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The Development of a BIM-Based Interoperable Toolkit for Efficient Renovation in Buildings: From BIM to Digital Twin †

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Abstract: Nowadays, buildings renovation is a subject of special interest since the building and construction sector is the main body responsible for energy consumption and emissions. Hence, it is necessary to concentrate on refurbishment to achieve Europe's climate neutrality by 2050 according to European Agenda goals. The BIM4EEB Project, a BIM-based fast toolkit for the efficient renovation of residential buildings, directs the attention toward developing an exhaustive toolkit based on Building Information Modeling (BIM) to be adopted in the renovation of existing residential buildings, to make the flow of information efficient, decreasing intervention working time while improving building performances, quality, and comfort for inhabitants. BIM4EEB is developing a BIM management system connected to an operational and multifunctional toolkit for various architecture, engineering, and construction (AEC) stakeholders, integrating a set of tools for improving BIM adoption in renovation environments based on an interoperable flow of information. This paper presents the Horizon2020 Project and the framework used to develop the toolkit. In addition, the first outcomes of the toolkit development are outlined. The validation procedure in real environments has started to demonstrate the efficacy and applicability of the methodology and tools. Although the project is still in progress, benefits connected to the framework and the BIM-based toolkit result in an enhanced building renovation process.

Keywords: BIM; renovation; interoperability; prefabrication; off-site; Lean Construction 4.0; panel

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1. Introduction: The BIM4EEB Project

To bring existing buildings to consume less energy, release less CO2, and improve the comfort of inhabitants living in unhealthy homes are among the principal objectives of Europe toward the goal of climate neutrality by 2050. According to studies, the architecture, engineering, and construction (AEC) sector is responsible for 40% of the energy consumed and 36% of greenhouse gas emissions from energy, and moreover, only 1% of buildings are undergoing retrofitting to become more energy efficient [1]. Consequently, it is necessary to stimulate the practice of renovating and reusing buildings [2,3]. However, issues such as improving the quality of renovations, reducing the time of the building construction phase, minimizing the impact on tenants, and guaranteeing that cost–benefit targets are accomplished need to be addressed [2]. An enhancement of data and information exchange due to a more organized and structured data collection and management throughout the building lifecycle, better communication between the involved actors, and the facilitation of testing and surveying methods' application are some of the benefits deriving from digital tools [4]. The waste of time and the consequent waste of money caused by inefficiency is limited and reduced with digitalization that results in using resources more efficiently and responsibly.

Given this scenario, BIM is defined as "a modeling technology and associated set of processes to produce, communicate, and analyze building models. The outputs of BIM processes are building models or BIM models". It enables partners to improve communication, collect and share information with fewer errors, and, therefore, contribute to optimizing the building process [5–8].

Europe is moving toward the renovation wave supporting different initiatives and projects. For example, a program has started in 2019 with the goal of developing BIM-based tools for efficient retrofitting [9]. In this context, several Horizon2020 projects can be mentioned, including BIM4EEB, BIM4REN, BIM-SPEED, BIMERR, and ENCORE [10–14].

BIM4EEB, a BIM-based fast toolkit for the efficient renovation of residential buildings, focuses on the implementation of a complete Building Information Modelling (BIM)-based toolkit to be used during renovation of existing residential buildings, in order to increase the efficiency of the information flow, decreasing intervention working time while improving building performances, quality, and comfort for inhabitants. Among its main objectives are the reduction of at least 20% of renovation time, 15% of the average renovation cost, 10% of net primary energy use for a residential flat, and the reduction from 3 to 1.5 working days required for a deep energy audit [15]. Given these objectives, to assess their achievement the project uses a validation methodology based on key performance indicators (KPIs).

A multidisciplinary approach was adopted within the project, relying on the collaboration and integration of different skills, competences, and needs, considering buildings' and informatics competences, public and private research, small- and medium-sized enterprises (SMEs), large enterprises, technology providers, end users, inhabitants, and the European umbrella organization representing all 600,000 European architects present within the consortium [15].

BIM4EEB is developing a BIM management system, an open, integrated BIM-based collaboration environment, enabling the continuous updating, enhancement, improvement, and enrichment of available models by the AEC industry stakeholders based on robust modeling guidelines that will be provided by the project, to ensure the sustainability of project developments and enhance its exploitation potential even after the end of the project [15].

From a technological point of view, BIM4EEB will offer an easy, practical, operational, and multifunctional tools set for different actors of the construction industry, merging tools for improving BIM adoption in renovation works based on an interoperable flow of information [15].

This paper investigates the ongoing European funded project—BIM4EEB—starting from the framework definition necessary for the toolkit development aiming at outlining the first results. The BIM management system development, which allows the connection and integration of the toolkit, is described in its specificities. Furthermore, a part of the project is reserved for the structural definition of a BIM-enabled design process for prefabricated thermal insulation components. To test the developed tools and their achievement of the project's target goals, three real-world case studies were chosen in different climate locations.

The paper is organized as follows: The methodology of the research project is described in Section 2. The main component of the BIM-based toolkit—namely, the BIM management system, is explained in Section 3. The BIM-enabled design process for prefabricated thermal insulation components is outlined in Section 4. Following this, the case studies and the first results of the research are presented in Section 5. Finally, Sections 6 and 7 include discussion and the resulting conclusions.

2. Methodology

Initially, the European project outlined needs and requirements to be accomplished during the renovation process to guarantee the best adaptation of the methodological and technological features of the BIM4EEB toolset to the peculiar needs.

For example, to develop the BIM management system, needs and requirements for designers, construction companies, service companies and owners, and inhabitants were studied [16]. On the other hand, considering the needs and requirements of services companies helped in the creation of a digital logbook that aims at reducing technical renovation obstacles such as lack of information or incomplete or incorrect knowledge about building information.

The last step of the research methodology foresaw the validation and testing of the toolkit in real-world case studies. The validation was based on the use of KPIs. These changes according to the tool and demo site considered are presented in Table 1.

2.1. Renovation Process Map

One of the first investigations carried out was focused on the process of building renovation with the analysis of information workflow for each actor, searching for feasible shortcuts in information exchange and simultaneously determining how the BIM4EEB toolkit could be used to make the building process more efficient [17].

Firstly, the study individualized the involved stakeholders in the renovation intervention, focusing on their needs and requirements to be addressed [18–20]; it defined every activity undertaken by the several stakeholders during the different stages, and it described the outputs emerging from those activities. Then, according to EN 16310: 2013 [21], the stages were outlined. Finally, since the project involves different European countries, possible differences were searched and any shortcuts investigated. The analysis, led on both public and private projects, was summarized on a process map. An excerpt of the process map is shown in Figure 1.

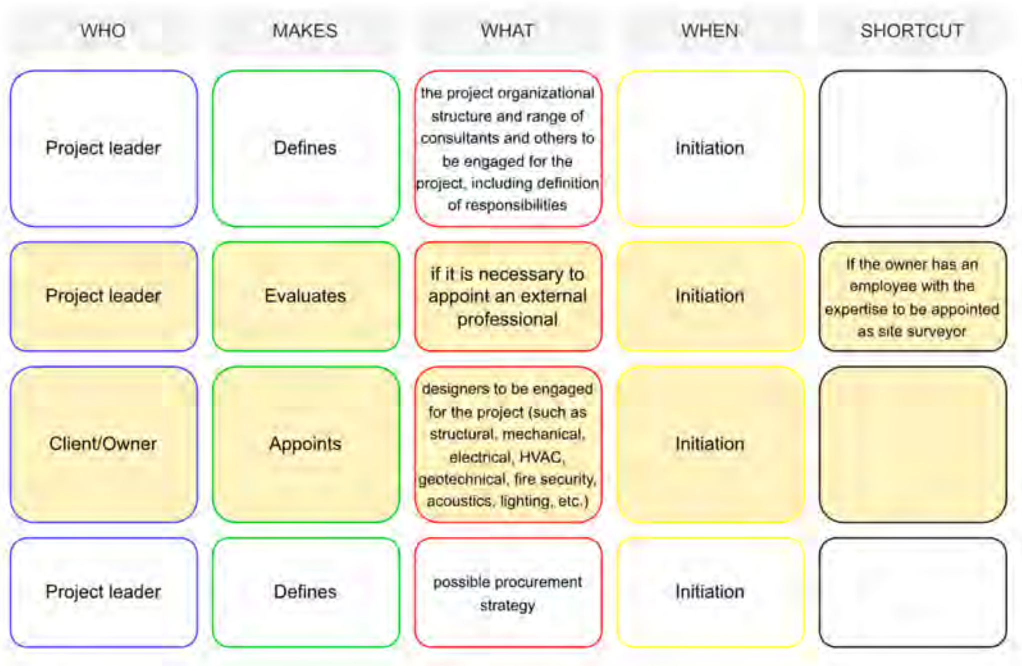

Figure 1. Public projects—initiation step: activities of a renovation process [22].

Table 1. The distribution of key performance indicators according to demonstration site and tool considered.

Category of KPI	KPI	Italian Site						Polish Site				Finnish Site			
		BIMMS	**Fast Mapping**	**BIM Easer**	**BIM4 Occupants**	**BIMcpd AUTERAS**	**BIM Planner**	**BIMMS**	**Fast Mapping**	**BIM4 Occupants**	**BIMcpd AUTERAS**	**BIMMS**	**Fast Mapping**	**BIM Easer**	**BIM Planner**
Renovation process	Renovation Time Reduction	X	X	X		X	X	X	X		X	X	X	X	X
	Renovation Cost Reduction	X		X			X	X				X		X	X
Comfort	Occupancy Profiling Accuracy				X					X					X
Energy performance	Primary Energy Savings			X		X					X			X	
	Energy Performance Accuracy			X		X					X			X	
Social	Improved monitoring/access to information during renovation works	X	X				X	X	X	X		X	X		X
	Increased easiness in information exchange and tracking (data accessibility)	X	X			X	X	X	X		X	X	X		X
	Modular design and development of the BMS platform	X						X				X			
	Interoperability and data storage capability of BMS platform	X						X				X			
	Use of BIM in renovation business		X	X					X				X	X	
	Use of dynamic simulation tools for energy assessment			X										X	
	Development of digital logbooks for renovated building; management of as-built data in operational BIM models	X						X				X			

2.2. The Digital Logbook

To overcome frequent barriers during the renovation process, such as lack of communication or improper exchange of information, the BIM4EEB Project investigated the potentialities of a logbook. The logbook, seen as an archive of all building-related information, such as energy consumption and maintenance interventions, could be conceived as a bilateral tool that enables users and third parties to be connected fulfilling service companies' needs and requirements [23–25].

The result was a digital logbook [26] assumed as a building data collector in a digital format joined with a renovation roadmap within the Individual Building Renovation Roadmaps (iBRoad) project [27,28], leading building owners through the building renovation process and providing a customized renovation plan [23].

The logbook developed is not an electronic file but stored within the BIM Management System (BIMMS); data could be inserted and continuously updated (Figure 2). Each actor of the renovation process, from owners and clients to facility managers, public authorities, designers, and installers, can have access to it [16]. In this way, information collected from buildings could be monitored on regular basis, avoiding discrepancies between building operation and design, and at the same time, inhabitants could comprehend the design intent and building performance, improving their comfort and productivity [23].

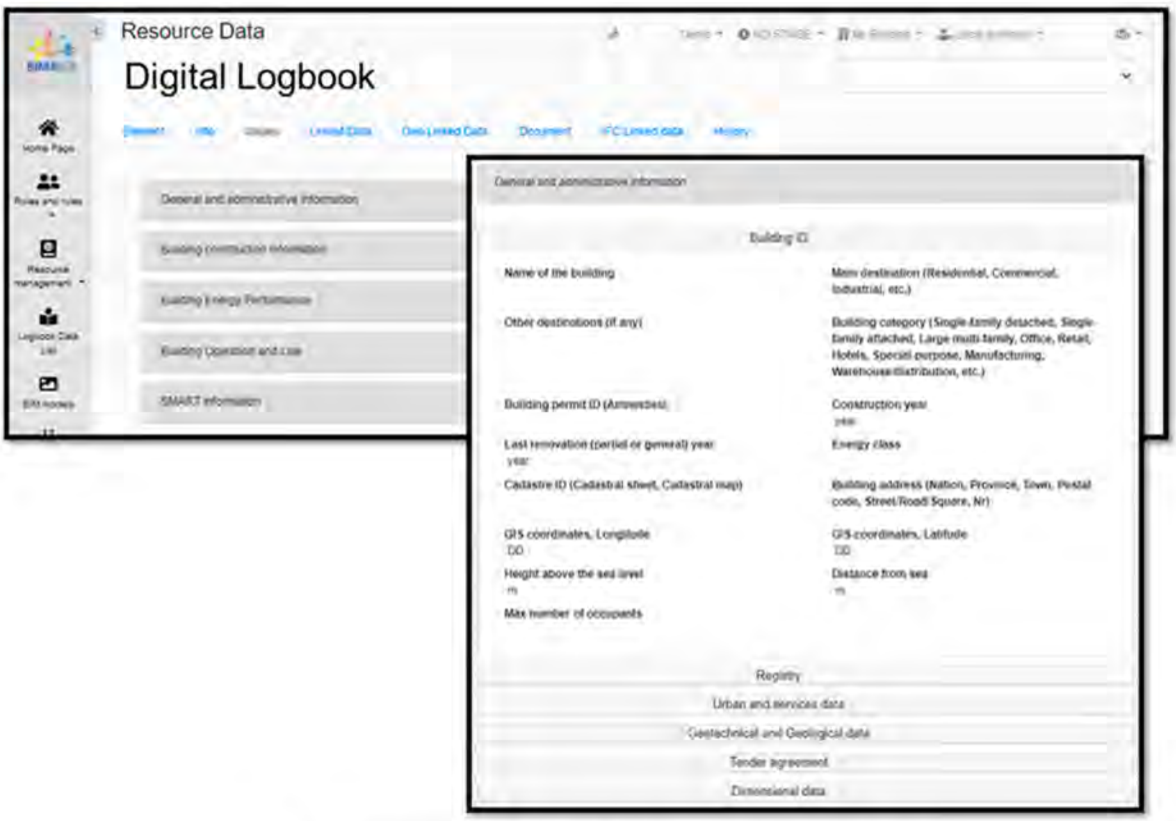

Figure 2. Excerpt of the digital logbook present in the BIMMS.

3. Development of the BIM Management System: Specifications and Overall Design

Collecting and managing information about existing buildings is crucial for the building renovation, in all stages of the construction process, i.e., design, construction, and operation. Hence, the BIM4EEB Project integrates a group of digital tools within a web-based platform, i.e., an innovative BIM management system (BIMMS) for designers, construction operators, and inhabitants, to facilitate the renovation processes through collaboration [15]. Exploiting linked data, this toolset integrates the management of different activities that can be developed by different stakeholders of the renovation process, from designers, constructors, supplies, and public authorities, to end users and operators [29]. The BIMMS has been implemented in accordance with specific technological and procedural requirements based on the indications about Common Data Environment (CDE) provided by the ISO 19650 parts 1 and 2 [30]. The BIMMS arises from different requirements: the need to work with an open format such as a BIM-based collaboration environment, the need to extend model informative content through linked data, the need to guarantee the fundamental functionalities of CDEs (workflows, permissions, information states, classification, etc.), the need to effectively retrieve data (queries), and the need to integrate new services and tools (Application Programming Interface (API)) [15].

The resulting BIMMS is an open-source, interoperable, web-based platform, accessible through the internet to all of the participants of a renovation project. Its goal is to offer a reliable example of CDE integrated with linked data, compliant with the principles of BIM Level 3 [31]. The platform is developed with the involvement of different standardization institutes (ISO TC 59 SC13, CEN TC 442, UNI, buildingSMART), as it proposes enhancements in the information exchange standards framework and the integration of disciplines for renovation such as building energy performance, building acoustics, occupants' behavior and comfort modeling, economics, environmental sustainability, and Geographic information system (GIS).

Within the BIM management system platform, the 3D model of one or more buildings can be viewed. The 3D model is subdivided in IfcZone, and after selecting an apartment, the different types of Internet of Things (IoT) sensors installed and their related identification codes and details can be visualized in a dedicated box. Then, users can investigate the 3D model of the building, monitoring its daily performances and current state and tracing any anomalies in real time (Figure 3).

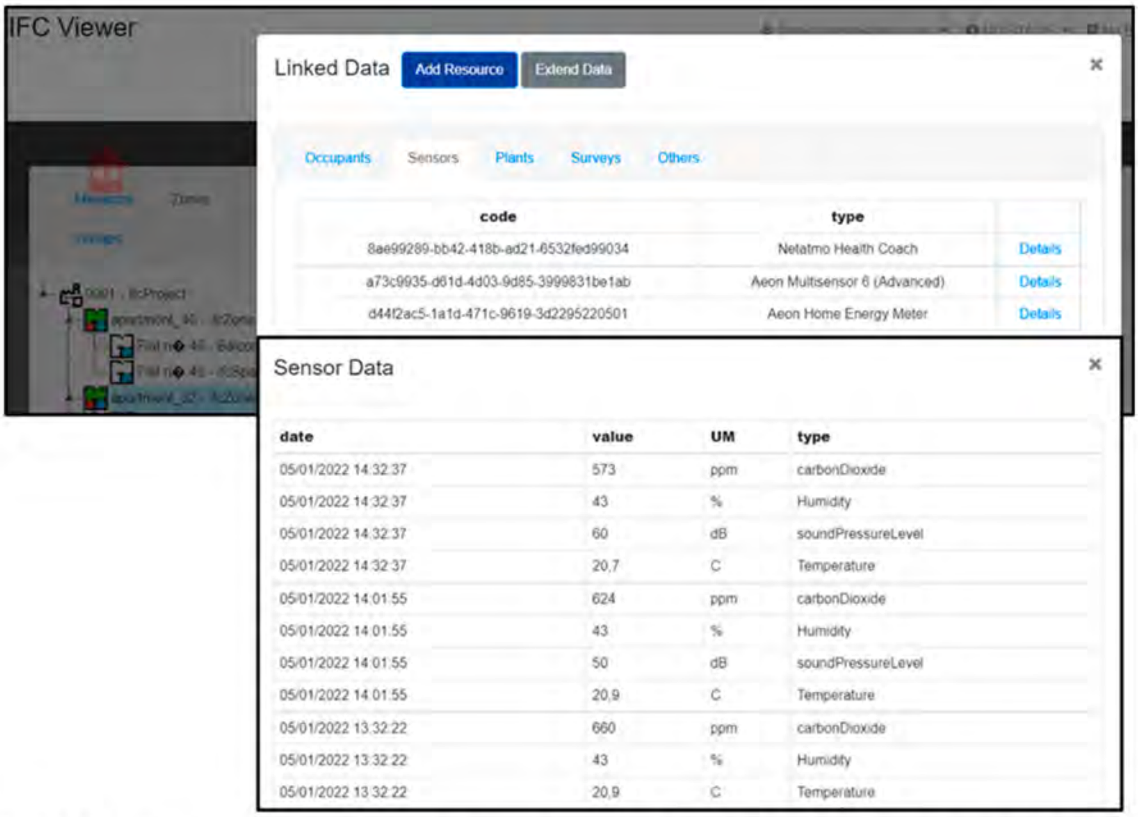

Figure 3. Data streaming from multi-purpose sensor measuring humidity and temperature visible in BIMMS.

The integration between IoT devices and the 3D model brings the project closer to a digital twin approach. Digital twin, defined as the concept of creating a digital replica of a physical product and synchronizing data from the physical to the digital realm [32], allows information to be stored and managed by the individuals involved, as well as planning, predicting, and simulating the performance of building assets, contributing to building process optimization. Its main components are BIM and IoT, as well as artificial intelligence. BIM can be considered part of DT and the starting point for its creation, acting as the semantically rich 3D model [33].

For example, a digital twin requires the integration of different sources of data such as real-time sensors and building management systems. The integration of acquired data from other sources into the 3D model enables data analytics and helps decision making.

In the platform developed by the BIM4EEB Project, it is possible to display data in three dimensions and in real time.

In addition, the platform contains the integration of the tools of the BIM4EEB Project (Figures 4 and 5). The toolkit covers different stages of the lifecycle of a typical building renovation process. Firstly, *BIM4EEB Fast mapping tool* includes the purpose of collecting information, promptly generating BIM models of existing buildings, and exploiting the latest technologies for building surveys (AR, laser scanning, thermo scanning, etc.). Then, in the initiation and design phase, *BIMeaser* and *BIMcpd* aim at, respectively, supporting decision making and being used as a BIM-assisted energy refurbishment assessment tool, together with the room automation system design tool *AUTERAS* [15]. For the construction and operational stages, *BIMplanner* and *BIM4Occupants* are designed, on the one hand, to offer designers a digital environment for up-to-date activities planning, and on the other hand, to offer occupants a web-based platform to provide feedback about their comfort and their activities during construction.

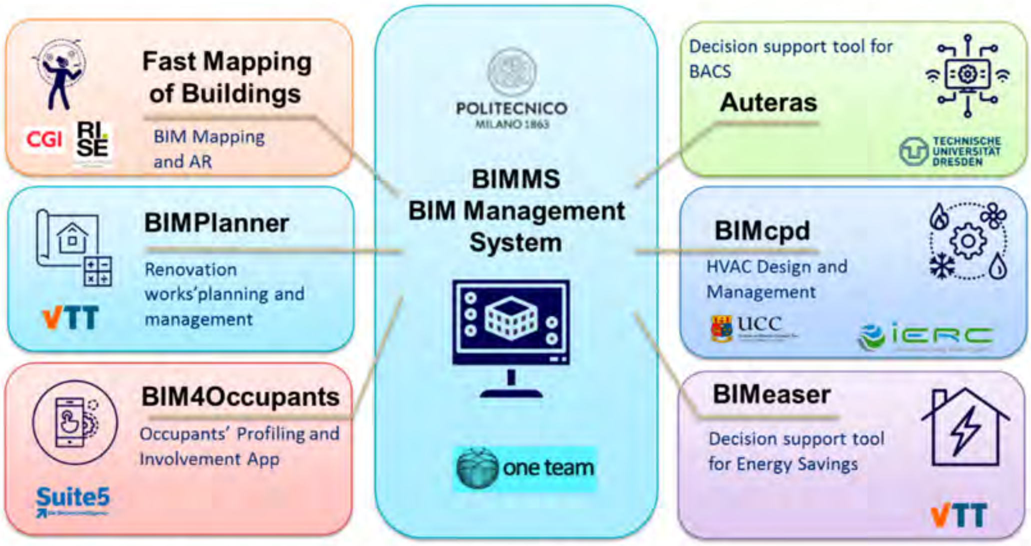

Figure 4. General overview of the BIM-based fast toolkit.

Ontology and Linked Data Integration in BIMMS: Toward Digital Twin

In the construction industry, the data are generated from different sources, using different tools or applications that involve different roles such as architects, manufacturers, designers, etc. Thus, there is an issue of interoperability between these data. To resolve this issue, the semantic web and linked data approaches were adopted in the BIM4EEB Project, for achieving efficient data management and data interoperability in the process of existing building renovations. The adopted mechanism for the process of data management and data carrying is ontology development [34].

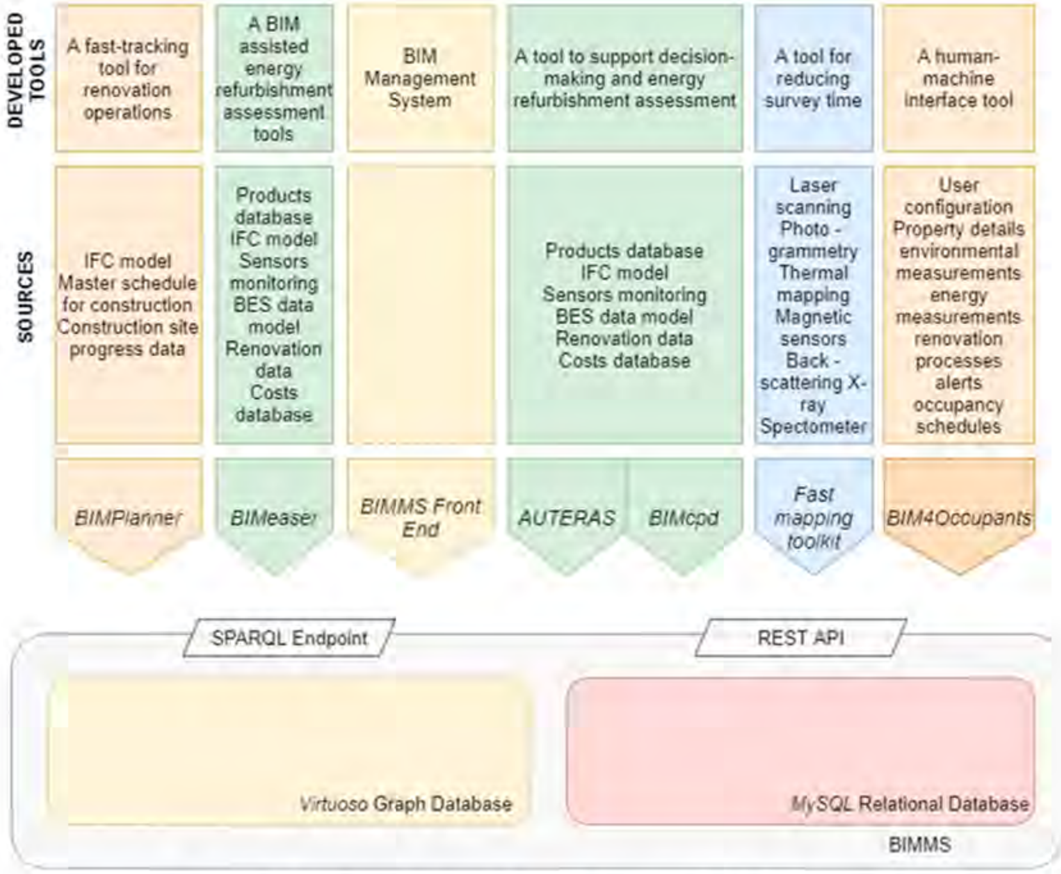

Figure 5. Developed tools and their relation with BIMMS [8].

As a part of the BIM4EEB Project, a framework of ontologies was developed to manage information exchange during this process and provide an example for future exploitation in standardization processes. Based on the findings regarding the preliminary tasks of the project, a set of ontologies was developed by the BIM4EEB partners to support specific activities typical for the renovation of residential buildings. This project integrated "third-party ontologies", as a whole or in part, to maximize the reuse of existing models and concepts. The linked data modeling and sharing framework are based on a "Modularly Networked Set of Ontologies" (Digital Construction Ontologies) consisting of ontologies developed by BIM4EEB [35]. The ontologies developed in this phase of the project were used during the implementation of the BIMMS. For example, the BIM4EEB Digital Construction Ontologies Suite (DICO) is a framework for digital construction semantic representation of buildings' product–process modeling. It includes ontologies about entities, processes, occupant behavior, indoor air quality, building materials, etc. The DICO objective is to focus on the semantic challenge by providing features and elements of construction and renovation projects, in order to improve the interoperability between different systems and data sources [36,37].

The ontology viewer in BIMMS enables the ontological data stored in BIMMS to be presented in a graphical form, with functionalities to visualize how data are linked together, as well as their relationships. It is also possible to navigate between resources in a graphical way, discovering relationships between them. This visualization tool is useful to explore the richness of semantic nets by creating graph layouts of resources. The development of the BIMMS tool takes into consideration the implementation of graph database technologies with Resource Description Framework (RDF) and (SPARQL Protocol and RDF Query Language) SPARQL support. The database is scalable to load linked datasets and perform fast queries through data. The development takes into consideration the W3C SPARQL

Protocol specification and the support of RDF serialization formats. Moreover, open-source frameworks and libraries were used for further implementations and developments.

To implement the ontologies in BIMMS, the structure of the Industry Foundation Classes (IFC) file format was considered, as 3D BIM models stored and shared in the platform use this format. To support this form of structure, a workflow was developed that allows the storage of IFC files into two databases. One is for the relational Structured Query Language (MySQL), where all entities are stored in tables, and relationships between them are recreated to allow models to be queried and read as if they are common records in a database. This feature allows a faster presentation of IFC data to the client interface, as well as a faster definition of complex queries and return of results. Another one facilitates the functionality to make the IFC items available in the graph view of the Virtuoso platform, which was the database platform chosen to manage the linked data in BIMMS. This platform is used as data storage for linked data resources directly uploaded as RDF, triples creation and modification, and stores geo-linked data, as well as resource graphs and ontologies. Virtuoso is configured also to enable SPARQL queries through the resource graphs in the Virtuoso SPARQL Endpoint, available on the BIMMS Web Portal. For linked data view, the IFC file is converted into the two most common ontologies that support IFC files: ifcOWL and Building Topology Ontology (BOT) [38]. The conversion in ifcOWL and BOT occurs using the open-source IFCtoLBD (https://github.com/jyrkioraskari/IFCtoLBD (accessed on 10 September 2021) converter, with little changes to the source code (with Apache License 2.0 permissive license), to allow the alignment of the URIs with named graphs stored in the BIMMS Virtuoso Server [38].

To develop the ontological representation, all contents of BIMMS CDEs were considered as resources using the RDF, in the form of triples (subject–predicate–object, Figure 6) [39]. Common use case workflows can be useful to explain how BIMMS integrates the ontologies and to create the ontological representation of the resources. When a user creates new resources in BIMMS using the web application or the BIMMS REST Services, the uploaded files attached with the resource or the properties assigned during resource creation will be used to define a set of relationships based on triples. The proposed structure allows linking a PDF document to an IfcWindows item in an IFC Model previously uploaded by another user. In the same way, a link could be made between the properties of the resource. These properties could be labels defined as objects, literals, or other node references. This kind of reference could be conducted, for example, between devices and their characteristic features, such as measurement properties, measurement list, etc. [36]. The relationships described were made using a BIMMS custom ontology in Virtuoso, to define the resources.

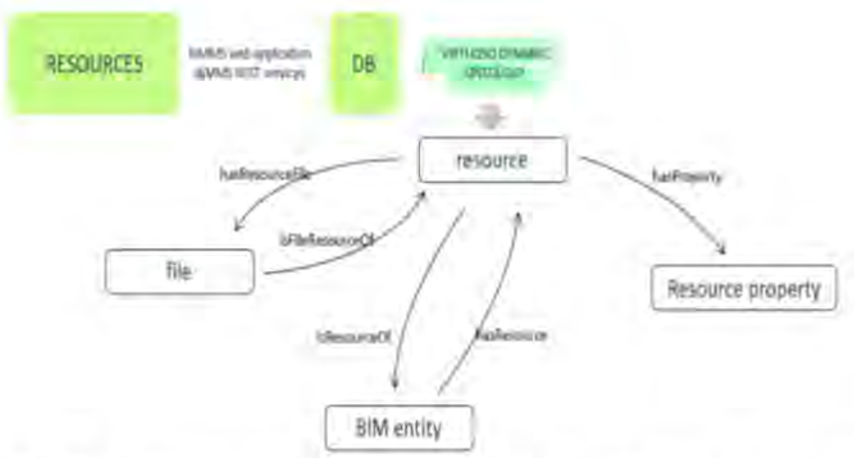

Figure 6. BIMMS resources Virtuoso linked data view: a resource (subject) that has resource property (predicate) and a file (object) [37].

The implementation of ontologies within BIM4EEB was accompanied by a comparative analysis of the existing standards related to collaboration and interoperability in the construction sector. According to the ongoing trends regarding the development of standards about ontologies and semantics in the AEC sector, these results were presented in working groups that develop standards at the national and European levels, to instigate the improvement of existing standardization practices.

4. BIM-Enabled Design for Prefabricated Thermal Insulation Components

Different research studies [40,41] suggest that, compared with traditional techniques, the use of prefabricated panels can provide significant advantages in the recladding of existing buildings for their energy retrofit. Among these advantages are 80% energy savings and up to 30% faster process, higher quality, and safety, owing to the off-site operations typical of these solutions [42,43], falling in the wider concept of design for manufacture and assembly (DfMA). Digital tools may enable the implementation of an off-site approach also to building envelope retrofitting, characterized by irregular geometries and the need for bespoke components with a high degree of customization. Advancements in BIM allow the adoption of prefabricated solutions also in common residential buildings [44], achieving the purpose of Lean Construction 4.0 to industrialize the building sector [45].

The purpose of this research was to structure a BIM-enabled design process for prefabricated thermal insulation components, based on meta-product data (panels) valid for different construction technologies. According to this framework, the first step was the creation of information flow (*"in-flow"*) of data through the whole design and installation process (Figure 7). Based on the evidence from existing products (either on the market or developed in research projects), the flow describes the information typology, the task, the software, and the data type involved in each phase.

Figure 7. "In-flow" during the entire panelization process.

A geometrical survey and the collection of technical documentation were the starting points to create a 3D model of an existing building with its information and data. The design phase defined the required performances through the application of a design optioneering process, with parametric tools in a BIM environment. The third step concerned the optimization of size, number, joint, and anchors of panels with a specific data transmission to manufacturers, who usually adopt CAD/CAM software for the manufacturing processes. Finally, panels are delivered on-site, where a plan for supply and logistic management is necessary, together with a detailed description of the construction steps for the skilled workforce.

The theoretical framework was tested on the outcomes of the EASEE project (*Envelope Approach to improve Sustainability and Energy Efficiency in Existing Multi-Story, Multi-Owner Residential Buildings*) [42], which demonstrated the recladding of a residential building in Cinisello Balsamo (Milan) through the use of innovative off-site sandwich panels in textile reinforced concrete (TRC) with an insulated core in Expanded Polystyrene (EPS).

The last step of the research was the development of guidelines to support the design of prefabricated thermal insulation components within a BIM approach and speed up the operation time on site. All necessary information was taken into account, including a BIM-based detailing of the system, information exchange with the manufacturer, description of the information exchange with logistics and site operations, data related to installations, and commissioning of the system.

5. Results

The several functionalities of the developed tools and BIMMS were tested and validated in a real-world environment represented by three pilot sites, located in different climatic locations—Italy, Poland, and Finland. The choice of these three best practice examples was based on their representativeness of the project's application targets and considering selected end users.

The Italian demonstration site is located in Monza, northern Italy. It is a nine-story public housing built in 1981 and managed by the BIM4EEB partner Aler Varese–Como–Monza e Brianza–Busto Arsizio (ALER VCMB). The polish pilot site is in the south of Poland, in the town of Chorzow. The residential building was built in 1902, and it is characterized by 5 floors, 12 apartments, and 3 commercial areas located on the ground floor. The Finnish demonstration site is a residential building built in 1998 and placed in the city of Tampere. The complex is owned by YH kodit, and it consists of 2 buildings of 5 stories each, with a total of 52 apartments.

The three demonstration sites described are shown in Figure 8.

Figure 8. Demonstration sites chosen for the validation of the BIM4EEB developed tools: (**a**) Italian pilot site; (**b**) Polish pilot site; (**c**) Finnish pilot site.

For the testing and validation purpose, it was planned to perform hardware installation in the demo sites, and a relative hardware topology was defined to accomplish the requirements about the following features:

- Monitoring the thermal and visual comfort, i.e., temperature, relative humidity, occupancy, luminance;
- Checking indoor air quality, i.e., CO_2, PM2.5, PM10, VOC;
- Controlling the electric power consumption and the gas consumption, i.e., electricity meter, gas meter.

To acquire sensorial data transmitted by sensors, a system gateway was also installed, and, due to connections to its API, data can be stored into the BIMMS platform, as described in Section 3. Among the different gateway systems available on the market, the one that enables the integration of several sensors and devices systems was chosen.

The installation occurred in specific apartments and rooms according to the availability of residents of individual apartments for demonstration activities, the diversification due to their exposition, as well as the technical conditions of individual apartments.

After the installation of sensors and gateway, teamwork proceeded in evaluating the level of achievement of a given objective, as established in the early stages of the project, and assessing the project results. The validation methodology was based on BIM4EEB PMV methodology, with the respective KPIs. The KPIs were divided into categories such as "Renovation Process KPIs", "Energy Performance KPIs", "Human Comfort KPIs", "Economic Performance KPIs", "Social Related KPIs", and "Environmental and Safety KPIs", to outline which are the main pillars of interest in the project and to simultaneously evaluate objectives and fulfillment of stakeholders' requirements, investigating, for instance, the performance of the renovated buildings such as energy consumption or the impact of BIM4EEB regarding occupants' thermal and visual comfort, and building acoustics comfort.

6. Discussion

This study was developed in the context of an ongoing European research project that aims at making buildings renovation more efficient through a set of BIM-based tools.

The proposed framework developed within the project shows benefits for the entire AEC sector and its stakeholders, investigating typical issues and barriers of the renovation process and overcoming them with tools based on BIM. In fact, one step toward the renovation process is the exploitation of digital tools such as BIM. Another instrument that can be used is the Internet of Things. BIM4EEB Project exploits BIM and IoT devices, as shown in Section 5.

IoT technologies have relevant roles in capturing data and enabling the linkage of the 3D model with real-time data. The importance of IoT technologies is outlined in the three real-world demonstration sites. In this study, the project focused also on the value of sensors and controls in making buildings smarter and more energy efficient.

The approach is relatively new and innovative. Several stakeholders can have access to the same platform and visualize data and information useful for improving the renovation process, avoiding errors, and saving time. BIM-based tools developed with different purposes are integrated within the BIM management system. Here, the BIM model of the building can be viewed: It contains information about its current state with tools to monitor and detect performance. This strict relationship between BIM and real-time data brings the research of the project closer to the digital twin context.

In addition, the DICO ontology development is an added value of the project, with the aim to merge information from different decentralized sources over the building lifecycle. It is integrated with the development of BIM4EEB tools for different areas of renovation projects, from the fast mapping of existing buildings to fast-track construction management. Its application is focused on information exchange among applications and mappings from and to application data.

Another important point regards the relationship with users. The whole project in development relies on an approach focused on the user, taking into account different involved users. Specifically, stakeholders such as designers, construction companies, and service companies will benefit from the application of BIM-based processes in accordance with the methodology and tools developed within the project [15]. Moreover, even inhabitants are considered in the development of the toolkit. For this reason, social houses and residential apartments were identified as case studies, as BIM4EEB takes the needs of vulnerable occupants into account.

7. Conclusions

This paper began from the outcomes of an ongoing European-funded project—BIM4EEB—and it proposed a framework for the development of a BIM-based toolkit.

Firstly, it reported the methodology used for establishing the toolkit. The method includes the definition of stakeholders' needs and requirements, outlines of problems to overcome and requests to fulfill, and lastly, the final testing and validation of created toolkit to real-world demonstration sites based on KPIs. Establishing a sensor network to create a real-time digital model and the consequent data acquisition and transmission were other relevant steps for the purpose of the project. IoT devices enable the acquisition and transmission of data about specific environmental factors controlling the performance of the building and making it smarter. A limited number of sensors were used in this case, and only five parameters (temperature, humidity, luminance, occupancy, and CO_2) were monitored. Nevertheless, the framework could be extended and utilized for other, more comprehensive purposes.

The validation of the developed tools and the proposed methodology is ongoing in three best practice examples, to demonstrate their applicability, relying on actions of development, piloting, testing, and validating in relevant environments by the use of demonstrative workshops.

In future research, on the one hand, data collection from real-time sensors will continue, and parallelly, the integration of data and digital models will be carried out so that building assets could be investigated at different levels, monitoring their status in real time. On the other hand, the validation of the toolkit based on KPIs will demonstrate its applicability and achievement of project objectives.

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