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Dynamic Multi-Model Container Framework for Cloud-Based Distributed Digital Twins (dDTws)

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Abstract: The increasing complexity of data management in the Architecture, Engineering, and Construction (AEC) industry, driven by the adoption of distributed digital twins (dDTws) and cloud-based solutions, presents challenges in interoperability, data sovereignty, and scalability. Existing Building Information Modeling (BIM) and Common Data Environment (CDE) frameworks often fall short in addressing these issues due to their reliance on centralized and proprietary systems. This paper introduces a novel framework that transforms the Information Container for Linked Document Delivery (ICDD) into a dynamic, graph-based architecture. Unlike conventional file-based ICDD implementations, this approach enables fine-grained, semantically rich linking and querying across distributed models while maintaining data sovereignty and version control. The framework is designed to enhance real-time collaboration, ensure secure and sovereign data management, and improve interoperability across diverse project stakeholders. The framework leverages graph databases, semantic web technologies, and ISO standards such as ISO 21597 to facilitate seamless data exchange, automated linking, and advanced version control. Key functionalities include federated data storage, compliance with local and international regulations, and support for multidisciplinary workflows in large-scale AEC projects. To demonstrate the feasibility of the proposed framework, a simplified use case scenario is implemented and analyzed. By addressing critical challenges and enabling seamless integration of emerging technologies such as digital twins, this study advances the state of the art in data management for the AEC industry, providing a robust foundation for future innovations.

Keywords: distributed digital twins; data sovereignty; graph-based framework; interoperability; Architecture, Engineering, and Construction (AEC); semantic web technologies; ISO 21597; data management

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1. Introduction

The rapid digital transformation in the Architecture, Engineering, and Construction (AEC) sector has introduced complex data management challenges that necessitate innovative approaches to handle the vast, multidisciplinary data generated across a project's lifecycle. The advent of digital twins in the Architecture, Engineering, and Construction industry has transformed construction project management, enabling real-time data monitoring, analysis, and optimization. However, with this shift towards data-driven methodologies, there is a growing emphasis on construction data management and data sovereignty, as stakeholders increasingly require secure and interoperable data frameworks that protect proprietary and sensitive information. Ensuring data sovereignty—where each

entity retains control over its data assets—presents both technical and regulatory challenges. These challenges are exacerbated in cloud-based environments where distributed digital twins (dDTws) are integrated across diverse disciplines, raising concerns around secure data sharing, access control, and version management [1,2].

The construction industry's increasing adoption of advanced digital technologies like Building Information Modeling (BIM), Digital Twins (DTws), and cloud-based platforms has significantly enhanced project collaboration and lifecycle data integration. However, ongoing challenges around interoperability and data sovereignty continue to pose significant obstacles to these systems. While these tools enhance data sharing and operational efficiency, they remain constrained by significant challenges related to interoperability and data sovereignty. The lack of universal standards across BIM software and platforms hinders seamless data exchanges, leading to inefficiencies and potential data silos [3]. Furthermore, cloud-based systems, though critical for scalability and collaboration, raise concerns over data ownership and control, as proprietary data may be stored across multiple jurisdictions, potentially breaching local regulatory requirements [4,5]. Addressing these limitations is pivotal to realizing the full potential of digital transformation in the AEC industry while ensuring secure and sovereign data management practices.

Building upon the foundational multimodel methodology introduced by Fuchs, this research presents a graph-based dynamic multimodel container framework for distributed digital twins. Unlike conventional file-based multimodel containers, the proposed framework leverages graph databases to enhance scalability, facilitate real-time collaboration, and uphold data ownership principles. By embedding data access control mechanisms, this model provides stakeholders with greater control over their data assets, advancing a decentralized approach to construction data management. This research addresses critical challenges in data management for cloud-based distributed digital twins (dDTws) in the Architecture, Engineering, and Construction (AEC) industry. Specifically, it focuses on the integration of graph-based dynamic multimodel container frameworks to enhance data interoperability, sovereignty, and scalability. To achieve these objectives, this study formulates key research questions aimed at addressing gaps in existing frameworks and exploring innovative solutions for real-time collaboration:

RQ 1: How can a graph-based dynamic multimodel container framework enhance interoperability in cloud-based distributed digital twins (dDTws) for the AEC industry?

RQ 2: How can the proposed framework ensure data sovereignty in distributed digital twin environments while complying with international and local data regulations?

RQ 3: How can the integration of technologies like digital twins, semantic web, and graph-based databases improve real-time collaboration across diverse stakeholders in construction projects?

This paper is structured as follows: Section 2 presents a comprehensive literature review, outlining the state of the art in data management, interoperability, and data sovereignty in cloud-based distributed digital twins (dDTws) within the AEC industry. Section 3 introduces the proposed graph-based dynamic multimodel container framework, detailing its architecture, components, and functionalities. Section 4 discusses the research methodology employed to validate the framework, including case studies and performance benchmarks. Section 5 presents the results and analysis, highlighting the framework's impact on interoperability, scalability, and data sovereignty. Finally, Section 6 concludes the study by summarizing the findings, discussing implications for the industry, and identifying directions for future research.

2. Background

2.1. Foundations of Construction Data Management

In the Architecture, Engineering, and Construction (AEC) industry, the surge in digital tools such as Building Information Modeling (BIM) and digital twins has fundamentally transformed data generation, accessibility, and usage. BIM serves as a comprehensive digital representation of a building's physical and functional characteristics, facilitating collaboration among stakeholders and enhancing decision-making processes. Digital twins extend this concept by creating dynamic, real-time digital replicas of physical assets, enabling continuous monitoring and optimization of building performance. The integration of these technologies results in the generation of vast amounts of data, encompassing design specifications, construction processes, and operational parameters. This influx of data necessitates advanced frameworks for effective management, including data integration, interoperability, storage, processing, security, and privacy. This evolution supports sophisticated project management techniques but also brings complex data challenges that necessitate advanced management frameworks to handle the extensive data generated throughout a project's lifecycle [6–8].

Koutamanis [9] highlighted that the integration of these technologies requires advanced data processing, storage, and management solutions to handle diverse data types and formats, ranging from real-time sensor data to historical building information. This integration challenge is central to data complexity in AEC. A systematic review highlights the development of emerging technologies facilitating the evolution of BIM to digital twins in the built environment, emphasizing the need for effective data management strategies to leverage these advancements [10,11]. Omrany et al. [12] emphasized that effective data management can address issues such as data silos, redundant data storage, and security vulnerabilities by centralizing data access and enforcing standardized protocols. Such frameworks are crucial for supporting collaborative workflows, minimizing errors, and maintaining data consistency across the lifecycle.

The proliferation of data in AEC projects introduces challenges related to data interoperability, integration, and security. Managing large datasets across various project phases and ensuring seamless data sharing between stakeholders' demand advanced data management frameworks. In modern AEC projects, data management has become essential for harnessing the potential of BIM and digital twins. As data volume and complexity continue to grow, robust frameworks are necessary to ensure effective data integration, accessibility, and security. Implementing these frameworks can enable the AEC industry to leverage digital transformation fully, optimizing project performance and achieving better outcomes throughout the building lifecycle.

2.2. Interoperability Challenges in Existing BIM and CDE Solutions

Interoperability has been a persistent challenge in the Architecture, Engineering, and Construction (AEC) industry, as project stakeholders increasingly rely on digital tools to manage complex projects. With the rise of Building Information Modeling (BIM), digital twins, and other collaborative technologies, the need for seamless data exchange has intensified. However, the lack of standardized protocols across software platforms hinders effective communication and data sharing, resulting in inefficiencies, data duplication, and project delays [13,14].

BIM is widely adopted as a digital tool for modeling and managing construction data. However, the interoperability challenges between BIM tools primarily stem from the fragmentation of software ecosystems and their reliance on proprietary file formats. These interoperability gaps manifest in various forms. For example, inefficiencies arise when project stakeholders must manually merge design files from different disciplines,

introducing delays and potential errors. Data silos are prevalent as actors rely on isolated authoring tools with limited cross-communication, leading to fragmentation. Additionally, exporting models often results in information loss—such as missing metadata or relational context—due to incompatible data schemas or software limitations. While open standards like the Industry Foundation Classes (IFC) and BIM Collaboration Format (BCF) are widely promoted, their adoption is inconsistent, leading to incomplete data transfers or loss of semantic information during model exchange [15]. For example, the IFC schema often struggles to capture project-specific data attributes, which causes difficulties in transferring complex BIM models between tools [16]. Common Data Environments (CDEs), on the other hand, provide a centralized platform for managing project information, enabling real-time collaboration. However, interoperability issues arise when integrating heterogeneous data sources such as BIM models, documents, and schedules. The absence of standardized CDE interfaces and data exchange protocols restricts cross-platform compatibility, resulting in data silos and inefficiencies [17].

Research has extensively highlighted these interoperability issues. For instance, Lu et al. [18] discuss the challenges of integrating BIM and digital twins, emphasizing the need for standardized data formats to facilitate effective communication among stakeholders. Similarly, Alonso et al. [19] highlight the interoperability challenges in the AEC industry, noting that the lack of standardized protocols leads to data silos and inefficiencies. Furthermore, Tulubas and Arditi [20] examine the impact of digital transformation on the AEC industry, identifying interoperability as a critical factor affecting the successful implementation of BIM and digital twins. Existing BIM systems primarily rely on file-based data exchanges, such as those using Industry Foundation Classes (IFC). However, IFC-based workflows often fail to capture the full range of project-specific data attributes, leading to information loss and misinterpretation during transfers [21].

To address these limitations, recent developments focus on linked data and multimodel approaches. The Information Container for Linked Document Delivery (ICDD), introduced under ISO 21597 [22], offers a potential solution by enabling the structuring and linking of heterogeneous data within a container model. However, its practical application is limited by the lack of seamless integration with existing CDEs and the absence of automated validation mechanisms for linked data [23]. Unlike traditional federated CDEs that mainly centralize access to static models, the proposed framework supports dynamic and versioned multimodel management. It further introduces semantic linking across heterogeneous models and aligns with the needs of distributed digital twin environments, enabling greater flexibility, scalability, and real-time model synchronization across multiple stakeholders. Nevertheless, while ICDD improves structured data exchange, it remains constrained by its file-based nature and dependency on manual validation processes. Additionally, the file-based nature of ICDD constrains real-time collaboration, as updates must often be manually reconciled across different stakeholders.

2.3. Shared Data Environments and Cloud-Based Solutions

The Architecture, Engineering, and Construction (AEC) industry has embraced shared data environments (SDEs) and cloud-based solutions to address the inherent complexity of project collaboration and data management. Shared data environments (SDEs) are centralized or distributed platforms designed to collect, manage, and share project data among various stakeholders throughout a project's lifecycle. They aim to provide a "single source of truth", where data are accessible, reliable, and up-to-date. Building Information Modeling (BIM) tools, often integrated with SDEs, enable stakeholders to visualize, simulate, and coordinate project components effectively [24]. Standards such as the BIM Collaboration Format (BCF) and Industry Foundation Classes (IFC) have been developed to

facilitate data exchange, although their adoption and implementation remain inconsistent across regions and organizations [25]. These technologies have transformed traditional workflows, enabling better coordination and integration across stakeholders. However, challenges such as interoperability, data ownership, and scalability remain. While SDEs enhance project coordination, their centralized nature often leads to challenges related to data control and access rights. Proprietary solutions provided by leading BIM vendors, such as Autodesk and Bentley Systems, often lock users into specific ecosystems, which hinders interoperability [26].

Cloud-based solutions have become integral to modern SDEs, offering scalability, flexibility, and remote access to data. They enable real-time collaboration, reduce IT infrastructure costs, and provide enhanced data security through advanced encryption and access control mechanisms [27]. These solutions are particularly valuable for distributed teams, as they allow seamless interaction and data sharing regardless of geographical location. However, cloud-based systems introduce challenges related to data sovereignty and regulatory compliance. For instance, sensitive project data stored in international servers may fall under foreign jurisdiction, raising concerns about intellectual property rights and adherence to local laws [25,26]. Moreover, the reliance on cloud service providers can create dependency risks, where disruptions or changes in service agreements may significantly impact project workflows.

Researchers and practitioners are exploring federated platforms to address the limitations of centralized SDEs and cloud solutions. These platforms distribute data across multiple systems while maintaining interoperability through standardized protocols and governance frameworks. Federated solutions ensure that stakeholders retain sovereignty over their data while enabling collaboration through regulated data-sharing agreements [26]. Governance models, such as data cooperatives, have been proposed to provide a trust-based framework for shared data environments. These cooperatives establish shared ownership and decision-making processes among stakeholders, ensuring that data use aligns with collective goals while safeguarding individual interests [27].

2.4. Data Sovereignty in Cloud-Based AEC Environments

In the Architecture, Engineering, and Construction (AEC) industry, the shift towards cloud-based systems has revolutionized data sharing, collaboration, and project management. However, these advances have also raised significant concerns regarding data sovereignty—the ability of stakeholders to retain control and ownership over their data while ensuring compliance with local regulatory frameworks. Cloud computing inherently involves the storage of data across multiple jurisdictions, which can lead to conflicts between local data protection laws and global cloud services. For example, the General Data Protection Regulation (GDPR) in Europe imposes strict restrictions on the cross-border transfer of data, potentially clashing with the global infrastructure of major cloud providers like AWS or Microsoft Azure [28]. In the context of AEC, Turk et al. [29] highlighted that construction projects involve a dynamic network of partners, forming a "virtual organization" that changes throughout the project lifecycle. This dynamic nature complicates security management as partners may simultaneously collaborate on different projects with varying security requirements and potentially conflicting interests. The lack of clear jurisdictional boundaries can create vulnerabilities and legal risks.

One promising approach to addressing data sovereignty concerns is the use of federated cloud systems. These systems enable stakeholders to share and manage resources while retaining local control over data storage and compliance [30]. Federated cloud environments align with the principles of data sovereignty by distributing data across nodes managed by different organizations, ensuring that sensitive information remains

within its regulatory jurisdiction [31]. Jaskula et al. [32] propose a federated CDE using blockchain to integrate multiple CDE solutions and provide a single source of truth for project data, aiming to address limitations of centralized BIM implementations. They argue that blockchain's decentralization, data immutability, and intellectual property protection can potentially solve some of the sovereignty challenges [33].

The integration of federated data platforms with semantic web technologies is another emerging trend in the AEC industry. Werbrouck [16] highlighted that these technologies provide machine-readable data structures, allowing stakeholders to enforce data sovereignty rules dynamically. Additionally, organizations can leverage access control mechanisms and metadata validation to ensure that only authorized entities can access sensitive information. From an organizational perspective, clear governance frameworks are crucial. Implementing contractual agreements that outline data ownership, usage rights, and compliance responsibilities can mitigate disputes and enhance trust among project participants [30]. Ensuring data sovereignty in cloud-based environments also entails addressing security and privacy concerns. Sacks et al. [34] propose a Cloud BIM (CBIM) paradigm that leverages semantic web technologies to integrate federated data platforms and address the limitations of current BIM practices, particularly in collaborative multidisciplinary design. The integration of federated data platforms with semantic web technologies holds significant potential for transforming BIM practices and creating a more intelligent and interconnected data ecosystem for the AEC industry.

Weber [28] advocates for data governance frameworks like Gaia-X, emphasizing the importance of data sovereignty in cloud-based AEC environments. She highlights that Gaia-X, a European project for federated and secure data infrastructure, supports decentralized infrastructure solutions. It emphasizes transparency, data security, data protection, interoperability, and scalability in its services, reflecting values aligned with data sovereignty. She advocates for data governance frameworks like Gaia-X, emphasizing the importance of data sovereignty in cloud-based AEC environments. By enabling data analysis across decentralized datasets while preserving local privacy, such frameworks offer practical solutions for AEC projects involving multiple stakeholders and jurisdictions.

2.5. Advancing Construction with Semantic Web Technologies

To overcome the challenges of fragmented data exchange in distributed environments, it is necessary to move beyond static multimodel containers and adopt more flexible data structures. This shift aligns with the broader push for dynamic, service-oriented infrastructures in the AEC sector. As Godager [35] aptly observed, "existing BIM formats can meet future requirements, where the potential in the construction industry to fully utilize semantic web technology is difficult with today's BIM standards" This vision reinforces the rationale for a distributed, graph-based multimodel container framework that adapts to varying stakeholder needs and project configurations.

To facilitate information exchange in the architecture, engineering, construction, and operation (AECO) sector, several international standards have been agreed upon. The Industry Foundation Classes (IFC) was the first standard developed by buildingSMART International [36]. In a "conventional" building information modelling (BIM) model, IFC is primarily used to represent the building design. However, most of the existing BIM authoring tools also support the export of building models as an IFC file. To capture the design details of the building, IFC contains a sophisticated schema. The second standard is the ISO 19650 series that standardizes information management covering the whole life cycle of an asset under construction using BIM. It is a business process standard that defines requirements for organizing operations information in construction processes. The standard defines a procedure for the appointing party to specify requirements for information

delivery and management [34]. The series provides specifications for the execution of BIM-based construction projects. As a single source of truth, the common data environment (CDE) is defined according to ISO 19650 for information delivery aspects. The CDE is the cornerstone of transition in the processing of building data by facilitating the structuring information and data exchange processes in the course of a project between different stakeholders and providing tools for cloud-based collaboration [37]. Using centralized data storage within a CDE, the risk of data redundancy is reduced and timely access to up-to-date data is ensured. Last but not least, ISO 21597 "Information Container for Linked Document Delivery (ICDD)" specifies ontologies for the representation of interlinked datasets as a single source of information of federated data models and documents that could be used for the exchange of static state of project content between projects parties and also for archiving and documentation purposes.

On the other hand, technologies like digital twins and graph-based containers enhance multi-discipline overarching collaboration. In the course of a project's lifecycle, digital twins serve as a powerful platform for sharing information, fostering collaboration, and enabling informed decisions. It enables real-time sharing of project data, by providing a virtual replica of the physical asset or project and allowing team members from different domains to visualize and interact with the project in a shared virtual environment [38]. As Esser et al. [39] highlight, the iterative nature of AEC projects demands robust version control and change-tracking mechanisms, which are inadequately supported by current file-based data exchange solutions. This reinforces the need for a more dynamic, graph-based multimodel container capable of supporting fine-grained, temporal data management. The adoption of graph-based containers facilitates real-time data interchange and collaboration among stakeholders in the construction industry, resulting in improved project outcomes and heightened efficiency. The advantages are evident as this technology enables seamless communication, immediate progress updates, and early detection of potential issues before they escalate, and ultimately expedites decision-making processes. Considering the numerous parties involved in construction projects—ranging from architects to contractors—it can be daunting to ensure everyone is well informed about developments at each stage. Graph-based containers alleviate these challenges by furnishing a centralized platform where all stakeholders can access pertinent information promptly and without confusion or delay. By doing so, they empower better teamwork coordination leading to overall success while minimizing errors arising from miscommunication or inadequate access to up-to-date plans and documents.

Manipulating these standards made the multi-disciplinary collaboration between teams in a construction project possible. Currently, many collaborative platforms are used to share information in projects. By enabling a continuous flow of information and file updates, these collaborative platforms are seen as an overarching solution to improve collaboration. In a literature review published by Lindholm et al. [38], it is found that merging multiple approaches and leveraging their respective capabilities, such as knowledge graphs, common data environments, and digital twins, could support an integrated, automated system. By utilizing these platforms, all project actors can effectively communicate and collaborate, which results in improved collaboration performance, enhanced interoperability, continuous integration, advanced information retrieval, and streamlined workflows.

3. Approach

In response to the limitations outlined above, this paper introduces a dynamic multimodel container framework. This framework is specifically designed to enable flexible, semantic linking of heterogeneous data sources while preserving model sovereignty and enabling scalable management. The proposed framework constitutes a core component of

the iECO project (2022). The project, amongst others, aims at developing a Gaia-X-based decentralized platform for a distributed digital twin and supporting collaboration in the construction industry [40]. In this chapter, we will demonstrate the framework architecture and explain the selection of each component, namely; graph database, dynamic multimodel container (DMMC), and distributed digital twins (dDTws).

3.1. File-Based vs. Graph-Based Multimodel Approach

The Multimodel (MM) approach firstly was developed in the Mefisto project [41] to represent linked building model data. A common basis of the approach is the connection of separate elementary models, in their original state, using ID-based links [42]. The links describe n-array relations between (two or more) individual elements of different models using an XML/XSD representation in separate link models and, together with the elementary models are saved in the MM container (MMC). When the approach was standardized as an Information Container for Linked Document Delivery (ICDD), the links were created and saved in RDF files, and the whole container—including the file with the link model—was compressed as a ZIP archive file with the extension '.icdd', as shown in Figure 1 (on the left). This modular but file-based architecture stores metadata and linksets across multiple RDF/XML documents (e.g., index.rdf, linkset.rdf, model-a.rdf). In contrast, the right side illustrates the proposed graph-based alternative, where the same entities and relationships are natively modeled as nodes and edges in a property graph database (e.g., Neo4j). This enables efficient querying, dynamic updates, and seamless navigation across interconnected models, improving interoperability and scalability for distributed Digital Twin environments. Even though using a file- or document-based database to store RDF data offers advantages such as flexibility and scalability, it is not suitable when dealing with the semantic complexity of multidisciplinary data, maintaining consistent cross-file references, and supporting dynamic, real-time updates across distributed systems.

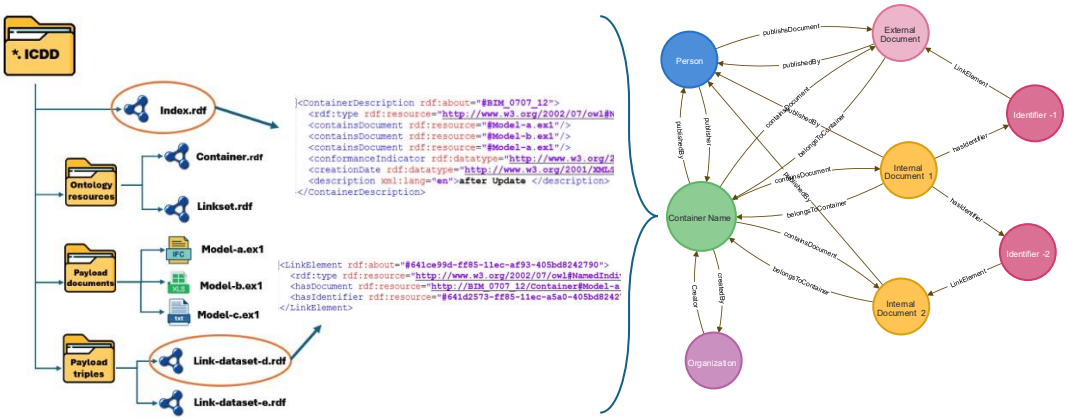


Figure 1. File-based ICDD (**left**) and graph-based multimodel container based on ICDD schema (**right**).

In that respect, however, multiple types of databases need to be considered when it comes to storing RDF triples. The most common choice for storing RDF triples is a relational database. It provides a structured way to store data and allows for efficient retrieval. However, due to its rigid table-based schema, it becomes difficult to represent complex and evolving RDF data structures that do not fit neatly into predefined categories. This mismatch leads to challenges when modeling semantic relationships and dynamically linked entities. Moreover, as the dataset grows, relational databases—especially if not optimized for the application domain—struggle with scalability because complex queries often require numerous joins across large tables, which significantly increases query latency and impacts overall performance [43].

On the other hand, graph databases are schema-free. They store and query RDF data in a more natural way, making it efficient for handling large amounts of interconnected data. They use a graph structure with nodes, edges, and properties (of nodes and edges) to represent and store data. Buron et al. [44] state that the use of graph databases is particularly beneficial for storing RDF triples as it aligns with the nature of the semantic web. By organizing data into easily navigable graphs, queries can be executed quickly without sacrificing accuracy or scalability. However, scalability may depend on the underlying graph database implementation, graph complexity, and deployment strategy, and should be evaluated carefully when applied to large-scale, dense digital twin networks. As such, graph databases are therefore essential when dealing with dynamic and interconnected data sets that require fast and accurate retrieval methods. Moreover, artificial intelligence (AI) technologies can benefit from knowledge graphs, because they provide a reliable semantic for knowledge-driven data storage. They enable semantic linking across sub-graphs, and provide an added layer of information. Knowledge graphs are also a good substitute for exact geometry, as they contain spatial relationships required for machine learning AI tools [37].

3.2. Dynamic Multimodel Container (DMMC)

The Multimodel Engine (MME) was developed firstly by Al-Sadoon et. al. [45] based on the standardized schema of the ICDD to implement functions as specified in ISO 21597, namely: create a container, add (internal and external) document(s), and create links between the added documents and between elements inside them. Then, dynamic functions were added turning it into a Dynamic Multimodel Engine (DMME) to allow for efficient collaboration among parties in a construction project and to provide more valuable services for overarching interdisciplinary decision-making; these functions are:

- Add dynamic values: this function was developed to enable the allocation of multiple dynamic values to elements in the building model, thereby enabling the consideration of dynamically changeable building elements' status at simulation runtime where the dynamic values contribute to real-time interoperability of interlinked simulation components and modules. This is crucial for achieving more reliable and precise simulation outcomes, especially in emergency events [46];
- Automation of document versioning and links update: To expand the workability of the ICDD and enhance its usefulness beyond pure data exchange, dynamic functions were developed. These include automatic document versioning whenever a new document is uploaded into the container and accordingly links of the linked elements contained in the newly added file will be automatically updated. As such, they ensure that the Multimodel container is capable of automatically managing document versions and updating linksets to maintain consistency and validity [47].

However, the DMMC created by this engine was file-based as well and used compressed ZIP files. The document itself is saved in the Payload documents folder, and the created links are saved as RDF files in the Payload triples folder as explained in Section 3.1.

In the file-based multimodel container, the container metadata, namely: container name, organization, names of internal document(s), and URLs, where external documents can be accessed, were saved in the so-called index file. Created links are saved as RDF triplets in a so-called linkset files. However, in our new approach here, we re-enacted the engine as a graph database-based engine using the graph database management system Neo4j, in which the created container and all its content are saved in a graph database instead of a file-based database. In the Neo4j-based implementation of the graph-based DMME, key nodes include Container, Internal Document, External Document, Document Version, Access Control, Identifier, and Organization. These are linked by relationships

such as ContainsDocument, version_Document, hasIdentifier, AllowAccess, and CreatedBy as shown in Figure 2. For example, versioning is handled through version_Document edges connecting multiple versions of a file, while AllowAccess links enforce access policies between Access Control nodes and documents. This graph structure enables flexible, low-latency queries that are essential for cross-referencing documents, tracking provenance, and enforcing fine-grained data governance across disciplines.

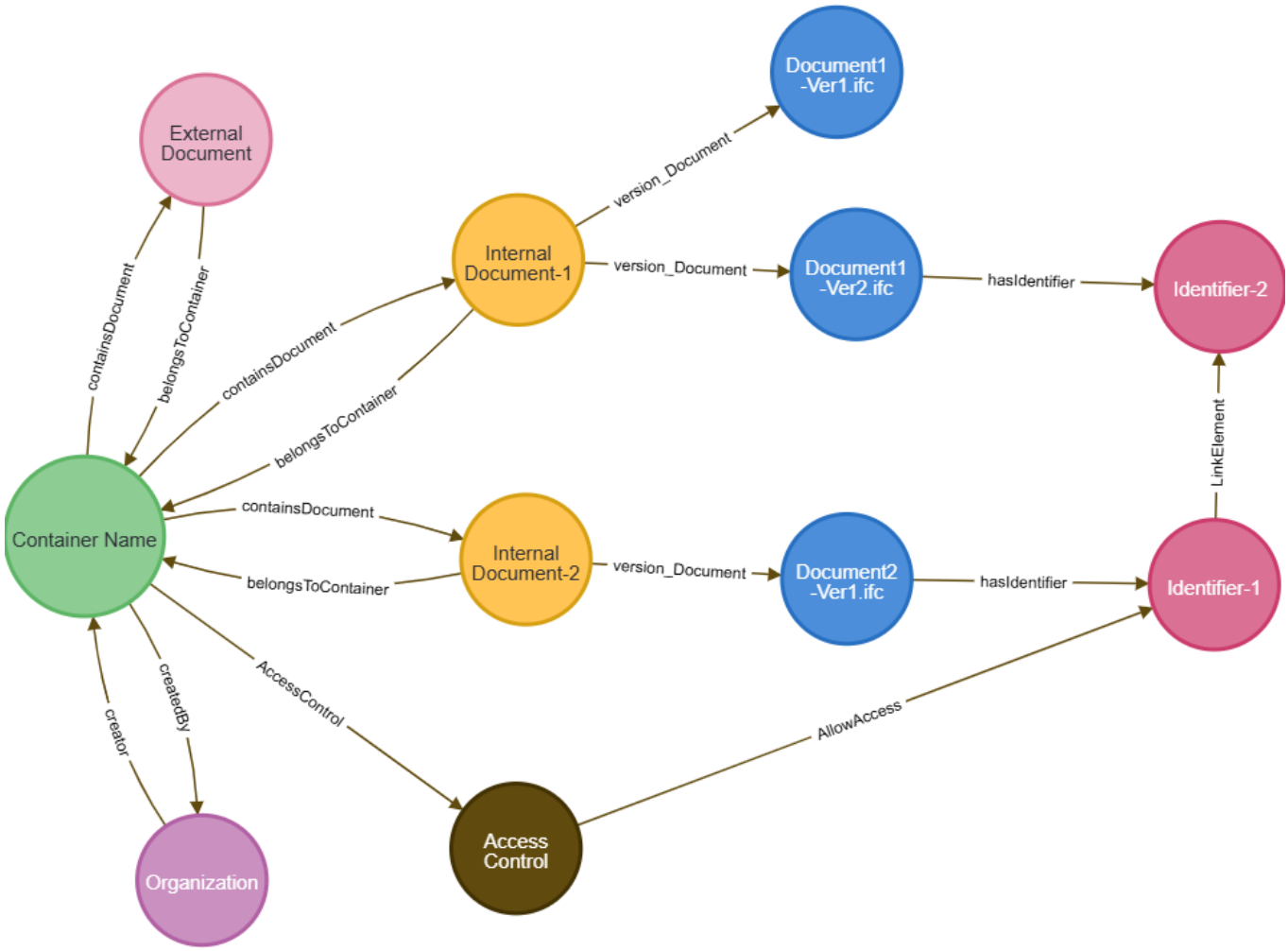


Figure 2. The graph-based DMME.

3.3. Access Controlled Dynamic Mulimodel Container (DMMC)

Data governance according to the Data Governance Act of the EU (DGA) needs management of the access rights of the data in the DMMC. This access right information should show a sufficient granularity and should be part of the meta-information of the DMMC. Therefore, we propose to restrict the access rights to complete documents and models of the DMMC, because each of these documents does have a unique author and hence an Intellectual Property right (IPR). As a sufficient granularity we propose to add to the DMMC an additional entity namely; **Access Control**. The entity has three properties: *Access Allowed*, *Access Allowed Partially*, and *Access Not Allowed*. This entity could be added at the document level, to define accessibility when creating links at the document level. Moreover, it could be added at the elements level to facilitate linking at the elements level. In this case, the value of **Access Control**, at the document level, shall be *Access Allowed* when all document elements could be shared for linking or *Access Allowed Partially* when some elements are allowed to be linked. To model partial access, the Access Control node

is linked via *AllowAccess* relationships to specific Document Version or Identifier nodes, rather than entire documents. This enables element-level access control, where users or agents can retrieve only permissible model elements or document sections, supporting granular data sovereignty while maintaining an auditable model.

The framework proposed here is developed based on the architectural design used within the iECO project [48], and is based on Gaia-X Principles [49,50]. The platform architecture was designed to enhance IT-based data sharing and collaboration in the AEC and operations sector through a generic IT architecture for decentralized digital twins aiming at increasing the efficiency of the entire building life cycle while simultaneously satisfying heterogeneity and decentralization requirements and maintaining the sovereignty of all participants. Strnadl et al. [51] defined the major elements of the dDTw architecture and the associated logical data flow between these components. The proposed distributed digital twin (dDTw) architecture consists of the following layers as shown in Figure 3, respectively:

- Gaia-X Federation Catalog domain (light green-yellowish color in Figure 3);
- dDTw services domain (darker green);
- Policy and trust management domain based on distributed ledger technology (DLT) (dark and light purple).

Here in our research, the focus will be on developing a framework for the dDTw services domain, defining the entities and logical data flow, whereas the other layers are currently out of our research scope. Therefore, data flows from/to the Gaia-X Federation Catalog and policy and trust management domains are eliminated from Figure 3.

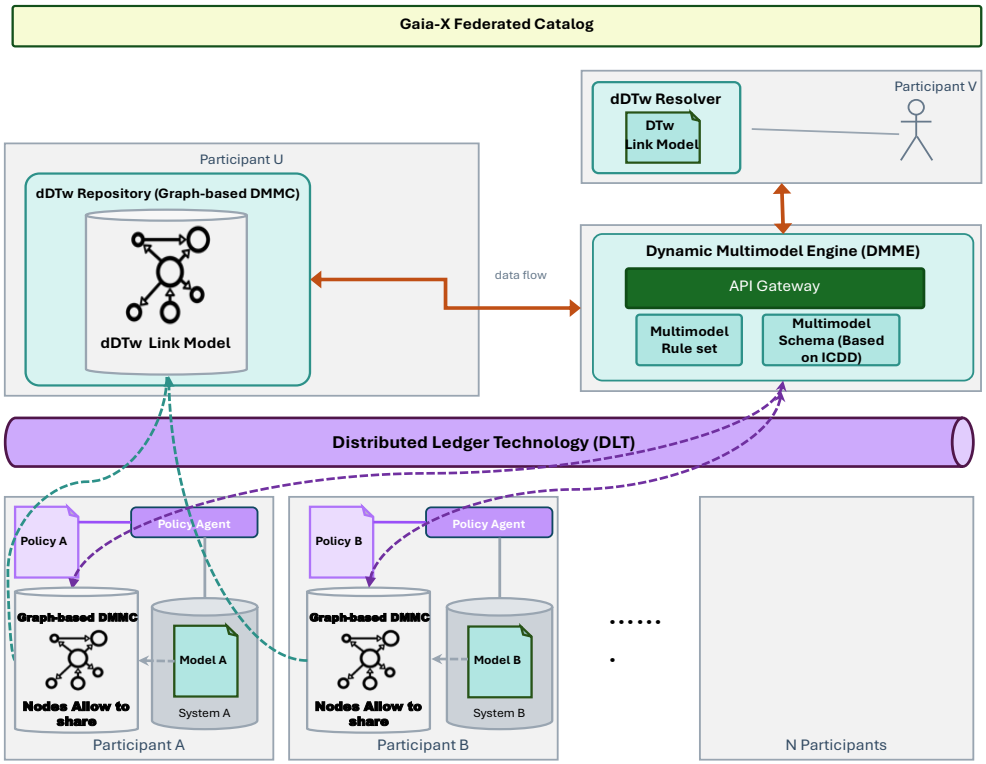


Figure 3. The architecture of the distributed digital twin (dDTw) illustrating the integration of the Gaia-X Federation Catalog, the dDTw services domain, and the Policy and Trust Management layer.

At the core of the dDTw concept, which is focused on data management, the dDTw Repository only stores the Link Model, i.e., the overarching model of a digital twin linking all its constituting sub-models and the relations between individual elements of entities of any sub-model. All actual data (e.g., the many different BIM models for the various professions, internet of things (IoT) data relating to different devices of a building) are

stored at facilities nominated by the participants alone (e.g., they may store data on premise in their own computing center or nominate another trusted party, even a hyperscaler or another trusted cloud provider, to store these data sets). This allows all participants who create and expose data to maintain ultimate sovereignty over these data; otherwise (viz., if all data need to be stored at a central facility), the configuration will be equivalent to another common data environment (CDE).

Taking that into consideration, the core components of our graph-based dynamic multimodel framework architecture illustrating the data flow and the roles of core components across distinct layers are as follows. The framework is centered on the dDTw services domain, structured into two logical layers: a dDTw domain model layer and a dDTw core services layer. In the dDTw domain model layer, each participant creates a graph-based Dynamic Multimodel Container (DMMC) hosting their own domain models (e.g., Models A and B) and defining the value of *Access Control* for the model itself and each element thereof. In addition, for each domain model, policies shall determine who is allowed to retrieve the various sub-models of the distributed DTw, whereas, the dDTw core services layer contains the central Dynamic Multimodel Engine (DMME) that governs schema and rule sets based on ISO 21597, and manages link models through a DMMC-based repository. Data flow from individual participants' systems through policy-enforced access (shown in purple dashed arrows) into the shared link model is managed by Participant U. This supports a sovereign, interoperable exchange of multimodel data. The distributed ledger technology (DLT) facilitates decentralized trust between participants, while the Gaia-X Federated Catalog provides federated service descriptions.

4. Framework Verification

To verify the proposed framework, a use case is utilized here. Referring to Figure 3, firstly, domain models are created by systems in dDTw domain models layer. In our use case, we propose that the building model BeyerBau_Arch.ifc is created in system A. The architectural model comprises 1446 IFC elements representing architectural components. Participant A then creates the Graph-based Dynamic Multimodel Container, adds the building model as an Internal document to the container and assigns the *Access Allowed Partially* property at the document level, and assigns the *Access Allowed* property for the building's columns elements only (IFC column). In system B, the Project schedule file BeyerBau_schedule.xlsx is created. The Excel file includes 19 activities with planned start and end dates. Participant B then creates the Graph-based Dynamic Multimodel Container for system B, adds the schedule file as an Internal document to the container, and assigns the *Access Allowed* property at the document level; accordingly, all its elements are allowed to be shared.

Participant U on the dDTw service layer creates the Graph-based Dynamic Multimodel Container for the dDTw repository. For our current use case, Participant U firstly retrieves the elements that had the property *Access Allowed* from both domain models; Participant A and Participant B then create links between these elements. Figure 4 shows the query to retrieve the Identifiers, Descriptions, and URIs for the elements that have the property *Access Allowed*, from the building model BeyerBau_Arch.ifc. Moreover, the same query is performed on the BeyerBau_schedule.xlsx. Then, as an example, Participant U creates links between the columns from IFC file and their related schedule from the Excel file and saves the links, which contain the elements' URIs, as an external document in the Container. As such, the Container in the dDTw service layer contains only links that reference the sharable individuals in the dDTw(s). Finally, to prove the capability of accessing and processing the linked data, an API call is performed on the linked model using the elements' URIs to retrieve the data of the linked elements from the distributed digital twins. This API

functionality is demonstrated using the linkage between an IFC file (BeyerBau_Arch.ifc) and an Excel schedule file (BeyerBau_schedule.xlsx). Figure 5 illustrates how the dynamic multimodel API enables cross-domain querying. The GET requests return JSON-formatted metadata for a 3D IFC model and its associated schedule, semantically linked through graph-based identifiers and properties.



Figure 4. Retrieving the elements with property *Access Allowed* from System A.

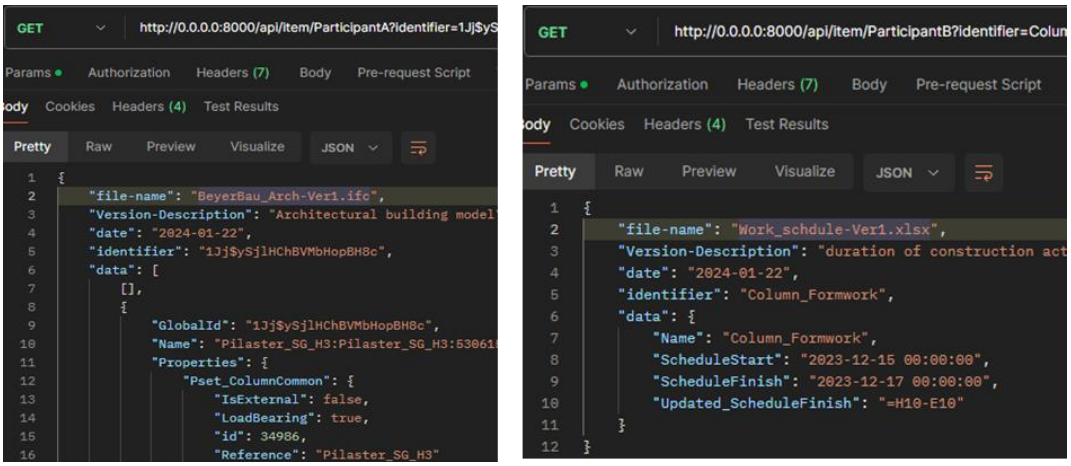


Figure 5. API implementation to retrieve the data of the linked elements.

To evaluate practical feasibility, we assessed the response time required to execute a semantic query for retrieving linked schedule elements associated with a given IFC component. As shown in Figure 4, the round-trip API response time was approximately 83 ms, demonstrating the efficiency of the graph-based linking framework in retrieving data across distributed sources.

5. Discussion

The proposed graph-based dynamic multimodel container framework significantly enhances interoperability in distributed digital twin (dDTw) environments for the AEC industry. By replacing the traditional file-based multimodel approach with a graph-based architecture, the framework overcomes limitations associated with siloed data exchanges and semantic inconsistencies (responding to the first component of RQ 1). The verification demonstrates that this approach supports seamless integration across diverse domains and platforms, as evidenced by the ability to link and retrieve heterogeneous data from distributed sources in real time (addressing the second component of RQ 1 regarding real-time data retrieval and platform independence). This improvement directly addresses

Research Question 1, showcasing how the graph-based approach supports effective data exchange and collaborative workflows.

The framework's design emphasizes data sovereignty by embedding access control mechanisms within the multimodel container. Through granular access rights at both the document and element levels, stakeholders maintain control over their data while ensuring compliance with international and local regulations. These features were validated using the proposed use case, where participants could manage access rights dynamically and restrict sensitive data as needed. This capability aligns with Research Question 2 by demonstrating that the framework not only facilitates interoperability but also ensures trust and sovereignty in data sharing (corresponding to the twofold focus of RQ 2: control over access and legal/regulatory compliance).

The proposed framework significantly enhances collaboration in distributed digital twin (dDTw) environments by providing a centralized yet dynamic platform for real-time data sharing and interaction. By leveraging graph-based multimodel containers, the framework enables seamless linking of heterogeneous data sets, facilitating efficient communication and coordination among multidisciplinary teams. This capability addresses a critical need in the Architecture, Engineering, and Construction (AEC) industry, where effective collaboration among stakeholders is essential for project success. The integration of technologies such as dynamic linking, automated versioning, and semantic enrichment facilitates that all project participants have access to consistent, up-to-date information, reducing misunderstandings and errors. This improvement directly aligns with Research Question 3 (RQ 3), which seeks to explore how the framework fosters real-time collaboration across diverse domains.

While the proposed framework demonstrates significant advancements in interoperability and data sovereignty, its scalability remains a topic requiring further investigation. Graph databases, such as Neo4j, offer structural advantages over traditional relational databases when handling highly interconnected data. Unlike relational databases—which rely on join operations that become increasingly expensive as data grow—graph databases utilize index-free adjacency, allowing traversal queries to execute in near-constant time regardless of data size or relationship complexity. This makes them particularly suitable for dynamic, semantically linked data across multiple domains in the AEC industry. However, we acknowledge that performance in real-world applications depends not only on query efficiency but also on how the system handles growing datasets, distributed deployments, and concurrent queries. The framework's verification was conducted using a simplified use case involving only two data sources. While this scenario illustrates the feasibility of integrating heterogeneous data sets in a controlled environment, it does not fully capture the complexities and performance demands of large-scale, multidisciplinary AEC projects. Conducting extensive performance testing under diverse scenarios to identify and resolve potential bottlenecks. Moreover, potential adoption barriers must be considered. The AEC industry's traditionally cautious approach to new technologies may pose challenges, requiring targeted awareness initiatives, training programs, and clear demonstration of the benefits to various project stakeholders.

6. Conclusions and Future Work

This study presents a graph-based dynamic multimodel container framework designed to address key challenges in data management for distributed digital twins (dDTws) in the Architecture, Engineering, and Construction (AEC) industry. The framework demonstrates significant potential in enhancing interoperability, ensuring data sovereignty, and facilitating real-time collaboration among stakeholders. By leveraging graph databases, semantic web technologies, and standardized approaches such as ISO 21597, the proposed

solution provides a robust platform for integrating and managing heterogeneous data sources in cloud-based environments. Validation through use cases highlights the framework's effectiveness in linking diverse datasets and improving collaborative workflows, though scalability requires further exploration.

Future work will focus on enhancing the framework's usability and accessibility by integrating a chat-based user interface to facilitate the creation of semantic links between data sources. This feature aims to simplify interaction with the system, allowing end users to perform advanced query functions without requiring expertise in query languages. By providing a user-friendly interface, the framework will enable a broader range of stakeholders to engage with and benefit from its functionalities, further democratizing access to sophisticated data management tools. Additionally, comprehensive testing with larger and more complex datasets will be conducted to refine the framework's scalability and optimize its performance in real-world AEC applications. While our framework demonstrated effective integration at the prototype level, future work will explore scalability enhancements, particularly in performance benchmarking in large-scale distributed deployments.

These developments will ensure that the proposed framework evolves into a comprehensive and scalable solution, fostering innovation and efficiency in the management of distributed digital twin environments.

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