The BIMERR Interoperability Framework: Towards BIM Enabled Interoperability in the Construction Sector

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Abstract

Interoperability is an ever-present challenge for the construction industry despite the intensive research and standardisation efforts, including Building Information Modelling (BIM), and Common Data Environments (CDEs). This paper presents the BIMERR Interoperability Framework (BIF), a cloud-based platform aiming to facilitate seamless data integration, leveraging flexible ontology and data model management capabilities combined with flexible querying and retrieval mechanisms, to allow secure collaboration of legacy systems and cutting-edge applications in construction projects. The design principles of the BIF and interactions of any construction tech application with the BIF are elaborated while the perspectives opened up through the demonstration activities in the construction sector summarize this work.

Keywords –

BIM; Semantic Interoperability; Data Integration; CDE; Construction Tech; BIMERR; BIF

1 Introduction

From the collaboration between relatives from the same family towards a common goal in the stone age [1], up to the cooperation of highly specialised teams in the construction field that reaches the modern era, communication, trust and information act as core enablers that would allow the production of material goods, services and infrastructure as a sum of collective intelligence and the division of labour [2]. Contemporary digital technology however, replaced the old school, and heavily human-dependent tools of information capturing, such as drawing boards and paper documentation, with powerful software products featuring automation capabilities, that in contrast to their predecessors, were found to be unable to converse in a mutually comprehensible language, thus resulting in data fragmentation [3] and creating the so-called "islands of information" [4].

In general, interoperability can be defined as the "ability of two or more systems or components to exchange information and to use the information that has been exchanged" [5]. Interoperability aims to bridge these isolated islands and has been widely studied in the field of construction within the previous 30 years with ever-evolving shifts in the point of view that led to the emergence of the research-intense topic of Building Information Modelling (BIM) and the conception of new paradigms for the construction of the future [6]. However, the industry still struggles with the adoption of BIM and the efficient management of the resulting information overload by organisations that are rendered in a state described as 'drowning in data' [7].

In this context, this paper aims to present the BIMERR Interoperability Framework (BIF), a cloud-based platform developed within the EU-funded project BIMERR [8]. The BIF is built on the principles of interoperability and standardisation, aiming to lay at the core of IT systems that integrate a multitude of construction tech tools requiring the communication of heterogeneous data for optimal collaboration, and embracing the centralised data exchange paradigm proposed by Common Data Environments (CDEs) [9], by actively supporting extensible semantic modelling, mapping and linking capabilities accompanied by flexible querying and reasoning functionalities. In Chapter 2, the paper studies interoperability in the AEC sector through a brief literature overview of three core concepts: BIM, Standardisation and CDEs. This study acts as the basis to extract the principles that underlie the design of BIF and are presented in Chapter 3. Following, Chapter 4 outlines the interactions foreseen in the context of BIF in the form of use cases, highlighting the envisioned flow of actions and the added value brought by BIF to the every-day data exchanges that take place among stakeholders and applications in AEC projects. Finally, the paper concludes in Chapter 5 with a summary of the presented BIF framework and the upcoming demonstration activities for the validation and testing of the proposed solution in real-life conditions.

2 Literature Review

2.1 BIM

Building Information Modeling (BIM) is an information-based representation of a built asset for effective data management throughout its entire lifecycle, that is supported by a set of processes, roles, policies and technologies [10]. As per [11], BIM is the "use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions", thus spanning over several phases of the project, from conception and design, up to the maintenance and demolition of the built asset and facilitating collaboration and decision-making by diverse teams. To allow for informed decisions, BIM is not limited to the physical construction or to the inclusion of the temporal factor, but shall encapsulate other aspects such as safety, costs, resources, graphs etc. The multi-dimensional BIM paradigm (nD BIM) [12] has emerged to encompass the various modeling dimensions, without however having reached a clear consensus on the succession of dimension spaces and the individual dimensions per se [6]. According to the BIM dictionary [13], 3D BIM corresponds to the geometrical representation of the built asset, 4D BIM extends the geometrical representation with the addition of time, and the dimensions go up to the 5D BIM that also incorporates the cost parameter. The inclusion of additional parameters to the building modeling, has expanded the application areas of BIM in construction, with use cases in scheduling, construction simulation, construction logistics, site monitoring, clash detection, safety management, visual communication, cost estimation, quality control and more [6]. At the same time, Construction Tech systems that incorporate BIM can be categorized under the following four types: Design and construction management tools, BIM-to-field (i.e., tools realizing designs in the actual field), Robotic applications, field-to-BIM tools (i.e. tools capturing data from the fields and updating the BIM) [14]. The exponential growth of construction project data, resulting from the adoption of BIM - voluntarily to achieve better collaboration or a market edge, or after governmental [15] - and spawning for the multitude of available BIM solutions, is not by default beneficial, as it has led organisations to a state of 'drowning in data'[7], while the fragmentation of the data models used in the various project phases and by the various software lead to generic, incomplete 3D BIM representations, with little value for the post-construction phases [6]. Whereas BIM has been recognized as the most efficient concept in the AEC towards effective information management [16], it needs to adapt to the changing landscape of construction IT that calls for intersection with the domains of IoT and AI, that is now not possible due to incompatibility of legacy formats with the semantic web. A proposed solution towards this end is the Digital Twin paradigm [6].

One of the challenges that emerge from the variety of BIM-related software is that not all participants within a project use the same BIM solutions. ClosedBIM environments dictate the use of the same software (or even the exact same software version) by all key stakeholders. Such environments can be restrictive, as they require familiarity with specific tools and vendors, and hinder true interoperability. On the contrary, the approach of OpenBIM platforms is based on non-proprietary, neutral file formats, and the use of open standards, to allow seamless exchange of information regardless of the selected authoring solutions [17].

2.2 Standardisation

Integration of construction IT with emerging digital technologies such as the semantic web, cloud computing and IoT open new technical means of collaboration [16], while at the same time emphasizes the inefficiency of traditional import/export functionalities to serve the data exchange requirements between an overwhelming number of Construction Tech tools and platforms aimed at different stages of a project's lifecycle [6]. Standardization of data exchange is a core feature towards supporting semantic and technical interoperability and has been extensively studied as an enabler against data silos and fragmentation.

The first standardization attempts for the construction industry can be traced back to the late 1980s with the conception of the ISO STEP standards for the integration of computer-aided design (CAD) and computer-aided engineering (CAE) software [18] defining specific information exchange mechanisms and EXPRESS as the common descriptive language and establishing a standard implementation method with the STEP format [16]. Efforts for the further development of the ISO-STEP standardization have been shifted in the early 2000s towards the specification of the open, object-oriented and industry-led Industry Foundation Classes (IFC) for building assets and infrastructure representation [19]. Since the first registration of the IFC with ISO in 2013, it continues evolving to cover needs raising from practice and to incorporate the latest advancements in the IT and constructions. Standard Model View Definitions (MVD) are subsets of the complete IFC schema, developed to narrow down the otherwise large and complex IFC schema for specific applications of interest, using the Information Delivery Manual (IDM) [20] as a standardized method for specifications definition. More recently, the integration of linked data and ontologies is seen as a possible way to address the rather static nature of classic IFC that does not allow dynamic model modifications [6], resulting in developments such as the ifc-OWL [21][22], an ontology representation that offers a more flexible basis for interoperability [23]. Construction Operations Building Information Exchange (COBie) is a non-proprietary data format standard for the collaborative collection of a construction project's information in defined project stages, allowing communication among teams and the handover of complete documentation by the project's end to the client [24]. It is oriented towards capturing asset data without their geometrical characteristics and is the designated format for non-geometric information exchanges in open data formats according to the UK National Annex within [25]. Other ontologies in the domain include the BIM Shared Ontology (BIMSO), CBim, cityGML, SEMANCO, SAREF, DogOnt, ThinkHome, SEAS, IC-PRO-Onto [26].

Despite the wide adoption by OpenBIM solutions, of the IFC standard for built asset representation, and COBie for BIM information exchange and management [27], true interoperability is a challenge that can be view under the 'interoperability aims'(access data, re-use data, check data, retrieve data, link data, combine data, combine data hubs) that should be served through the communication of systems.

2.3 CDEs

Common Data Environments are technology solutions that enable collaborative working in the AEC sector [9]. The term CDE was initially conceived in the code of practice BS1192-2007 for collaborative information production and management in the AEC and was part of the PAS 1192-2 specification [28], that were later both superseded by BS EN ISO 19650 [11], and refers to systems that serve as a single source of information, responsible for the collection, management and dissemination of documentation, graphical models and non-graphical data (i.e. including both BIM and conventional data) among teams involved in a project to avoid duplications, erroneous data and unavailability of the latest information.

Towards this end, CDEs deliver a mix of services to their users, with core features including: file publication, document management, data security, search capability, reporting/dashboarding, information viewing, mobile and field support, integration potential [9]. From the perspective of technical interoperability, CDEs fulfill what they promise through cloud and web-based technologies, as for example with the implementation of REST APIs in place of traditional direct file-based exchange [29], while from a semantic scope the adoption of open data formats and federated data models is key for the seamless collection and reuse of data authored in different tools and formats. Except for semantic and technical interoperability, CDEs need to address key challenges touching upon legal and organizational aspects. More specifically, a CDE shall handle issues concerning among others, data security [30], data ownership and copyright [31], data sovereignty [32], data privacy [33] and more.

In correspondence to the closed versus open BIM approach, CDEs have evolved in a similar way. This has led either to the development of closedCDE solutions offering high levels of interoperability between tools of the same suite, based on proprietary formats and specifications, while excluding competitive or open solutions, or to openCDE tools that follow the openBIM guidelines for vendor-neutral interoperability. Ongoing efforts are also directed towards the specification of openCDE APIs aiming to further improve interoperability within the AEC software ecosystem through closely-knit, domain-specific APIs. Going beyond the level of information exchange between tools within a single CDE, to cover interoperability requirements introduced by concepts as the construction digital twins, [17] suggest a paradigm that considers multi-dimensional interoperability among CDEs. According to this paradigm, interoperability can take place between tools within one CDE (one-dimensional CDE), between CDEs within a project or company (two-dimensional CDE) or among collaborative and digital twin platforms (three-dimensional CDE). With the addition of dimensions, comes inevitably an increase in complexity for handling a wider range of data formats, and environments, that could be addressed with the assistance of semantic web and linked data technologies [34].

3 BIF Design Principles

Interoperability in the AEC sector remains a challenge. Construction Tech solutions with high specialization operate in a siloed manner as they use their own internal representations and perform any required data exchanges with other tools in a bilateral manner. In the meantime, the industry is still in the progress of efficiently adopting Level 2 BIM that focuses on full collaboration, whereas the latest developments in construction IT (e.g., digital twins, AI, field-to-BIM solutions etc.) call for full integration through truly interoperable data – what is known as Level 3 BIM maturity.

The BIMERR Interoperability Framework (BIF) aims to remediate this gap in the BIM chain by providing a technological enabler for achieving holistic interoperability between the various tools and stakeholders in AEC projects. Through the BIF, applications involved in the same building construction or renovation project, no longer need to exchange data in a direct bilateral way. On the contrary, BIF will act as the mediator, incorporating the required data models, functionalities and access-control mechanisms that allow the collaborating tools and actors provide and consume data in a centralized manner.

Semantic interoperability is supported by the underlying ontologies and common data models [35] developed from the in-depth analysis and enrichment of existing AEC-related data models and ontologies, to cover the semantic linking and data model population needs of the interoperating tools. Each data model corresponds to a different dimension of a renovation project; tangible objects (i.e., the building assets, materials), sensor data, analytics data and results (i.e., occupants' comfort profiling and prediction, renovation scenarios), processes and time (process modeling, workflows and schedules), communication (e.g., annotations by occupants or workers, health and safety issues). The distinction of the data models per domain allows easy exploration and identification of concepts suited to each user (application or human actor). However, the case of multi-domain data residing within the same data asset is common among construction tools, thus requiring the support of data model linking and cross-domain reuse of common concepts and data fields.

Interoperability is often tightly related to standardization. Therefore, the basis for the development of the BIF common data models is comprised of open and standardized models that are widely adopted in the domain, including IFC [36], obXML [37], SenML [38], SAREF4Building, BCF. In alignment with the latest trends in construction technologies that highlight the need for dynamicity and extensibility [6], data models in BIF are implemented as living entities supporting versioning, continuous evolution and backwards data compatibility. Existing data models can be managed throughout their entire lifecycle, to cover newly identified modeling needs and allow integration of information coming from new tools and platforms, while the overall data model collection can be expanded in a continuous manner to cover new domains of interest and allow even more construction applications enter the BIF framework, thus expanding the scope of interoperability in various phases of a build asset's lifecycle.

From the perspective of data, their compliance to standardization is a natural outcome of the mapping to the common data models that follow greatly the existing standards. For further alignment with the ISO 19650 specifications for CDEs, BIF provides versioning, status and category metadata options. Finally, as BIF follows an openCDE approach, the utilization of open data sources is possible through the available data collection and mapping mechanisms.

The design of the appropriate technological means for data exchange facilitates interoperability at a technical level. Driven by flexibility [29], BIF provides REST-based data collection methods, using APIs provided either by the interoperating applications or exposed by BIF, while also providing the option for direct file upload as a secondary method. Users can utilise the APIs to send plain text data or accompanied by binary files, such as audio, video, photos, ifc files and more. Further customization of data collection aspects, such as collection and processing periodicity, and the capability of data enrichment with static or dynamic parameters, allow users tailor the process to the needs of their applications. Another interoperability need that needs to be satisfied is the 'access to data' [27]. BIF integrates a search and query engine for the exploration of available data and the definition of customizable queries for data retrieval. The available filtering, sorting modules facilitate easy identification of data assets of interest and an enhanced user experience, while the integrated search functionality supported by data indexing methods allows efficient and fast keyword-based searches to be performed over field names and content. A query configuration interface provides the user with the option to fully customise the incoming results that will be fed to the requesting application, be selecting the subsets of data they need and query parameters that can be utilised upon request for filtering. The actual data retrieval mechanism is corresponding to the respective upload method, being either direct file download or API based retrieval. Various data linking challenges (such as semantic, temporal and spatial homogeneity) can be addressed through the combination of the mapping to context-related concepts inside the models and the retrieval mechanism allowing to join data from multiple datasets.

Security in BIF is addressed in a multi-dimensional approach. User authentication and authorisation is enabled through the integration with the Keycloak open identity and access management solution. Token-based API access authentication is enforced for all API requests to the BIF either for data collection or retrieval purposes. An important aspect in the exchange of data among different stakeholders and tools concerns access control. In compliance with the principles of organizational interoperability, the original owners of the data shall be able to define explicitly the applied access policies. Elaborate research on the requirements of AEC projects and stakeholders, revealed that for data that are not intended to become publicly available, access can be decided on user-level (identity or assigned role within an organisation), application-level, project-level or even on apartment-level. Once defined by the data owners, the access policies are enforced on the data assets and the access control mechanism is activated whenever a user or application tries to gain access to data, at search or querying time, to ensure that the requesting actors gain access only to the parts of information they are eligible. Data ownership and intellectual property rights, another legal and organizational interoperability requirement, is resolved through the attachment of licensing metadata on the data asset, defining various aspects of proper data usage based on preloaded Creative Commons, Community Data License Agreement and Open Data Commons licenses for public data, or customized licenses composed from the selections of the user. The operational status of BIF is constantly monitored through a deployed application monitoring and error tracking software that offers real-time alerting, customizable error logging and performance overview features to ensure timely response and operational stability.

Although the BIF integrates AEC data models, it is a platform that can in the future be generalised and used in other domains too, by integrating the respective data models (such as the energy, cybersecurity, health and more). Opposed to other open-source solutions, it provides a flexible mechanism for data exchange and reuse by applications with different specifications and processing capabilities, based on the use of common data formats and going further from simple file exchange functionalities

4 BIF Interactions

The BIF aims to serve the collaborative working paradigm as a central cloud-based information point, ensuring the seamless and secure data exchange among the individual construction tools and applications. It has been designed and developed in the context of the H2020 project BIMERR [8], that envisions the design and development of an ICT-enabled Renovation 4.0 toolkit comprising tools for Architecture, Engineering & Construction (AEC) stakeholder support throughout the energy efficiency renovation process of existing buildings. However, the extensible and application-agnostic approach in the design and implementation of BIF will allow its adoption in AEC projects outside the renovation stage, facilitating semantic interoperability throughout all phases of the complete lifecycle of building assets and infrastructures.

Figure 1 demonstrates the internal architecture of BIF along with the typical data exchanges that take place between BIF and interoperating tools but also among the BIF subcomponents. The functionalities and implementation and deployment of the BIF subcomponents are extensively documented online [8]. Additionally, the specific data exchanges that take place in the context of the BIF interactions (Model Management, Data Upload, Data Retrieval) are depicted in three detailed sequence diagrams developed in the context of the BIMERR architecture.

4.1 Model Management

The Building Semantic Modelling subcomponent is the facilitator of semantic interoperability with the support of the underlying data models that are created, integrated and maintained within the framework by users of the BIF assigned with the role of model manager. The users can navigate and manage the models of the BIF throughout their entire lifecycle using the graphical interface of the Model Manager. During the model creation stage, the user can add the data model concepts and fields, defining their main details

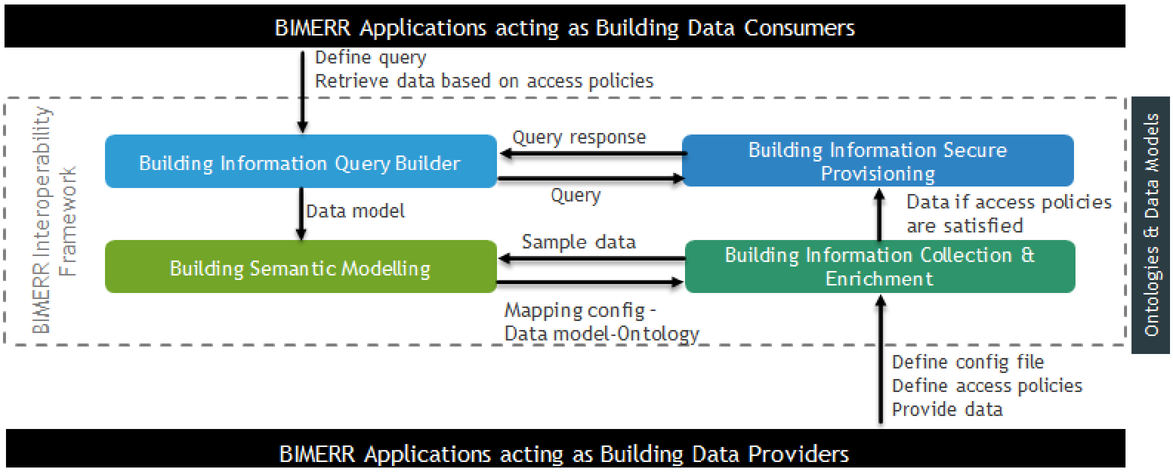

Figure 1. Overview of the BIMERR Interoperability Framework (BIF) components and interactions

and adding various metadata, such as the field type and cardinality, but also defining parameters, as for example the related terms, that will be fed to the mapping prediction engines of BIF for improved and efficient data retrieval. As a good practice in the design of the models and to ensure compatibility with industry applications, the models created for the BIF can be built upon existing semantic models directly or indirectly related to the AEC, coming from a multitude of sources, without any technical restrictions to creating totally new models being imposed by BIF. To further facilitate the linking with existing domain standards and ontologies, the user can assign to each field the corresponding standard it is associated to. Building semantic links as bridges between individual data models is an efficient way to avoid duplication of concepts that are common among different AEC domains. During the semantic linking step, the user attempts to link different data models, along their concepts in a drag-n-drop manner, thus reusing concepts that have already been modelled, saving time and ensuring the unified modelling of data representing the same type of entities. As time goes by, existing models are updated, while new ones may emerge, and individual concepts or complete models may become obsolete. Additionally, during the application of the data models, any inefficiencies and omitted concepts or misunderstandings in the initial conceptualisation of the model will be revealed. The functionalities for these dynamic adjustments and expansions can be realised following a semantic model reconciliation process through the Semantic Model Lifecycle Management tool. Any changes performed in the data models at operation time, are also applied by the data scientist to the respective ontologies through the Ontology Manager Framework.

4.2 Data Exchange

Once the underlying data models are available, the other services of BIF are launched in a distributed manner to instantiate the models and populate them with actual data. During this phase, real-time and batch data are ingested through APIs from the interoperating tools and users can start acting as data consumers and providers in a workflow that will be described in the following paragraphs. The envisioned use case follows the journey of a data asset in BIF, from the initial collection preparation steps and the actual data collection, processing, and storage up to the moment it is retrieved by another interested tool or user.

AEC professionals are participating in a construction project and want data generated from their application to become available to other teams. They first need to access the Building Information Collection & Enrichment user interface to configure the various aspects around data collection, such as method of data collection (through their application's API, using an API generated by BIF on demand, or even with direct file upload), the periodicity of collection and data processing, as well as specify the subset of the data that shall be harvested. Afterwards, the user is prompted to the Building Semantic Modelling UI, where she can semantically map the data that will be provided by their tool to the BIF common data models, in a drag-n-drop manner. The underlying mapping prediction engine that is built on schema matching techniques, generates mapping recommendations with an assigned confidence level to speed up the overall process. If the user identifies any missing fields or concepts from the available data models, she can make ad-hoc requests that are forwarded to the Model Manager component and appropriately assessed and handled by the data model administrators in case model remediations are required. Once the mapping is completed by the user, a background validation check is performed to ensure error-free data transformations when the actual mapping service is invoked, and the user is appropriately informed of any discrepancies. To complete the data collection configuration, the user is led to the loader configuration step to define the name and description of the data asset. Once the configuration process is completed, a configuration file encapsulates all the information and is used by the underlying orchestrator for the timely invocation of background services provided by the Building Information Collection & Enrichment and Building Semantic Modelling components for the collection, mapping, enrichment, processing and finally the indexing and storage of the data asset, that is now transformed from the native format to the target format of the common data model, thus allowing other tools retrieve and re-use it for their operations. At any time, the user acting as the original data owner of the data can define and update the asset's metadata, to make them available to the other users of the BIF, specifying apart from informative details, such as related keywords, language, format, also the fine-grained access policies that shall be enforced by the Building Information Secure Provisioning tool and will regulate access provision based on various aspects thus ensuring data privacy and security.

On the other side of this journey, we find applications that want to consume data assets for their operations. To facilitate this, the developers of the application shall access the Building Information Query Builder UI and explore the available data assets – note here that they can only view assets they are eligible for based on applied access policies - utilising the filters, keyword search and sorting modules of the Search UI to easily identify the appropriate data assets. Then the user can proceed with fully customising a query for the retrieval of the selected data asset(s), by explicitly indicating the fields she wants and defining query parameters, previewing a sample of the query results to ensure that the data asset indeed fits the needs of the consuming tool and finally utilise the retrieval API provided by BIF. Token-based authentication/ authorisation prevents any illegitimate access to data. The fully configured query can be used multiple times by the consuming application to retrieve information and is stored in the Building Information Query Builder for easy access and updates by the user who created it.

5 Conclusions

Technical and semantic complexity, coupled with legal and organisational factors act as prohibitors for the adoption of truly interoperable solutions in the constructions industry. The BIF, developed in the context of the BIMERR project, aims to surpass these limitations, by providing the appropriate data management and integration functionalities and following widely adopted industry standards and design principles, that will allow any construction tech application retrieve and provide semantically coherent data for efficient collaboration. Considering the ever growing of data-intensive technologies entering the construction IT landscape, the need for the development and adoption of efficient, flexible and extensible interoperability solutions such as BIF becomes even more apparent.

The offerings of the BIF will be showcased in the context of the upcoming demonstration activities within the BIMERR project, that will validate its added value and will act as a proof-of-concept for the overall vision of BIF. Several applications involved in the overall lifecycle of a renovation project, from building information capturing and modelling up to renovation design support, planning and monitoring, will exchange data through BIF. More specifically, these will include software and hardware-enabled tools developed as part of the BIMERR Framework. The demonstration activities will take place in the upcoming period, in two real-life multi-family residential pilot sites that will undergo renovation, in Poland and in Spain.

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