: The VT works with two panorama layers of 128 tiles—low and high resolution. This is to optimise loading and prevent lagging during navigation. The panorama is rarely, if ever, reconstructed in full. When a user loads a new panorama, their browser initially requests the blurred (lighter) version of the entire panorama, which loads much faster. Only the sharper tiles included in the user's viewing frame are loaded shortly after. This process is completed with the JavaScript library PhotoSphereViewer [71], which takes care of displaying the panorama. It places the tiles in the right position and updates them in real time as the user browses the site. (6) Access security: Images are stored and accessed by the tour server behind an authentication protocol. This allows for control of access at several levels, granting different users varying rights. For example, it permits accredited members of the public to navigate exteriors and public spaces, specialised scientists to access any room, and researchers dealing with confidential data to access real-time information. Upon accessing the tour, a login interface is prompted, and certain areas of the tour may or may not be accessible based on the user's credentials.

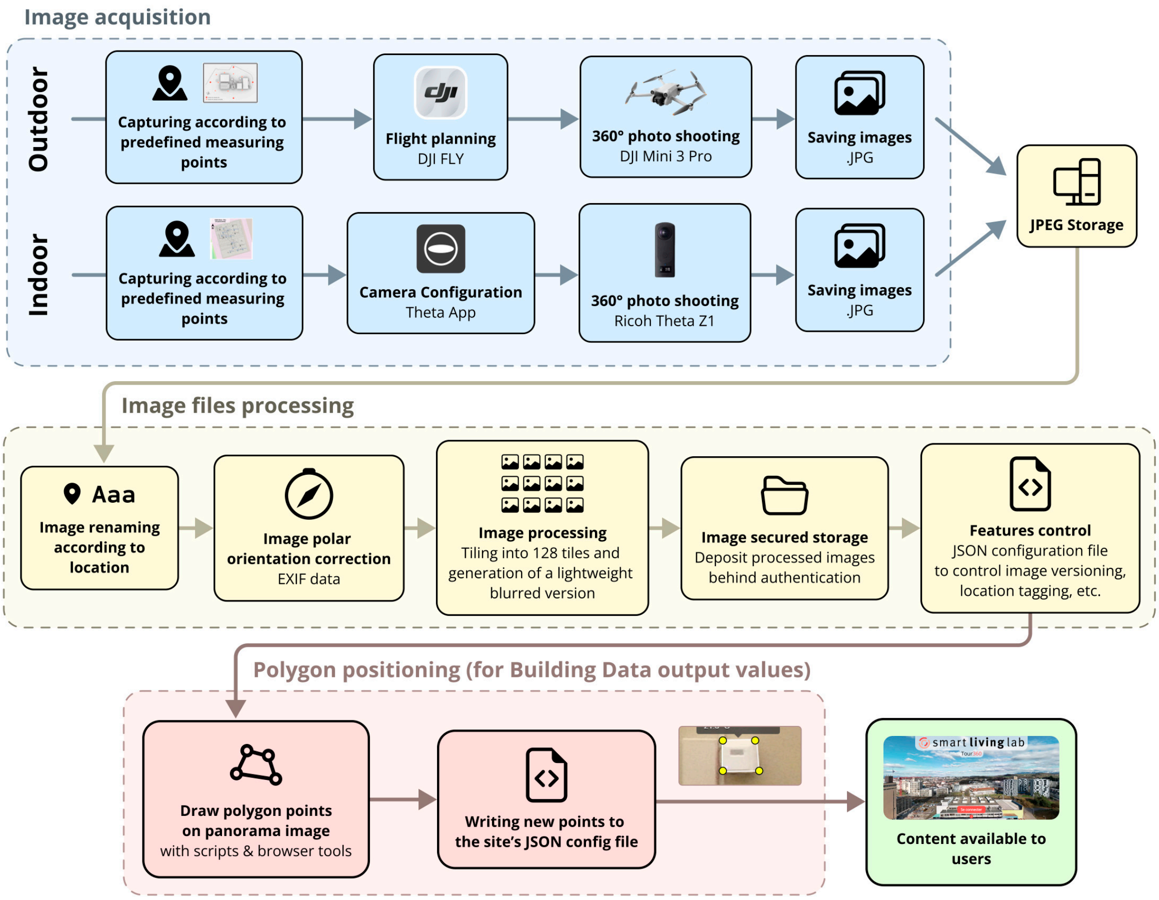

Figure 3. Workflow for VT construction and definition of database-linked elements.

Step 5: Integration of IoT (see Figure 3—'polygon' positioning). This step involves creating a reference geometry (typically a polygon or boundary representation) superimposed on a visible object within the VT. For example, the silhouette of a temperature sensor. Once defined, the polygon becomes a georeferenced object within the VT, enabling connection with other objects in a database. In the example, when an accredited user clicks on the temperature polygon, a graphic displaying the history of stored temperatures is prompted (see Figure 4). While adding new polygons may be time-consuming, the fact that they are geolocalised objects assures their correct position independent from image versioning.

Hence, it is a process that takes place only once. The data shown in the graph of Figure 4 are acquired by MileSight sensors, as described in section 2A, and stored in a local server (see "Monitoring" in Table 1).

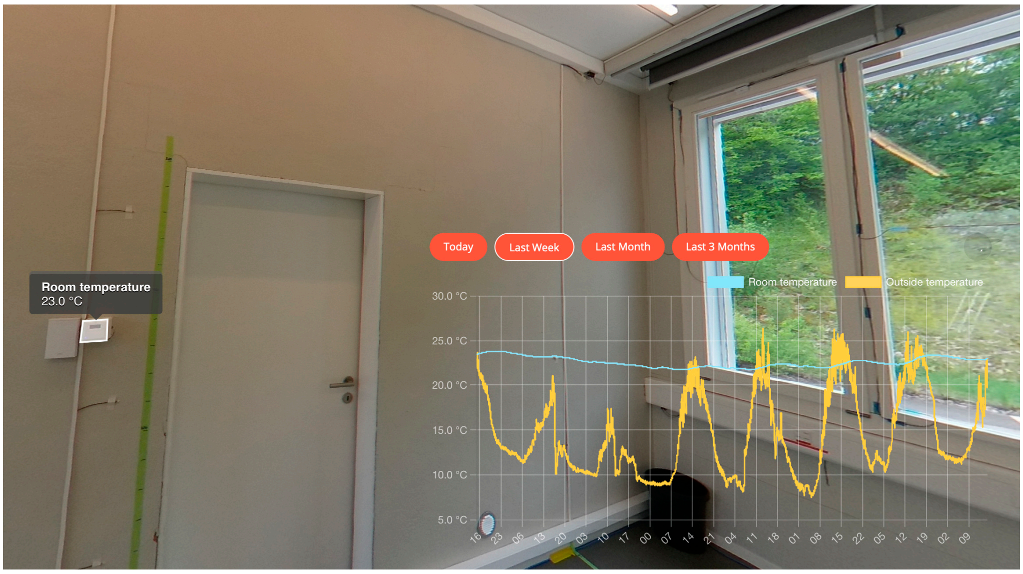

Figure 4. Example of historical values of temperature accessed from the VT.

Table 1. Data source, generation process, and data storage for the steps described in this section.

Data Source	Generation	Storage
Monitoring	Predominantly MileSight sensors installed in the CELLS facility	BBData: server CISCO Hyperflex Edge, located in the university
Photo capturing	Cameras of DJI Mini 3 Pro drone and Ricoh Theta Z1 360° camera	None: temporary storage in USB drive, then destroyed
Photo processing	Treatment by scripts run on photo captures, as described in Figure 3	Tour360 web server protected by an authentication protocol, as described in Figure 3
Polygons	Tracing of polygonal shapes using scripts and browser tools	
BIMs	Web-uploading of digital mock-ups modelled by Autodesk Revit	Speckle web server

Step 6: Connection to BIMs (Figure 5). The platform for 3D data, Speckle [47], is selected as the CDE. Speckle is an open-source digital platform designed for hosting 3D models, facilitating interoperability between software silos, real-time collaboration, data management, versioning, and automation. This platform is ideal for research needs, as it supports BIMs version management and utilises HTTP protocols, enabling linking various online databases, including the VT developed by the authors. Based on Speckle's API for public streams, "GET request of the HTTP protocol", by using the "Downloading a Single Object" [72], it is possible to connect a photo location in the VT to the specific correspondent room object in the BIMs. The response for this query contains all properties stored in Speckle associated with the object in question, from which the ones to be prompted in the VT can be chosen. Additionally, the http address directing to the object can be added as a hyperlink to the interface, allowing the user to visualise the object in the BIMs' platform viewer. Once in the platform's environment (i.e., Speckle), the user can inquire about additional geometrical or alphanumeric data contained in the uploaded BIMs. Figure 6 shows the Speckle interface as prompted when the user clicks on the link "View object on BIM model" (see Figure 5). The object in question ("Room 2" in this case) is blue-

highlighted in the viewing zone, while other objects (i.e., the architecture or MEP models) can be added and filtered by the user (data tree on the left-side column and geometries in grey on the viewing zone). Additional properties related to the object (Room 2) are also available (right-side column).

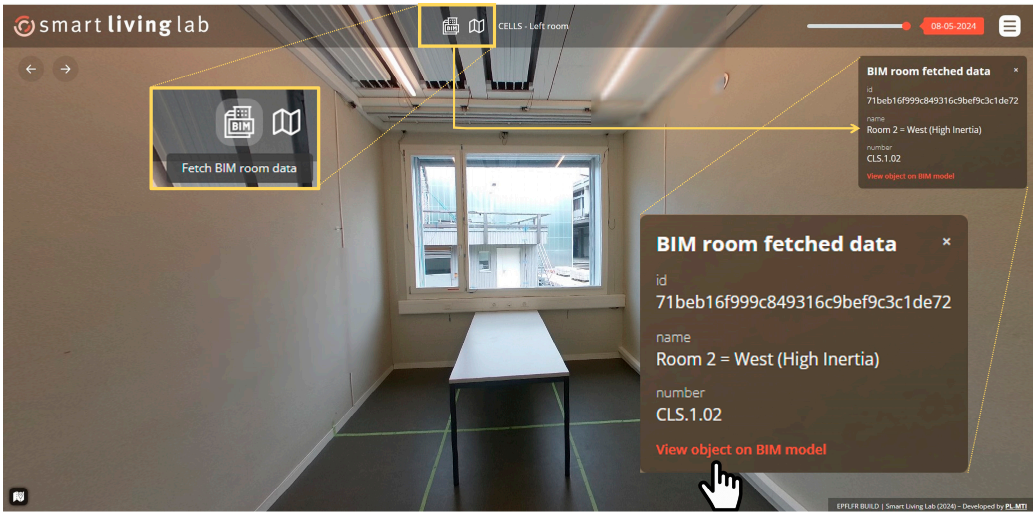

Figure 5. Example of '*Room 2*' in the VT connecting to BIMs.

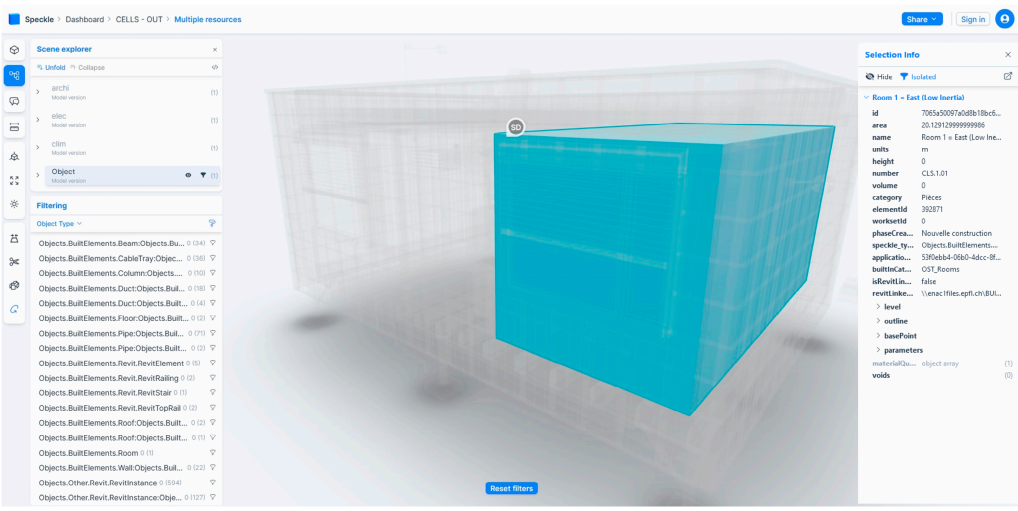

Figure 6. Example of '*Room 2*' in the BIMs' CDE platform [47].

Step 7: Scalability. The technical solution is currently implemented in other buildings in the district. For further details and evaluation of this process, please see the next section. Figure 7 shows the VT interface, using the orthophoto tool, to illustrate the current and future intervention spaces for escalating the solution. The spaces highlighted in this article are shown in green. In red are the 26 spaces under implementation (results expected in November 2024). The large yellow dot represents the future Smart Living Lab Building, which is the ultimate implementation target of this research.

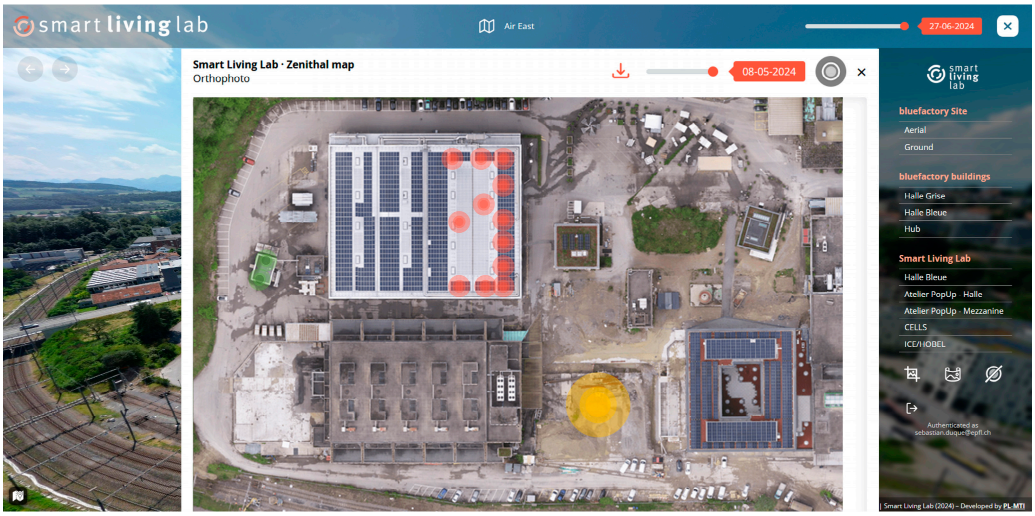

Figure 7. VT interface showing entire site orthophoto and spaces under implementation.

4. Discussion

The integration of Building Information Models (BIMs) and Virtual Tours (VTs) in the Architecture, Engineering and Construction (AEC) industry represents a significant advancement, particularly within Computer-Aided Facility Management (CAFM) and Computerized Maintenance Management Systems (CMMSs). The varying levels of detail required in BIMs at different building phases, combined with the potential of VTs to enhance BIMs and IoT-based CAFM, are crucial areas of development. The case study of the CELLS facility provides a practical example of this integration, showcasing flexible monitoring and remote control through IoT devices and VT models.

This research aligns with current trends in the field, focusing on CAFM and CMMSs in relation to BIMs and IoT [35,73]. However, the exploration of VT's potential to enhance BIMs in IoT-based CAFM is a relatively new area, laying a strong foundation for future research and developments.

In relation to CAFM systems using VR, it can be stated that the VT offers a user-friendly interface based upon a common web application, which can be easily mastered by any CAFM professional, independently of their technical skills. Daily manipulation also seems much simpler, only requiring a computer device connected to the hosting network. In contrast, VR requires sophisticated equipment, including VR helmets, performant graphic cards, and fixed stations. Troubleshooting for VR is also more frequent and often requires the physical presence of technicians [21,22].

In relation to CAFM systems using AR, VTs enable remote control. Most applications using AR evidently exploit the in-site lead of the technology, by superimposing data to the space information, which is being registered by the device's incorporated camera (i.e., a tablet or a smartphone). Access to data using AR is, therefore, only useful if the user is physically present in the implicated space [23,25]. In contrast, VT interfaces can provide full functionalities, both remotely and in-site.

In relation to CAFM systems using BIMs, the advantage provided by VTs lies in the realism of their detail and the relative ease with which they can be updated. To save time and machine-power consumption, CAFM users often require AEC professionals to deliver BIMs at LOG 300 or less and LOI 400-500. AEC professionals often use the room entity (i.e., IfcSpace) to associate most related information, including furniture, equipment, and other types of facilities for which no geometrical representation is modelled [1,2,4]. Therefore, a facility manager solely using BIMs will not have visual control of the specificities related to elements such as projectors, fire extinguishers, or window blinds in a given space. In contrast, the VT can provide full visual and realistic information about the different elements of a room. Moreover, if connected to the room element in the BIMs, as proposed in this article, such a layer of visual information can effectively complement the alphanumeric data stored in the BIMs room (see Figures 5 and 6). In addition, and as discussed earlier, updating a VT can be largely automated, requiring only manual image capturing over time, a task that can be performed by facility managers themselves and requires little training.

The methodology yielded successful results for the specific case study. Image capturing and processing remain reasonable for the service a VT may provide for CAFM purposes. The definition of linked elements, if well defined in advance by CAFM requirements, presupposes a more challenging but manageable task. Navigating a VT is smooth and user-friendly. VTs, unlike BIMs, are relatively easy to keep up to date, relying on less qualified personnel to perform the task. This offers considerable efficiency in performing CAFM routine tasks.

Table 2 summarises the level of difficulty encountered during the implementation and update of the technical solution and its scale-up potential.

Table 2. Implementation evaluation by task according to the following criteria: Feasibility (Y = Feasible, N = Non-feasible); Execution complexity: the difficulty of initially setting up the feature (1 = very easy, 2 = easy, 3 = moderate, 4 = complex, 5 = very complex); Scalability: how far can the functionality be escalated in terms of technical resources and feasibility? (1 = scalable, 2 = limited scalability, 3 = moderate scalability, 4 = barely scalable, 5 = not at all scalable); Update complexity: the difficulty of maintaining or updating the feature (1 = very easy, 2 = easy, 3 = moderate, 4 = complex 5 = very complex).

Feature	Feasibility	Execution Complexity	Scalability	Update Complexity
(Geo) location	Y	3	1	1
Versioning	Y	4	3	1
Object to IoT database	Y	1	3	2
Space to room in BIMs	Y	2	2	1
Object to BIM object	Y	2	2	2

Concerning the *execution complexity* parameters, ratings 3 and 4 refer to the difficulty in defining a reproducible method/process for adding images, which required a good understanding of the entire website setup and the PhotoSphereViewer library. Also, there was a need to write additional scripts to process the 360 images into small tiles, including the blurring effect, to avoid latency. However, once established and set up, the process was automated. Thus, the 1 or 2/5 rating for *update complexity*. The entire setup took about 120 h of work by skilled programmers.

Concerning *scalability, Versioning* rates 3 because the accumulation of images can be a relatively time-consuming task, especially when dealing with new versions that may weigh over 2 GB. This raises questions about the available server storage space. In relation to Object-IoT DB connection, the rating 3 derives from the specific database used (BBData) [74], in which queries between the site and the database are not well optimised. In the event that many objects are consulted, the database can be overloaded. This is because the database used lacks a single query that directly provides a value table for a desired sensor collection. In contrast, on the Tour360 side, the process is just as scalable as *Space to Room in BIMs* and *Object to BIM object*. The database is being improved to solve the issue.

The task of creating the initial polygons is relatively time-consuming. However, since the polygons are associated with geolocation information, there is no need to recreate them for subsequent versions.

The fundamental limitation of the technical solution is related to its implementation in a real-functional building (Step 7: Scalability, in Section 3). Three major challenges in this respect can be identified: the scale of implementation, the user evaluation, and the issues related to cyber-security and remote control.

As discussed in the previous section, the solution is under implementation in 26 spaces of an office building [68]. The project shows satisfactory results, as predicted in Table 2. Nevertheless, certain obstacles related to the escalation of the solution cannot be fully identified before the end of the implementation (November 2024).

The solution also lacks an evaluation mechanism by a real FM user. A methodology to evaluate the different aspects an FM user may require is under design. The proposed methodology will undergo testing with team members who will operate the 26-office system under real-world conditions. However, significant limitations can be anticipated, particularly in relation to the skills required for tasks such as setting up and maintaining the VT. This limitation is especially relevant in the context of image processing and the addition of new elements linked to the database.

Finally, an important issue raised by online IoT systems enabling remote control is the over-exposure to cyberattacks, unwanted third-party control, or the risks related to automation and alert-system failures (e.g., an automatically closing window colliding with a misplaced object). Further exploration, currently out of the reach of this research, must be addressed and integrated.

By balancing scalability challenges and the connectivity of different functional bricks discussed in this article, the development presented provides solid evidence for a reliable data flow for CAFM, allowing the linkage of BIMs, IoT elements, and VT platforms. Figure 8 summarises this connectivity.

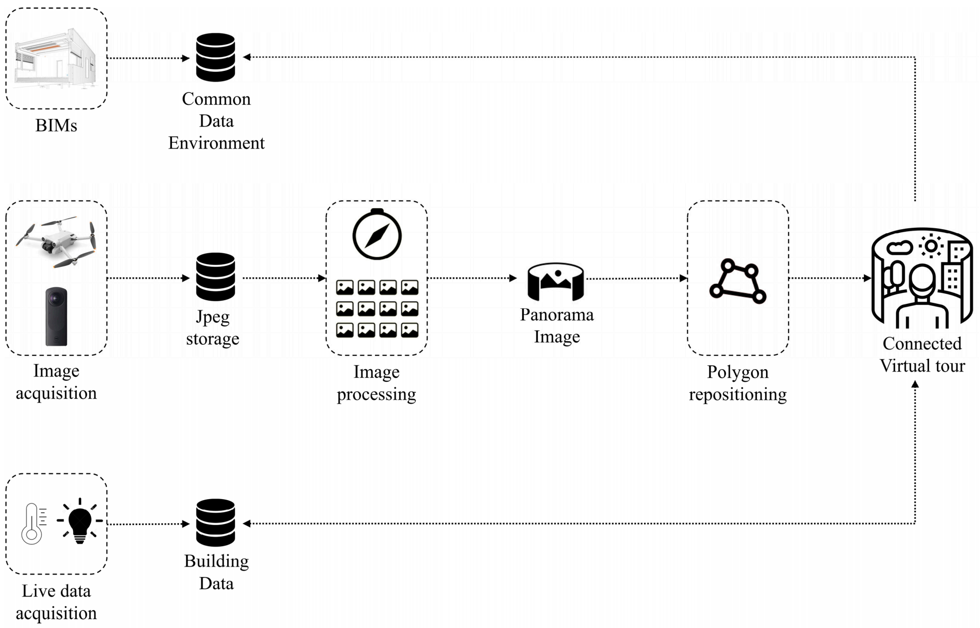

Figure 8. VT connected to live data and BIMs.

5. Conclusions

This research demonstrates the benefits of integrating IoT technology, BIMs, and VTs in the AEC industry, particularly within CAFM and CMMSs. The case study conducted on the BIMs and IoT-enhanced CELLS infrastructure serves as a practical example, highlighting how these technologies can be effectively implemented in real-world scenarios for CAFM. The literature review indicates that advanced research and real case examples provide evidence of effective connectivity between BIMs and IoT elements, as well as between VTs and IoT systems. The technical solution presented aims to close the connectivity gap between BIMs and VTs. This link is crucial, as it enables access to both real-time IoT and BIM data from a VT interface. Utilising VT as a central interface for CAFM users has the potential to significantly impact industry practices across several dimensions, which can be highlighted as follows:

(a) Virtual touring in space and time: CAFM users can utilise web-based intuitive interfaces to navigate through building assets, including interior, exterior, and chronological dimensions. If image capturing is well established in maintenance protocols, VT can serve as a tool for remote inspection, particularly when linked to IoT data monitoring.
(b) Intuitive interface for IoT monitoring and remote control: VT can serve as the entry point for intuitively consulting IoT real-time databases for a given room. This enables CAFM users to perform IoT-related tasks involving both monitoring (status consultation) and remote control (status modification). Such services can enhance CAFM operations, enabling informed decision-making and predictive maintenance and leading to cost savings and improved service delivery. Quicker response times and better maintenance planning become possible through real-time data access via VT.
(c) Rational use of BIMs: As discussed, the level of information required for BIMs is defined by the specific phase of a building's life cycle. As phases approach construction, geometrical and alphanumeric detail increases, transforming BIMs into large and complex data sets. As illustrated in Figure 1, the operation phase requires different types of information details that are not necessarily included in "as-built" BIMs, which will nevertheless be crucial for subsequent phases, including renovation and demolition. Moreover, updating BIMs to reflect daily minor transformations, such as equipment and furnishing changes, is costly and requires skills CAFM users typically do not possess. This article proposes an alternative to current practices (i.e., generating two types of BIMs: one for future renovation, the other for CAFM) by suggesting an interface serving two roles: (1) providing an intuitive access point to "as-built" BIMs, allowing non-skill users to navigate and inquire BIMs data; and (2) complementing BIMs by providing visual and minor-updating information on assets.
(d) Navigation tool centralising building data: the integration of the aforementioned dimensions enables VTs to serve as key interfaces for data centralisation. By linking visual, monitoring, and building information data, users can access and manipulate information from a central point regardless of whether these data are stored in different databases and can be visualised through various platforms. By connecting three types of web-accessible information (i.e., real-time monitoring data, georeferenced pictures, and informed 3D models), the presented development facilitates the centralisation of information while providing an intuitive and user-friendly interface for inquiries.

The integration of IoT, VT, and BIMs opens up new research opportunities aimed at simplifying the use of these technologies. This integration helps avoid data redundancy and rationalises storage space, data manipulation complexity, and Building Information Modelling requirements. Future research will face challenges, particularly concerning large-scale building implementations. However, the presented findings provide a strong foundation. Industry professionals can build upon these insights to drive innovation and refine existing practices, effectively bridging the gap between advanced technology and AEC industry standards.

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References

1. Ingram, J. *Understanding BIM*; Routledge: New York, NY, USA, 2020; Volume 10017.
2. Wong, J.; Yang, J. Research and application of Building Information Modelling (BIM) in the Architecture, Engineering and Construction (AEC) industry: A review and direction for future research. In Proceedings of the 6th International Conference on Innovation in Architecture, Engineering & Construction (AEC), Loughborough, UK, 9–11 June 2010.
3. Park, C.; Rahimian, F.P.; Dawood, N.; Pedro, A.; Dongmin, L.; Hussain, R.; Soltani, M. *Digitalization in Construction: Recent Trends and Advances*; Routledge: London, UK, 2023. [CrossRef]
4. Hadavi, A.; Alizadehsalehi, S. From BIM to metaverse for AEC industry. *Autom. Constr.* **2024**, *160*, 105248. [CrossRef]
5. Davila Delgado, J.M.; Oyedele, L.; Demian, P.; Beach, T. A research agenda for augmented and virtual reality in architecture, engineering and construction. *Adv. Eng. Inform.* **2020**, *45*, 101122. [CrossRef]
6. Tukur, M.; Schneider, J.; Househ, M.; Dokoro, A.H.; Ismail, U.I.; Dawaki, M.; Agus, M. The Metaverse digital environments: A scoping review of the techniques, technologies, and applications. *J. King Saud Univ. Comput. Inf. Sci.* **2024**, *36*, 101967. [CrossRef]
7. Parsanezhad, P. Towards a BIM-enabled Facility Management: Promises, Obstacles and Requirements. Ph.D. Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2019.
8. Oti, A.H.; Kurul, E.; Cheung, F.; Tah, J. The Utilization of BMS in BIM for Facility Management. In Proceedings of the CIB World Building Congress, Tampere, Finland, 30 May–3 June 2016; pp. 224–235. [CrossRef]
9. Poljanšek, M. *Building Information Modelling (BIM) Standardization*; Publication of European Commission and the Joint Research Centre: Luxemburg, 2017. [CrossRef]
10. Dautremont, C.; Dagnelie, C.; Jancart, S. Le BIM6D comme levier pour une architecture circulaire. *SHS Web Conf.* **2018**, *47*, 01005. [CrossRef]
11. Potrč Obrecht, T.; Röck, M.; Hoxha, E.; Passer, A. BIM and LCA Integration: A Systematic Literature Review. *Sustainability* **2020**, *12*, 5534. [CrossRef]
12. Societé Suisse des Ingénieurs et des architects, SIA2051 Building Information Modelling. 2017. Available online: http://shop.sia.ch/ (accessed on 29 July 2024).
13. BuildingSMART. *Industry Foundation Classes (IFC)*; BuildingSMART: Berlin, Germany, 2020.
14. Bauen Digital Schweiz, Définition swiss LOIN (LOD) BIM—Compréhension. 2018. Available online: https://bauen-digital.ch/fr/ (accessed on 29 July 2024).
15. G2.com Inc. g2/VR Game Engine Software. 2012. Available online: https://www.g2.com/categories/vr-game-engine (accessed on 29 July 2024).
16. UnityTechnologies. *Unity Cross-Platform Game Engine*; UnityTechnologies: San Francisco, CA, USA, 2005.
17. Shi, Y.; Du, J.; Lavy, S.; Zhao, D. A Multiuser Shared Virtual Environment for Facility Management. *Procedia Eng.* **2016**, *1*, 120–127. [CrossRef]
18. Calisto, M.d.L.; Sarkar, S. A systematic review of virtual reality in tourism and hospitality: The known and the paths to follow. *Int. J. Hosp. Manag.* **2024**, *116*, 103623. [CrossRef]
19. Schiavi, B.; Havard, V.; Beddiar, K.; Baudry, D. BIM data flow architecture with AR/VR technologies: Use cases in architecture, engineering and construction. *Autom. Constr.* **2022**, *134*, 104054. [CrossRef]
20. Johansson, M.; Roupé, M. Real-world applications of BIM and immersive VR in construction. *Autom. Constr.* **2024**, *158*, 105233. [CrossRef]
21. Han, B.; Leite, F. Generic extended reality and integrated development for visualization applications in architecture, engineering, and construction. *Autom. Constr.* **2022**, *140*, 104329. [CrossRef]
22. Aguacil, S.; Duque, S.; Stoll, A.D.; De Sousa Pereira, T.; Deschamps, L.; Bacher, J.P. Virtual reality enabled building-data management through the combination of a fully integrated IFC-BIM model and an IoT-based building management system. In Proceedings of the 17th IBPSA Conference, Bruges, Belgium, 1–3 September 2021; pp. 3262–3267. [CrossRef]
23. Mutis, I.; Ambekar, A. Challenges and enablers of augmented reality technology for in situ walkthrough applications. *J. Inf. Technol. Constr.* **2020**, *25*, 55–71. [CrossRef]
24. Tan, K.L.; Lim, C.K. Digital heritage gamification: An augmented-virtual walkthrough to learn and explore historical places. *AIP Conf. Proc.* **2017**, *1891*, 020139. [CrossRef]
25. Andri, C.; Alkawaz, M.H.; Waheed, S.R. Examining Effectiveness and User Experiences in 3D Mobile based Augmented Reality for MSU Virtual Tour. In Proceedings of the 2019 IEEE International Conference on Automatic Control and Intelligent Systems, Selangor, Malaysia, 29 June 2019; pp. 161–167. [CrossRef]
26. Napolitano, R.K.; Scherer, G.; Glisic, B. Virtual tours and informational modeling for conservation of cultural heritage sites. *J. Cult. Herit.* **2018**, *29*, 123–129. [CrossRef]

27. Mah, O.B.P.; Yan, Y.; Tan, J.S.Y.; Tan, Y.X.; Tay, G.Q.Y.; Chiam, D.J.; Wang, Y.C.; Dean, K.; Feng, C.C. Generating a virtual tour for the preservation of the (in)tangible cultural heritage of Tampines Chinese Temple in Singapore. *J. Cult. Herit.* **2019**, *39*, 202–211. [CrossRef]
28. Puerto, A.; Castañeda, K.; Sánchez, O.; Peña, C.A.; Gutiérrez, L.; Sáenz, P. Building information modeling and complementary technologies in heritage buildings: A bibliometric analysis. *Results Eng.* **2024**, *22*, 102192. [CrossRef]
29. Martí-Testón, A.; Muñoz, A.; Gracia, L.; Solanes, J.E. Using WebXR Metaverse Platforms to Create Touristic Services and Cultural Promotion. *Appl. Sci.* **2023**, *13*, 8544. [CrossRef]
30. Xi, W.; Cong, W. Remote Practice Methods of Survey Education for HBIM in the Post-Pandemic Era: Case Study of Kuiwen Pavilion in the Temple of Confucius (Qufu, China). *Appl. Sci.* **2022**, *12*, 708. [CrossRef]
31. Google LLC. Google Maps. 2005. Available online: https://www.google.com/maps (accessed on 23 July 2024).
32. 3DVista. Virtual Tour PRO. 1999. Available online: https://www.3dvista.com/en/ (accessed on 4 June 2024).
33. Jourdan, M.; Meyer, F.; Bacher, J.P. Towards an integrated approach of building-data management through the convergence of Building Information Modelling and Internet of Things. *J. Phys. Conf. Ser.* **2019**, *1343*, 012135. [CrossRef]
34. Natephra, W.; Motamedi, A. Live data visualization of IoT sensors using augmented reality (AR) and BIM. In Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC), Banff, AB, Canada, 21–24 May 2019; pp. 632–638. [CrossRef]
35. Dahanayake, K.C.; Sumanarathna, N. IoT-BIM-based digital transformation in facilities management: A conceptual model. *J. Facil. Manag.* **2022**, *20*, 437–451. [CrossRef]
36. Brümmendorf, E.; Ziegeldorf, J.H.; Fütterer, J.P. IoT platform and infrastructure for data-driven optimization and control of building energy system operation. *J. Phys. Conf. Ser.* **2019**, *1343*, 012040. [CrossRef]
37. Fotiou, N.; Siris, V.A.; Polyzos, G.C.; Kortesniemi, Y.; Lagutin, D. Capabilities-based access control for IoT devices using Verifiable Credentials. In Proceedings of the Security and Privacy Workshops (SPW), San Francisco, CA, USA, 22–26 May 2022; pp. 222–228. [CrossRef]
38. Borkowski, A.S. Low-Cost Internet of Things Solution for Building Information Modeling Level 3B—Monitoring, Analysis and Management. *J. Sens. Actuator Netw.* **2024**, *13*, 19. [CrossRef]
39. Baghalzadeh Shishehgarkhaneh, M.; Keivani, A.; Moehler, R.C.; Jelodari, N.; Roshdi Laleh, S. Internet of Things (IoT), Building Information Modeling (BIM), and Digital Twin (DT) in Construction Industry: A Review, Bibliometric, and Network Analysis. *Buildings* **2022**, *12*, 1503. [CrossRef]
40. Scianna, A.; Gaglio, G.F.; La Guardia, M. Structure Monitoring with BIM and IoT: The Case Study of a Bridge Beam Model. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 173. [CrossRef]
41. Hosamo, H.H.; Imran, A.; Cardenas-Cartagena, J.; Svennevig, P.R.; Svidt, K.; Nielsen, H.K. A Review of the Digital Twin Technology in the AEC-FM Industry. *Adv. Civ. Eng.* **2022**, *2022*, 2185170. [CrossRef]
42. Jourdan, M.; Vionnet, D.; Boesiger, M.; Bacher, J.-P.; Ch, M.J. Improving building energy efficiency through user behavior change driven by co-created ICT interface. In Proceedings of the 20th Status-Seminar "Forschen für den Bau im Kontext von Energie und Umwelt", Zurich, Switzerland, 6–7 September 2018.
43. Paone, A.; Bacher, J.-P. The Impact of Building Occupant Behavior on Energy Efficiency and Methods to Influence It: A Review of the State of the Art. *Energies* **2018**, *11*, 953. [CrossRef]
44. Revizto, S.A. Revizto. 2012. Available online: https://revizto.com/en/ (accessed on 22 August 2024).
45. BIMcollab. BIMcollab. 1992. Available online: https://www.bimcollab.com/en/ (accessed on 22 August 2024).
46. Datacubist Oy. simplebim. 2009. Available online: https://simplebim.com/ (accessed on 22 August 2024).
47. Aec Systems Ltd.; Stefanescu, D.; Cominetti, M. Speckle. 2012. Available online: https://speckle.systems/ (accessed on 22 August 2024).
48. Ekkodale GmbH. Ekkodale. 2020. Available online: https://www.ekkodale.com/en (accessed on 22 August 2024).
49. RIB Software GmbH. RIB. 1961. Available online: https://www.rib-software.com/en/ (accessed on 22 August 2024).
50. Archibus Inc.; Kenneth Forbes, B. Archibus. 1982. Available online: https://archibus.com/ (accessed on 22 August 2024).
51. Dalux. Dalux. 2005. Available online: https://www.dalux.com/ (accessed on 22 August 2024).
52. Libal GmbH. Libal. 2016. Available online: https://www.libal-tech.de/ (accessed on 22 August 2024).
53. Axxon System sàrl. AxeoBIM. 2005. Available online: https://axeobim.fr/ (accessed on 22 August 2024).
54. Sharma, A.; Kosasih, E.; Zhang, J.; Brintrup, A.; Calinescu, A. Digital Twins: State of the art theory and practice, challenges, and open research questions. *J. Ind. Inf. Integr.* **2022**, *30*, 100383. [CrossRef]
55. Tuhaise, V.V.; Tah, J.H.M.; Abanda, F.H. Technologies for digital twin applications in construction. *Autom. Constr.* **2023**, *152*, 104931. [CrossRef]
56. Petri, I.; Rezgui, Y.; Ghoroghi, A.; Alzahrani, A. Digital twins for performance management in the built environment. *J. Ind. Inf. Integr.* **2023**, *33*, 100445. [CrossRef]
57. El Ammari, K.; Hammad, A. Remote interactive collaboration in facilities management using BIM-based mixed reality. *Autom. Constr.* **2019**, *107*, 102940. [CrossRef]
58. Dave, B.; Buda, A.; Nurminen, A.; Främling, K. A framework for integrating BIM and IoT through open standards. *Autom. Constr.* **2018**, *95*, 35–45. [CrossRef]

59. Gerrish, T.; Ruikar, K.; Cook, M.; Johnson, M.; Phillip, M.; Lowry, C. BIM application to building energy performance visualisation and management: Challenges and potential. *Energy Build.* **2017**, *144*, 218–228. [CrossRef]
60. Han, Y.; Leung, C.; Kim, D.I. IoT-Assisted Metaverse Services. In *Metaverse Communication and Computing Networks: Applications, Technologies, and Approaches*; Wiley: Piscataway, NJ, USA, 2024; pp. 241–265. [CrossRef]
61. Wong, J.K.W.; Ge, J.; He, S.X. Digitisation in facilities management: A literature review and future research directions. *Autom. Constr.* **2018**, *92*, 312–326. [CrossRef]
62. Li, D.; Xiao, B.J.; Xia, J.Y. High-resolution full frame photography of EAST to realize immersive panorama display. *Fusion Eng. Des.* **2020**, *155*, 111545. [CrossRef]
63. Bauen Diital Schweiz, D.; Brühwiler, D.; Huber, M.; Meister, A. Catalogue des Champs d'information BIM2FM Document de Travail. 2020. Available online: https://bauen-digital.ch/fr (accessed on 1 June 2021).
64. Smart Living Lab. Smart Living Lab Building. 2024. Available online: https://building.smartlivinglab.ch/ (accessed on 27 July 2024).
65. RICOH. Camera 360° RICOH THETA. 2023. Available online: https://www.ricoh360.com/ (accessed on 4 June 2024).
66. DJI. Camera Drone DJI Mini 3 PRO. 2022. Available online: https://www.dji.com/ch/mini-3-pro (accessed on 4 June 2024).
67. Smart Living Lab; EPFL Building2050. Controlled Environments for Living Lab Studies (CELLS). 2016. Available online: https://www.smartlivinglab.ch/en/infrastructures/cells/ (accessed on 27 July 2024).
68. BFF SA; Lutz Architects. Blue Hall Building. 2015. Available online: https://bluefactory.ch/en/blue-all/ (accessed on 27 July 2024).
69. EPFL; HEIA-FR; UNIFR. Smart Living Lab. 2014. Available online: https://www.smartlivinglab.ch/en/ (accessed on 27 July 2024).
70. Autodesk Inc. Revit. 2023. Available online: https://www.autodesk.com/products/revit/ (accessed on 2 August 2024).
71. Heleine, J. Photo-Sphere-Viwer.js.org, JavaScript Library PhotoSphereViewer. 2017. Available online: https://github.com/JeremyHeleine/Photo-Sphere-Viewer (accessed on 4 June 2024).
72. AEC Systems Ltd. Downloading a Single Object. 2024. Available online: https://speckle.guide/dev/server-rest-api.html#downloading-a-single-object (accessed on 25 July 2024).
73. Mannino, A.; Dejaco, M.C.; Re Cecconi, F. Building Information Modelling and Internet of Things Integration for Facility Management—Literature Review and Future Needs. *Appl. Sci.* **2021**, *11*, 3062. [CrossRef]
74. Smart Living Lab. Big Building Data (BBData). 2018. Available online: https://www.smartlivinglab.ch/en/infrastructures/bbdata/ (accessed on 27 July 2024).