5G-Enabled Augmented Reality for Dynamic Interaction with Linked Building Data and Voxelised Spaces

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Abstract

The integration of Augmented Reality (AR) with Linked Building Data (LBD) presents a transformative approach to managing construction processes by combining intuitive visualisation with semantically rich data. This paper explores a novel framework that enhances LBD using voxelised space descriptions, enabling users to define and interact with dynamic queries and manage construction workspaces. By converting BIM models into RDF triples stored in a triplestore, we facilitate semantic interaction with building elements in AR. Voxelised space further enriches this system, allowing precise definition and spatial reasoning of work zones. The framework leverages AR as a user interface to dynamically query, visualize, and manipulate virtual building elements, providing an intuitive method for construction process planning. A prototype implementation demonstrates the system's potential through a practical use case, highlighting its usability, scalability, and efficiency. This work advances the application of AR and semantic technologies in the Architecture, Engineering, and Construction (AEC) industry, addressing challenges in spatial reasoning and data-driven decision-making.

Keywords

Augmented Reality, Linked Building Data, Voxelisation

1. Introduction

1.1. Background and Motivation

The Architecture, Engineering, and Construction (AEC) business is under growing pressure to produce more efficient, sustainable, and cost-effective projects. To fulfil these objectives, digital technologies such as Building Information Modeling (BIM), semantic web technologies, and Augmented Reality (AR) have become indispensable. Linked Building Data (LBD), which leverages semantic technologies to describe building information as machine-readable data, has emerged as an important tool for facilitating interoperability and advanced decision-making across varied stakeholders. However, despite these advancements, the interaction with linked data remains primarily confined to desktop-based applications and lacks an intuitive, spatially aware interface for field use [1] .

Augmented Reality (AR) introduces a natural and intuitive interface, offering human-computer interaction by superimposing virtual information on the real environment, creating a more natural interface for perceiving and manipulating digital content. Within the construction industry, it has been seen to increases efficiency, improve communications and safety [2] . With such capability, the motivation to research the potential of implementing AR by overlaying LBD onto the physical world, enabling real-time visualisation, query execution, and interaction with digital building data on-site is present. With the nature of 3D spatial interaction offered by AR technologies, this can be exploited to address spatial-related issues within the construction industry.

Voxelised space descriptions, a technique for dividing 3D space into discrete volumetric units (voxels), provide an appealing alternative for spatial management. This approach has been widely

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adopted in spatial computing, robotics, and simulation for its ability to discretize space into manageable units [3] . In construction workflows, voxelisation offers a structured way to define and analyse workspaces, enabling spatial reasoning for task planning, resource allocation, and hazard identification. However, voxel models are often disconnected from semantically rich data, limiting their ability to provide meaningful insights beyond spatial segmentation.

The introduction of 5G further strengthens this approach by addressing connectivity and performance constraints, which is often faced within a construction project due to geolocation reasons, offering the opportunity for remote data retrieval and multi-user collaboration.

This research seeks to elucidate the potential of augmented reality as a transformative tool for dynamic interaction with linked building data within voxelised spaces. Aiming to address the challenges within the construction management of the requirement for dynamic spatial reasoning and workspace delineation. By examining current developments and future prospects in this area, this paper aims to contribute valuable insights into how these aforementioned methods can be used to improve data connectivity, visualisation and spatial management.

2. Related Work

2.1. Linked Building Data (LBD)

Linked building data can be defined as the integration and administration of various building-related data sources via linked data. This technology is designed to improve interoperability, data exchange, and the overall management of building information across multiple disciplines and life-cycle stages. Linked data solutions use open protocols and W3C standards to help integrate various building data sources into a cohesive and interoperable system. The utilisation of linked data in Building Information Modelling (BIM) facilitates the seamless exchange of information among stakeholders. Ontology such as BOT [4] is used as a core vocabulary to describe high-level building topology, with BIM maturity level 3 [5] in mind. The application of linked data in the AEC industry has been demonstrated in works such as the use of linked data for geospatial description [6] , where building data was transformed into linked data through an ontology, enabling interlinking with geospatial datasets. Besides that, it is also used in building management as demonstrated in this paper, exploring the information exchange and management of a building's life cycle [7] . Aside from theoretical concepts, studies have also investigated the practical applications of such concepts, bringing theoretical perspectives and concepts into building management practices [8,9] . Furthering such application, various sources of data such as sensors, design plans, and maintenance records are combined to create a digital twins [10] . However, with such wide application of linked data in the AEC industry, in a survey for linked data interfaces [1] , a notable gap was identified in providing a user-centric experience for visualizing this data. Given the context of this paper focusing on Linked Building Data (LBD), which is intrinsically tied to physical objects, there is significant potential for these data to be rendered and visualized in ways that enhance user engagement and understanding.

2.2. Augmented Reality in Construction

The potential and recognition of augmented reality (AR) to transform the construction industry has been on the rise. This is due to its ability to enhance visualisation, improve safety, and increase efficiency. This technology offers the possibilities of innovative solutions to current challenges in construction, such as communication barriers, project delays, and safety risks. Augmented reality (AR) has become a prevalent tool in the field of construction management, employed for visualising and simulating construction activities. This technology allows stakeholders to have a solid grasp of the status of projects, both as-built and as-planned, facilitating informed decision-making. This technology assists in the monitoring of project progress and the addressing of issues encountered by field workers, thereby enhancing project management and execution as observed in multiple review and analysis papers on the application of AR in the construction industry [11–13] . As researched by an analysis paper [2] , the benefits of AR have been observed across different domains within the construction industry. As the technique of AR within the industry has been established, the motivation to enrich such geometries with semantic data seems to be prevalent.

2.3. Voxelisation in Built Environment

Voxelisation of space is the process of converting spatial data from various sources into a structured three-dimensional grid of discrete volumetric units, each representing a portion of space with associated attributes. This technique is widely used to represent and analyse spatial data. This approach is increasingly applied in various fields, including urban planning, environmental monitoring, and architectural analysis, to manage and analyse complex spatial data. Applications in the domain of urban and environmental management have been observed in works such as [14] , which voxelises point clouds of urban cities for urban planning purposes, and [15] , which voxelises 3D buildings and entities converted from 2D vector data with height data for urban spatial analysis. Additionally, [16] has experimented with voxelising aerial Light Detection and Ranging (LiDAR) data to analyse vegetation coverage. Specifically in the construction industry, there has also been research done in voxel-based point cloud representation [17] . The findings of these studies demonstrate that discretising workspaces to voxels has the potential to facilitate the analysis of 3D workspaces. This, however can be improved by integrating temporal datasets to address the dynamic nature of construction projects.

2.4. Knowledge Gap and Research Question

Despite significant advances in the integration of 3D spatial data into urban planning and analysis, several critical gaps remain. Current voxelisation methodologies often rely on static representations and oversimplified models, which fail to capture the dynamic and interactive nature of the built environment as discussed in chapter 2.3. Moreover, most approaches focus solely on horizontal or vertical spatial changes, neglecting the volumetric interrelationships between functional spaces, including the utilisation of free spaces. Although visualisation and spatiotemporal simulation techniques have improved, there is a notable deficiency in integrating voxelised spaces with semantically rich Linked Building Data (LBD), limiting the development of dynamic, on-demand query systems. Furthermore, the potential of augmented reality (AR) as an intuitive interface for interacting with complex building data has been underexplored.

This study seeks to address these gaps through the following research questions:

1. How can AR be employed to effectively visualize BIM-derived RDF data, including both mesh geometry and associated metadata directly on-site?
2. How can AR facilitate dynamic querying and real-time updates of BIM-derived data from a triplestore to support construction decision-making?
3. How can voxelised space, enriched with semantic attributes, enhance dynamic spatial reasoning and planning within construction workspaces?

3. Approach

3.1. System Architecture

The system architecture of this paper is designed to integrate Augmented Reality (AR), Linked Building Data (LBD), and voxelised space descriptions. It consists of three primary layers: the data layer, the processing layer, and the interaction layer. These layers work in synergy to provide users with a dynamic, interactive platform for querying, visualizing, and managing construction workspaces.

The data layer serves as the foundation of the system, handling the ingestion and transformation of building data. Building Information Models (BIM), typically provided in Industry Foundation Classes (IFC) or similar formats, are converted into triples to create a semantic representation using ontologies such as ifcOWL and BOT. This process extracts both geometric and semantic attributes of building components as metadata, linking them with spatial relationships like hasGeometry, containsInBoundingBox, and globalId. Then, the voxelisation process generates a 3D grid representation of the construction site, dividing it into discrete volumetric units. With the injection of BIM model(s) and 3D representation of the current state of the construction site into the workspace, each voxel is enriched with semantic attributes, including material properties, functional designations, and occupancy data as metadata. The RDF triples are stored in a triplestore, while the voxelised spatial data is managed in a voxel database, enabling efficient storage and retrieval.

3.2. AR Interaction Design

The AR interaction design allows users to engage with Linked Building Data (LBD) and voxelised spaces through a dynamic and intuitive interface. Connected to a semantic triplestore, the AR application retrieves building geometry, semantic data, and voxel information via on-demand queries. A fiducial marker is used to localize the AR device within the virtual environment, offering alignment between physical and digital spaces. Using the retrieved geometry, 3D meshes are generated on demand, allowing users to visualize and interact with up-to-date building elements and voxelised spaces in AR. Use cases include visualisation of different levels of (dis-)assembly order, sub elements that are related to the main component, and also visualising boundary boxes of the chosen component.

Users can select components or define workspaces for construction or deconstruction tasks. These actions dynamically update the voxel data in the triplestore, recording workspace boundaries, functional assignments, and usage schedules. Additionally, the framework supports the consideration of working machines or robots in workspace planning. Users can include their dimensions, operational zones, and movement paths during the workspace definition process, ensuring the spatial configuration accommodates both human and machine requirements. This inclusion facilitates planning for tasks such as automated assembly, material delivery, or demolition, enhancing collaboration between human operators and robotic systems.

The AR interface provides real-time feedback and contextual overlays to display relevant semantic information, improving decision-making and usability. This design not only supports efficient planning and management of construction workflows but also lays the foundation for integrating advanced automation into voxelised space management.

3.3. Voxelised Space Description

In this approach, voxelised space acts as a detailed and flexible representation of the building's spatial environment. Each voxel, a small volumetric unit within a 3D grid, is capable of holding multiple layers of information. From BIM data, voxels capture semantic information such as size, shape, material properties, and spatial relationships, accurately reflecting the building's properties within the space. Voxels extend beyond geometric representation by integrating diverse layers of semantic information. Each voxel is uniquely identified, facilitating integration with external datasets or systems. In addition to spatial geometry, voxels encapsulate functional data, including designations such as storage, work zones, or temporary sandpile areas as well as information pertaining to construction phases and designated safety zones. Moreover, the integration of temporal data allows for the tracking of changes over time, such as the evolution of a workspace from construction to operational status. Supplementary attributes, including access permissions, safety guidelines, and maintenance priorities, further augment the depth and utility of the voxelised data. By consolidating this wide range of information being embedded into the voxels as metadata, voxelised space becomes a valuable tool for advanced spatial analysis, on-demand queries, and interactive AR-based decision-making, making it a cornerstone of effective construction management and planning workflows.

4. Implementation

4.1. Tools and Technologies

The implementation of the proposed system integrates a suite of tools and technologies to ensure seamless functionality across data conversion, storage, and interaction layers. These tools work in unison to enable the transformation of BIM data into Linked Building Data (LBD), manage semantic and spatial data in a triplestore, and provide an intuitive AR interface for on-demand interaction.

4.1.1. Conversion of IFC to LBD

The transformation of Industry Foundation Classes (IFC) files into a Linked Building Data format that is compliant with semantic web standards is needed. The extraction of both geometric and semantic information from BIM models, such as building components, relationships, and attributes, and maps them into RDF triples based on ontologies like ifcOWL and the Building Topology Ontology (BOT). The resulting RDF data supports advanced queries and facilitates interoperability between building information and voxelised space representations. One of the tools that offers such functionality is the IFCtoLBD [18] converter.

```
inst:buildingelement_f8b9725e-9584
        props:guid                     "025M0Dimf438IBfJvt$G_z" ;
        lbd:containsInBoundingBox      inst:buildingelement_2f957744;
        rdf:type                       bot:Element ;
        props:volume                   0.000010701 ;
        lbd:description                "" ;
        lbd:containsInBoundingBox      inst:buildingelement_be2bab7d;
        lbd:containsInBoundingBox      inst:buildingelement_4b3208cf;
        props:lengthRelevant           true ;
        props:length                   87.00000000000001 ;
        props:material                 "Stahl" ;
        props:partType                 "xd_10" ;
        props:netSurfaceArea           0.021822 ;
        props:type                     "3D-Objekt5CSweep" ;
        props:detailObject             false ;
        props:layer                    "0" ;
        props:isNegative               false ;
```

Listing 1: An excerpt of IFC converted into LBD triples.

The tool maintains the data fidelity during conversion, while ensuring the alignment with established Linked Building Data practices. Below is an example of an IFC file converted to RDF triples. Metadata from the IFC that is extracted by the converter is stored as RDF triples, with properties and attributes represented as literals (including strings, numbers, and other data types) while meshes are converted and saved as Base-64 encoded strings. Listing 1 shows an excerpt of the converted IFC file of a building element with its metadata in the form of triples.

4.1.2. Triplestore

Triplestore is used to manage the RDF triples generated from the converted IFC. It is a high-performance graph database that supports SPARQL for executing semantic queries and handling spatial relationships within building data. Blazegraph [19] is chosen for its scalability and support for large datasets making it well-suited for storing complex building models and voxelised space information. Additionally, its SPARQL endpoints allow seamless integration with the AR application, enabling dynamic queries and on-demand data retrieval.

4.1.3. Development of the AR Application

An application development platform with an integrated development environment (IDE) is used. The development platform should support cross-platform AR functionality along with SDKs necessary for AR development. In this implementation, the application needs to handle on-demand mesh generation based on geometry data retrieved from RDF triples. It also manages user interactions with building elements, such as selecting components or defining workspaces, which are subsequently pushed back into the triplestore. Dynamic querying using the SPARQL queries, the AR application creates a dynamic query contingent to the building element that is tapped on the screen. A function then generates the query and retrieves information on the building element, returning the information to the user. The visualisation can be extended by highlighting the related building elements. The backend of the functions of the application is described as below:

1. Dynamic querying: Using the SPARQL queries, the AR application creates a dynamic query contingent to the building element that is tapped on the screen. A function then generates the query and retrieves information on the building element, returning the information to the user. The visualisation can be extended by highlighting the related building elements.
2. On-demand mesh generation: By using a query that retrieves the mesh geometry information, the application decodes the Base-64 encoded strings to vertices, lines and faces that can be rendered on demand. This process ensures that rendered meshes are always up-to-date in accordance with the triplestore and not some pre-loaded meshes into the application.
3. Voxelisation of workspace: The voxelisation is initialised by discretising the workspace into voxels. Each voxel is given a globally unique identifier (GUID) for identification. Using the layer function in the application, the application is able to classify different objects that are in the voxels, i.e., if the entity within the voxel is a machine, work zone, building element, or storage zone, while incorporating temporal data.

5. Use Case and Evaluation

5.1. Use Case Scenario

The use case in this study is carried out in an environment that demonstrates the framework's functionality within the non standalone 5G-enabled Reference Construction Site [20] in Aachen, which serves as a living lab for research in construction by simulating an actual construction site with real processes while still providing a controlled environment. Such a 5G environment is enabled with an omni-directional antenna mounted on a tower crane, establishing a wide coverage, while maintaining a stable network, independent of the crane's rotational operation. It is critical in ensuring high-speed connectivity and low latency to enable stable interaction with the triplestore and voxelised spaces through the AR interface. Figure 1 shows the as-planned BIM model (left) and the as-built structure (right).

Figure 1: (Left) As planned BIM model of the structure, (right) as-built structure on the site.

The high-speed data transfer facilitates the retrieval of large datasets such as LBD-derived geometry and metadata and voxelised metadata. 5G's low latency from the triplestore and rendering of complex 3D elements. Additionally, in a 5G-enabled environment, it supports multiple users simultaneously interacting with the system, making it crucial for collaborative planning scenarios in large-scale construction projects. This use case's framework also employed the usage of an edge server that is set up on the construction site. This allows a secure connection and computationally intensive tasks to be offloaded to the edge server. Figure 2 shows the connectivity framework of the application.

The scenario involves a construction and deconstruction process within the same structure. In the construction scenario, the user queries and visualizes the construction of a steel frame, seeing different assembly sequences and sub-assembly components. With the building elements superimposed on the actual structure, the user has an intuitive view of to-be-constructed elements with all their metadata, such as schedule and linked elements. Given such information, the user can define the working, operation and danger zones using the AR interface for planning. Working zone indicates the actual area where the actual building elements occur, operation zone indicates the area which is designated for machinery, workers and logistical activities.

In another deconstruction scenario, the user can visualize and query the metadata of the element that lies within the wall before the deconstruction process. Using the AR application, the user can make more informed decisions before deconstructing the wall, minimizing any unwanted damage to the workpiece or components within. Then, by querying the workspaces that will be used during the time of the deconstruction process to check if there will be any conflict of workspaces for other process during the planned execution time.

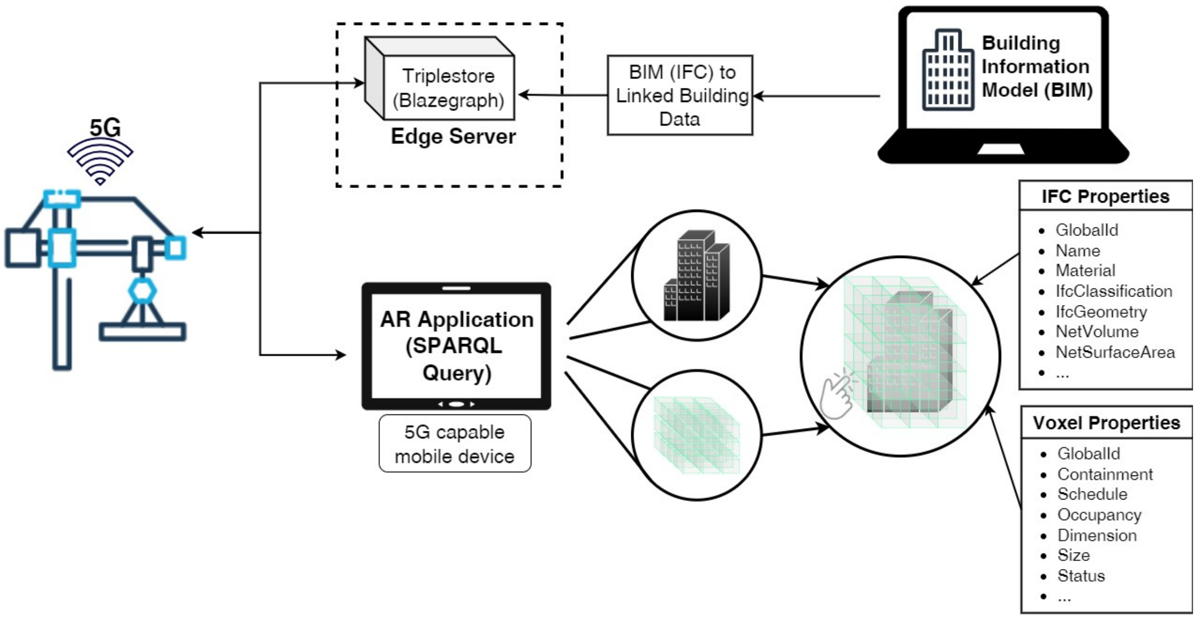

Figure 2: The setup and data flow of the system's framework

The detailed workflow of the framework is as follows:

1. Voxelisation of the construction site: The construction site is discretised by overlaying a 3D grid on its digital model, using a common zero-point coordinate for consistency between the physical and virtual environments. The voxels are preliminarily categorized into landscape and occupied as shown in Figure 3.

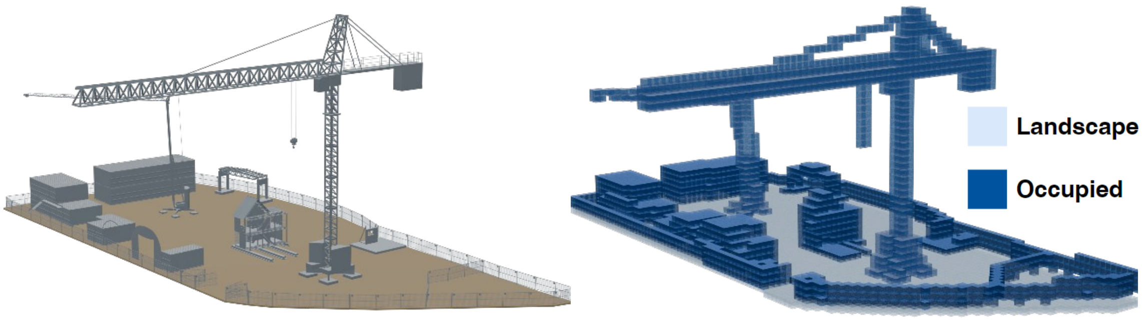

Figure 3: (Left) Digital model of the construction site, (right) discretised workspace of the construction site.

2. Marker scanning and query generation: A fiducial marker is scanned using an AR application to localize the user and generate context-relevant SPARQL queries. It retrieves all geometrically defined elements from the triplestore.
3. Data retrieval and rendering: The AR application processes the triplestore responses, rendering 3D meshes on demand and displaying metadata, for example, materials, weight, manufacturer, construction sequences, and dimensions to the user as shown in Figure 4 and 5.
4. Interaction with voxelised spaces: Users interact with semantically enriched voxels representing discrete spatial units. Through the AR application, they can define and snap voxel dimensions and positions to the pre-established grid from step 1 for planning tasks, such as designating work zones, allocating resources, or marking danger zones. Confirmed modifications are pushed to the triplestore for collaborative use.

5. Concurrent process for construction and deconstruction: The system allows for concurrent process management and facilitates simultaneous construction activities. Multiple users, sharing the same virtual space, can define workspaces for construction processes. Both users' inputs are integrated in real time, ensuring that the workspace definitions for both deconstruction and construction are synchronized and maintained within the knowledge graph.

5.2. Results

The system demonstrates the feasibility of integrating Augmented Reality (AR), Linked Building Data (LBD), and voxelised space for planning and managing construction or deconstruction workflows. The AR application successfully allows users to scan markers, generate queries, and visualize retrieved building elements on demand.

Figure 4 and 5 show two screenshots of the AR application, displaying the result of the generated SPARQL query on the interface. Figure 4 shows the building elements of an internal structure of a concrete wall, the green component shows the steel structure that is selected, generating a SPARQL query that returns metadata of the corresponding element. Figure 5 shows a steel frame module that is to be erected onto the existing structure. The dark green component shows the selected element, while the elements coloured in light green show all of its related sub-assembly elements. With the building elements being shown in conjunction with the real world, the user is able to plan for the workspaces that the process needs, for both construction and deconstruction. While injecting the voxels with semantics such as process, schedule, related building elements, and positions.

It was able to show key interactions, such as the visualisation of building elements and the display of metadata such as material properties, and voxelised spaces, embedded with process assignments, and task schedules. Listing 2 shows examples of triples of a voxel that are generated using the AR application when the user defines the deconstruction working zones along with their spatial occupancy.

Figure 4: Screenshots of the AR application, showing the building elements within a concrete structure and metadata generated from the SPARQL queries when the mesh is selected.

```
inst:ifcowl_ifcelementassembly_40606a3c-ec3f-
4f9f-8d0f-b9246f9788be
hasSubElement       beam_10e38798-b3de-4807-9557-
                    86c6e8927c70
hasSubElement       beam_d8835b04-07f7-4bc3-ade7-
                    7f7a002e9e60
hasSubElement       beam_2a39fa95-3658-43f4-b704-
                    4c50457ad403
hauptteil           "HEB120"
lieferscheinName    "Ladung 1"
gewichtBaugruppe    178.49326
label               "Traeger"
```

Figure 5: Screenshots of the AR application, showing the construction of another module of the steel frame and its subsequent sub-element with metadata when the mesh is selected.

```
inst:Voxel_051004 a vxl:Voxel ;
    vxl:guid "051004-xyz789-2025" ;
    vxl:layer "Layer_3" ;
    vxl:process inst:Deconstruction_ConcreteWall ;
    vxl:plannedTime "2025-02-01T09:00:00Z"^^xsd:dateTime ;
    vxl:space vxl:GroundFloor ;
    vxl:position [ vxl:x 7 ; vxl:y 15 ; vxl:z 3 ] ;
    vxl:size [ vxl:width 1.0 ; vxl:height 1.0 ; vxl:length 1.0 ] ;
    vxl:relatedTo inst:buildingelement_f8b9725e-9584 ;
    prov:wasGeneratedBy inst:VoxelPlanningSystem ;
    dct:description "Concrete wall deconstruction"^^xsd:string ;
    vxl:entryTime "2025-01-31T08:00:00Z"^^xsd:dateTime ;
    vxl:startTime "2025-02-01T09:00:00Z"^^xsd:dateTime ;
    vxl:endTime "2025-02-01T11:00:00Z"^^xsd:dateTime .
```

Listing 2: Proposed example of triples generated from a single voxel

The defined workspace planning show how users can define zones for construction tasks and dynamically update the associated voxel data, with RDF triples reflecting changes such as adjusted planned times and linked building elements. The system's performance metrics reveal its capability to handle complex data and interactions efficiently. The average time performance of the SPARQL queries sent to the triplestore to retrieve a result is documented in Table 1, with different amounts of data being queried and processed, within the 5G-enabled reference site. While the AR application is able to dynamically generate 3D meshes from retrieved geometric data, complex geometries and queries notably took more time to convert and render the meshes.

Localization using fiducial markers provided reliable alignment between the physical and virtual environments. The updated RDF triples illustrate the system's ability to maintain data consistency, with changes made through the AR interface immediately reflected in the triplestore, as shown in Figure 6. In the figure, on the left shows a screenshot of the voxels using the AR application, while on the right shows the queried voxels in a custom viewer within a virtual environment. This cross-platform ability shows the platform's capability to support collaborative planning using different devices and platforms.

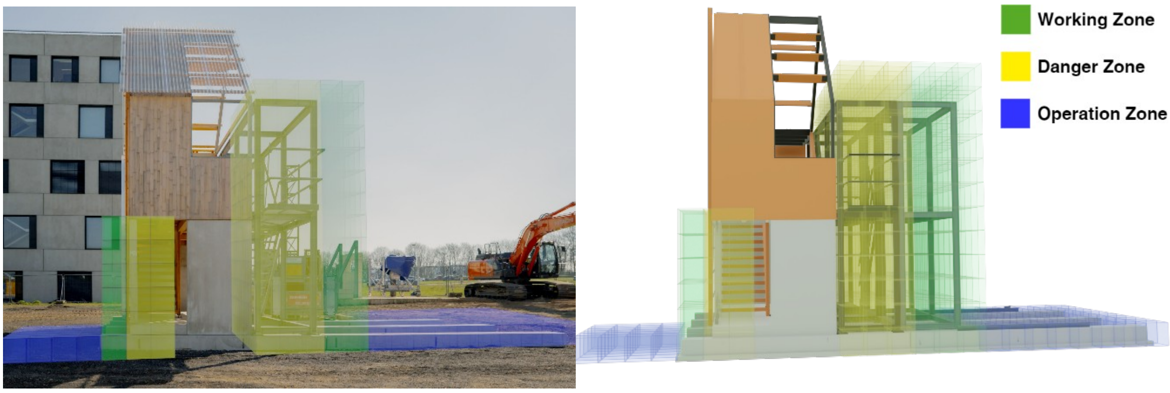

Figure 6: (Left) Screenshot of the AR application showing working zones of 2 different processes defined by the user. (Right) Visualisation of voxels using a custom viewer.

Table 1
Average time for the query to return a result and the time it takes to process the results to meshes.

Data Size (MB)	Triples Queried	Query Time (ms)	Process Time (ms)
0.144	196	149	144
2.61	3406	1257	943
50.41	82859	30357	17841

6. Discussion and Outlook

This study demonstrates the potential of integrating AR with LBD, while proposing a novel idea for a semantically enriched voxelisation of spaces in construction and deconstruction workflows. The framework supports on-demand mesh rendering driven by SPARQL query results, producing visualisations of meshes enriched with linked data. This capability addresses Research Question 1 by providing users with a comprehensive spatial understanding of construction and deconstruction processes. Moreover, by leveraging AR to overlay this enriched data onto a 3D environment, the system enhances users' ability to grasp the intricate relationships between building elements and their metadata, facilitating a more informed decision-making and effective process planning. Further, the AR application enables dynamic querying of the rendered meshes, providing users with an intuitive interface to explore building element data without needing to write SPARQL queries. The system also supports real-time SPARQL data updates for process management and scheduling, leveraging voxelised representations to enhance spatial context. This integrated approach effectively addresses Research Question 2 by simplifying data interaction and improving workflow planning. Additionally, voxelised space enhances spatial reasoning by embedding semantic attributes within each voxel, which supports precise task planning, effective workspace definition, and optimized resource allocation. This granular representation directly addresses Research Question 3 by demonstrating the potential of semantically enriched voxelised workspaces to improve construction planning and management.

Despite these advantages, the system has limitations. Reliance on fiducial markers for AR localization may not be ideal in some environments where markerless positioning would be more practical. Subsequently, dynamic SPARQL queries, while powerful, are somewhat predefined to a certain extent. Developing a more robust query generation could address this. The inclusion of 5G technology in the Reference Construction Site is anticipated to enhance on-demand query execution with higher bandwidth and lower latency, improving application response time. Integrating edge computing with 5G improves scalability, supporting multiple users and larger datasets in collaborative environments. However, in Table 1, it shows that the data size of 50MB has a query time of 30 seconds; this could be improved by using a more efficient triplestore as described in this paper [21] . Base64-encoded geometry storage, though efficient for serialization, may result in increased storage overhead. An alternative approach could involve referencing external 3D model files to reduce the load on the triplestore. Additionally, the rendering speed remains limited by the AR device's computational capacity. With more powerful computational chips and better rendering algorithms being developed, this is speculated to have an improved process time in the future.

When compared to similar systems, this approach stands out due to its on-demand mesh rendering with interaction capabilities and the integration of voxelised spaces with semantic data. The granularity of the voxelised representation, combined with dynamic updates, allows for more precise task planning than traditional methods. Advancements such as multi-user AR collaboration, adaptive voxelisation, holographic overlays, and 5G-powered edge computing present promising future directions. Ultimately, this system demonstrates how the integration of augmented reality, linked building data, and voxelised space can improve construction workflows, improving efficiency, precision, and collaboration in the AEC industry.

7. Future works

Future work could focus on fully defining an ontology for voxels in a construction site in order to better capture the semantics, interactions and temporal data required for effective planning, scheduling, and real-time management of construction workflows. The ontology could potentially be integrated with ontologies that address process descriptions, such as the Internet of construction process ontology [22] . These can provide a structured framework for representing workflows, task dependencies, and temporal relationships. Additionally, the degree and relationships of the adjacent neighbourhood [23] , as described in this paper, are also potential topics to be researched. The relational information to each of its neighbours can potentially be used to implement rules and constraints to the voxels, giving spatial management spatial reasoning, data validation and knowledge discovery. These ontologies are essential for describing activities like deconstruction, detailing associated tasks, stakeholders, and timeframes.

Besides that, the implementation of the voxels as triples can be used for robot controls, especially for navigation purposes. The voxels application has been seen in ROS frameworks such as Octomap [24] , which uses voxels to describe occupied spaces and UFOMap [25] that is an improved version of Octopmap, improving efficiency and integrating a new category of unknown space. Bringing such frameworks together presents the opportunity for a new method for human-machine interaction. Not limited to only 2D mapping, the 3D nature of voxels allows for the application to be extended to navigation for unmanned aerial vehicles (UAV) such as drones.

Lastly, incorporating different sensors into the knowledge graph could enhance automated decision-making. For example, implementing 5G signal strength into the knowledge graph could provide another layer of information to the A-Star path finding algorithm used in robotics, avoiding areas with low signal strength.

8. Conclusions

The paper contributed by presenting an innovative approach to integrating Augmented Reality (AR), Linked Building Data (LBD), and voxelised space descriptions to improve planning and management in building and deconstruction operations. The system enables on-demand, intuitive interaction with building data, allowing for dynamic querying, workspace design, and automated updates to a triplestore, therefore improving data-driven decision making. The 5G-enabled Reference Construction Site offers connectivity on-site, while the voxel ontology combined with process and

IoT ontologies enables spatial and temporal reasoning. The results demonstrate intuitive AR interaction, efficient voxel updates, and interoperability with BIM data, validating the system's potential for construction site automation. Therefore, presenting a novel AR-driven LBD framework that advances semantic digital twins, automation, and on-demand construction monitoring, bridging the gap between digital and physical construction settings.

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Declaration on Generative AI

During the preparation of this work, the author(s) used Grammarly in order to: grammar and spelling check, paraphrase and reword. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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