



## FROM SILOED CENTRALIZED INFORMATION SYSTEMS TOWARDS FEDERATED DATA ECOSYSTEMS: DEVELOPING AECO DATA SPACES

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### Abstract

The Architecture, Engineering, Construction, and Operations (AECO) industry faces challenges in seamless data exchange due to siloed, centralized systems. To tackle this challenge, a conceptual data space prototype is developed, using a federated system architecture. The implementation enables nested data spaces, metadata management, and role-based access control, ensuring transparency, scalability, and user-friendliness. Stakeholder feedback highlights benefits like centralized data visibility and alignment with industry standards, while also revealing limited user awareness regarding decentralized data storage mechanisms. Bridging theory and practice, this prototype offers a foundation for further research on the integration of federated data ecosystems in the AECO industry.

### Introduction

The digital transition in the Architecture, Engineering, Construction, and Operation (AECO) industry is generating diverse data across the building life cycle, ranging from static BIM data to dynamic IoT data. While this data has the potential to improve collaboration, efficiency, and decision-making, it is often stored in isolated, project-centered systems that are difficult to interconnect due to technological, managerial, and governance challenges (Donkers et al., 2020). These fragmented systems result in information silos, a challenge already identified by Matti Hannus in 1987 through his *'Islands of Automation in Construction'*<sup>1</sup>, highlighting both the challenge of bridging these systems and the persistent emergence of new silos. As a result, knowledge remains fragmented, obstructing seamless data flow, innovation, collaboration, and informed decision-making, ultimately resulting in inefficiencies, errors, and higher costs (Jaskula et al., 2024). A potential solution to address these challenges is to shift from centralized information systems, where data is stored in a single, centralized repository controlled by one entity, to decentralized systems, where data is distributed across multiple stakeholders with no single authority controlling the entire system, enabling more flexible and collaborative data exchange (Naderi and Shojaei, 2024; Stas

and Abrishami, 2024). Data spaces, as an emerging concept, can provide secure and controlled data access and enable seamless integration between software tools and disciplines. A data space can be seen as *'a data integration concept which does not require common database schemas and physical data integration, but is rather based on distributed data stores and integration on an "as needed" basis on a semantic level'* (Nagel and Lycklama, 2021, p. 7). From a governance perspective, a data space is *'a federated data ecosystem within a certain application domain and based on shared policies and rules'* (Nagel and Lycklama, 2021, p. 7). Using a decentralized network architecture, a data space enables secure, interoperable, and effective data exchange (Bader et al., 2020).

Despite its potential, practical implementations of a data space in the AECO industry have not yet emerged. Existing research on data spaces, such as Firdausy et al. (2022) and Atzori et al. (2023), predominantly focuses on backend development, addressing challenges such as data interoperability, security, machine-readability, and decentralized data storage. In contrast, frontend development, which shapes how end-users such as architects, structural engineers, and building managers interact with the data space, has received significantly less attention. This creates a gap in understanding how end-users can access, navigate, and utilize data spaces to support their workflows. To achieve system adoption, the development of user-friendly, transparent, and interactive user interfaces (UIs) is essential. A well-designed UI must translate the complexity of the backend infrastructure into intuitive, accessible, and trustworthy experiences for end-users.

Addressing this gap, the present study adopts a holistic approach, integrating both backend and frontend development into a proof-of-concept implementation. The backend focuses on establishing a secure, federated technical infrastructure for data storage and exchange, while the frontend is designed to ensure usability, transparency, and trust for users. In line with the International Data Spaces Association's (IDSA) recommendation to tailor data spaces to domain-specific needs (International Data Spaces Association, 2024), this study acknowledges that a single monolithic data space is unlikely to meet the needs of the diverse AECO industry. Instead, a more effective approach may involve a network of interconnected data

<sup>1</sup>Matti Hannus and Pär Sill'en, VTT, The Technical Research Center of Finland

spaces, each adapted to the needs of specific sub-domains, such as architecture, infrastructure, materials manufacturing, or urban planning, while still adhering to common interoperability principles. Hence, this approach does not replace domain-specific ontologies or standardized data schemas like the Industry Foundation Classes (IFC) but rather enables connections between these different domains without enforcing a monolithic structure.

Focusing specifically on building-level data exchange for commercial, residential, and mixed-use buildings, this study addresses data use and exchange across the design, construction, and operational phases of the building life cycle. It targets key end-users, including architects, engineers, project managers, and facility managers, while recognizing the future relevance of stakeholders such as tenants. The aim is not to develop fully operational AECO data spaces, but rather to propose a conceptual, user-friendly prototype for federated building information exchange in the AECO industry using the data space paradigm. While important topics such as data security, governance, and semantic linking are acknowledged, they are beyond the scope of this research. Accordingly, the research aims to answer the following research question: *How can a data space be designed and developed to enhance seamless building data exchange among end-users throughout a building's life cycle?*

The subsequent sections are organized as follows. First, the related works section discusses the theoretical foundations of data spaces, their application in the literature, and federated system architectures. System engineering, as the main methodological approach of the research, is explained next. The results section presents the prototype and its validation, followed by conclusions and directions for future research.

## Related Work

Data spaces are federated data ecosystems based on shared policies and rules in which data owners are in control of their data while being able to manage the authorization of other actors to access their data (International Data Spaces Association, 2024; European Commission, 2022). The emergence of data spaces emphasizes a transformative shift toward dynamic, interconnected information ecosystems in the AECO industry. Central to its design should be a clear and practical structure ensuring fair, transparent, proportionate, and non-discriminatory data access and use, supported by robust and trustworthy data governance mechanisms (European Commission, 2022).

## Data Spaces in the AECO industry

Atzori et al. (2023) examine core concepts of data spaces, covering system architectures and sector-specific initiatives across different domains. Similarly, Otto and Jarke (2019) discuss outcomes from the data space design process, including potential system architectures and regulatory tools to involve stakeholders. Scerri et al. (2022) explore the general challenges and opportunities associ-

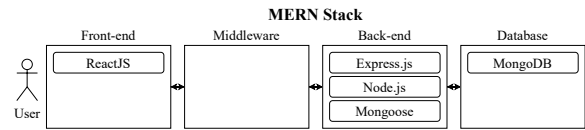


Figure 1: MERN Stack System Architecture

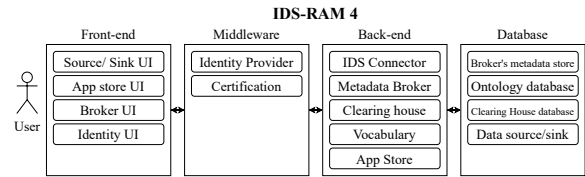


Figure 2: IDS-RAM 4 System Architecture

ated with data spaces. In that relation, Brost et al. (2018) address security requirements for a robust industry data space, presenting a comprehensive security architecture. Focusing specifically on the AECO industry, Cuno et al. (2019) propose an urban data space model based on a case study of a German municipality, and Gil et al. (2024) introduce a regulatory framework to digitize and automate building permit management, employing a building data space for compliance orchestration. In the context of smart homes, energy efficiency, and building information, the Swiss Federal Office of Energy (2024) presents a conceptual design of a decentralized data space in the building industry, addressing technical, governance, legal, economic, and ecological challenges.

While this research has laid the groundwork, the lack of effective, real-world implementations of data space concepts reveals a significant gap between theory and practice. Scerri et al. (2022) identified inter-organizational challenges such as lack of trustworthy data-sharing ecosystems, insufficient legal frameworks, slow adoption of standards, and scalability issues in decentralized data sharing, alongside intra-organizational concerns like data valuation, loss of control, trade secrets, and General Data Protection Regulation (GDPR) compliance.

## Data Space Architecture

To develop a data space, a robust and scalable system architecture is essential. This research explored several architectures, including the MongoDB, Express.js, React.js and Node.js (MERN) stack, the IDS-RAM 4 system architecture from the IDSA, the Digital System for the Built Environment (DSGO) architecture from DigiGO, and linked data-based system architectures. However, the focus is on the MERN stack and IDS-RAM 4, as shown in Figure 1 and Figure 2. The MERN stack is selected for its strengths in user interaction and intuitive user-interface development, making it well-suited for the development of a dynamic UI. On the other hand, the IDS-RAM 4 system architecture, the official framework proposed by IDSA, emphasizes the backend development of a federated information ecosystem.

The MERN stack, a JavaScript-based technology stack, is favored for its flexibility, simplicity, and performance

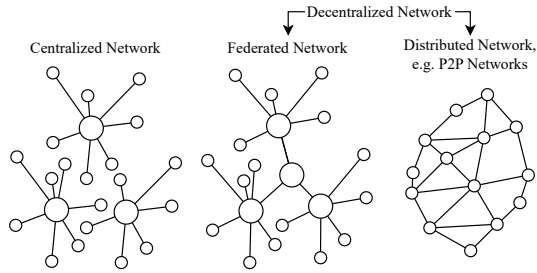


Figure 3: Centralized, Federated, and Distributed Networks Architecture

in creating dynamic UIs (Porter et al., 2019). It integrates scalable databases, RESTful routing, and high-performance server capabilities, making it ideal for modern applications. The IDS-RAM 4 architecture includes components such as data sources, IDS connectors, metadata brokers, and identity providers (International Data Spaces Association, 2024). While it focuses on a federated backend organization, it offers flexibility in frontend and database selection.

### Towards Distributed Information Networks

Both the MERN stack and the IDS-RAM 4 can be used to develop a decentralized information system. Information systems consist of interlinked nodes that exchange information (Brandín and Abrishami, 2021) and can be organized either centrally or decentrally, as shown in Figure 3. In a data infrastructure context, a node represents a user, organization, or computer, while the link represents the connection between the nodes.

In a centralized network, all nodes send their data to one central node, a server, which then sends the data to the next data receiver. In contrast, a decentralized network lacks this single controlling authority and includes both distributed and federated networks (Brandín and Abrishami, 2021). In a distributed network, data is shared directly among users or computers without any central authority (Brandín and Abrishami, 2021). Nodes in this network are interlinked in a way that allows data to ‘hop’ from one node to another to reach its final destination within the network, as seen in P2P networks. Federated networks consist of multiple autonomous centralized systems that interconnect and collaborate, allowing communication across the larger network while each retains control over its own data (Narayanan et al., 2012). To enable communication between the centralized systems, a common communication protocol is needed. This ensures interoperability and data sharing while preserving local control and ownership. The difference between the two networks is that there is no central authority or single point of control in a distributed network, whereas a federated network consists of several independent interconnected centralized networks that maintain autonomy over their own data storage and management (Narayanan et al., 2012).

The MERN stack typically supports centralized systems,

with the server handling client requests and connecting to a central MongoDB database. However, when configured with multiple databases, it can also support decentralized architectures. Thus, the MERN stack is not inherently centralized or decentralized but can be adapted based on system requirements. In contrast, the IDS-RAM 4 architecture emphasizes federated data management, enabling collaboration and secure data exchange while allowing users to retain control over their data. Although the IDS-RAM 4 excels in backend federation, it provides limited guidance for frontend or UI design, which is an area where the MERN stack offers significant advantages. Furthermore, the IDS-RAM 4 does not dictate data storage locations; instead, it serves as a framework to ensure secure, authenticated, and authorized data access. By combining the UI strengths of the MERN stack with the federated principles of IDS-RAM 4, this research proposes a proof-of-concept data space architecture tailored for the AECO industry needs with intuitive end-user experience.

### Methodology

The data space is developed using the V-shaped system engineering approach by Forsberg and Mooz (1992), which includes eight iterative steps: 1) stakeholder requirements formulation, 2) system requirements formulation, 3) system design, 4) prototype development, 5) prototype testing, 6) result integration, 7) system testing, and 8) system validation.

To define the stakeholder requirements, a workshop was organized with eight participants from various disciplines within the building construction sector. Using the Transition Model Canvas (TMC) tool, the workshop revealed the norms, values, and institutions influencing stakeholder behavior in the industry. As a result, the workshop provided insights into the norms, values, and institutions shaping stakeholder behaviors, identifying challenges, opportunities, and system needs in adopting a data space. A more detailed explanation of this methodology and the results is discussed in (van Zandwijk et al., 2025). For the system design, the research builds upon use case, sequence, and class diagrams before developing the conceptual system architecture. These diagrams are used to understand the essential data space components and interactions. Each diagram reveals different system needs. For example, the class diagrams represent the system’s static structure, including classes, attributes, and relationships, while the system architecture functions as the blueprint for the prototype development. Nevertheless, this paper will only discuss the class diagram and the system architecture.

The system is developed using Test-Driven Development. For validation, the prototype was presented to the same eight participants from the stakeholder workshop. Each provided individual feedback via a survey, followed by a group discussion on the prototype’s strengths and weaknesses. The survey included seven Likert-scale and seven open-ended questions based on the previously formulated stakeholder requirements. Hence, the questions focused

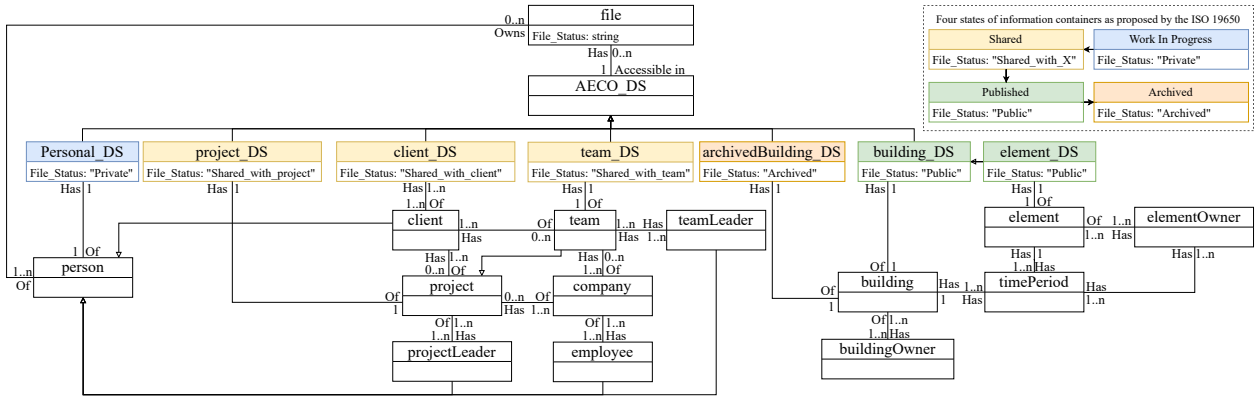


Figure 4: UML Class Diagram Showing the Proposed Class Structure of the AECO Data Spaces

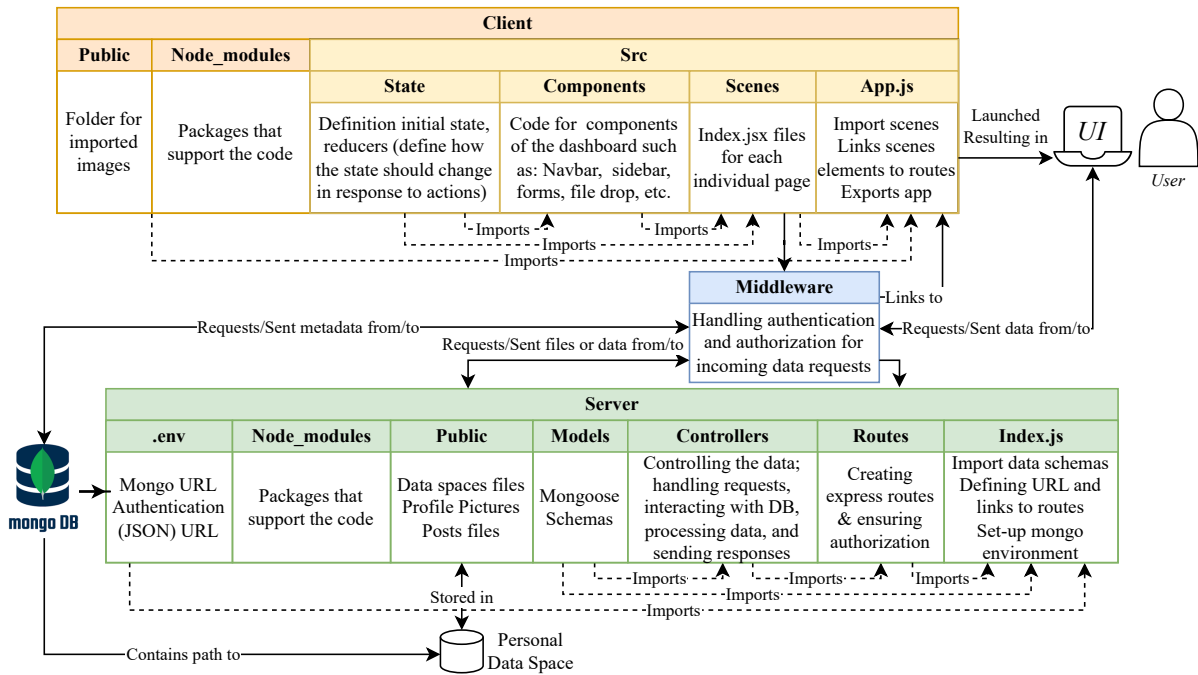


Figure 5: Visualization of How the Frontend, Middleware, and the Backend Interact

on user-friendliness, UI clarity, privacy, security, and overall value to the user’s workflow. Besides this feedback, it is evaluated to what extent the developed system meets the initial user and system requirements.

### Conceptual model of a Data Space

Figure 4 shows the class structure of the AECO data spaces. The stakeholder workshop showed the importance of adherence to the ISO 19650. Therefore, the research integrates the four states of information containers as proposed in ISO 19650<sup>2</sup>. The standard defines four states of information containers: (1) Work in Progress (W.I.P.), (2) shared, (3) published, and (4) archived. The ISO 19650 standard is a widely adopted international standard for managing building information throughout a construction project’s life cycle. As many AECO clients prioritize ad-

herence to this standard, significant deviations could hinder system adoption.

The stakeholder workshop revealed reliance on file-based workflows, exchanging entire files rather than specific data (Bucher et al., 2024). While files organize data in a structured format for easy management and access, data exchange focuses on sharing specific, targeted information rather than entire files, enabling more efficient communication, processing, and data storage. Data spaces aim to address this by enabling precise, effective sharing of only the necessary information. However, since the AECO industry is currently highly reliant on file-based workflows (Bucher et al., 2024), the present research focuses on enabling file exchange within the data space to address current industry practices. Nevertheless, future research should prioritize direct data exchange instead.

Hence, for this research it is assumed that each person

<sup>2</sup>ISO 19650 (2018). ISO 19650-1:2018

owns files, as shown in Figure 4. The files are accessible via the AECO data space, which follows a nested structure and acts as the overarching structure consisting of a set of smaller data spaces, which are the personal, project, team, client, element, building, and archived data spaces. Although these may appear as separate data spaces, they actually form one data space, with different users having different access rights to specific information. The files in a project data space are accessible only to employees of the company registered to that project, whereas files in a team data space are shared with employees from all companies registered to that team. Once ready for access by the client, the file becomes visible in the client data space. Each file is associated with metadata, including attributes such as the file name, description, owner, and file status. The file status reflects the readiness of the file to be shared with others and is aligned with the four states of information containers. Nevertheless, each file will always be visible in the file owner's personal data space, independent of the file status. The file status can be modified by the file owner in their personal data space, distinguishing between private, shared with the project, shared with the team, shared with the client, public, and archived. Depending on the user's role, such as employee, client, or project leader, the user has different access rights to view the files in the different data spaces. This structure provides users with a clear overview of their access rights and with whom their files are shared, ensuring transparency and ease of use.

Companies can have multiple projects and teams which both have one or more clients. In this case, a team is a collection of projects of one or more companies. Projects and teams can be linked to one or more buildings or elements. Each building has a building data space for published files and an archive data space for archived files. Buildings evolve over time due to events like renovations, altering the configuration and, thus, the combination of building elements. Elements have their own data spaces that are part of the building's data space for a specific time frame.

## System Architecture

The system architecture is based on the MERN stack framework. React is the frontend component, which allows for component-based web architecture. Node.js handles requests from the React frontend, communicates with the database, and sends responses back to the client using JavaScript. Express, a web framework for Node.js, simplifies building web servers and APIs, handling HTTP requests, routing, and responses. Finally, Mongoose defines data schemas and models, streamlining the interaction with MongoDB by structuring and validating data. MongoDB serves as the NoSQL database, offering scalability and flexible data schemas (Porter et al., 2019).

The MERN stack lacks a middleware component for authentication and authorization. Common authentication tools include third-party logins, Spring Security for Java, and Django's authentication system. However, this re-

search builds upon JSON Web Tokens (JWT) for access control, which provides a more flexible and secure approach. JWT, an Internet standard for secure data transmission (Mahindrakar and Pujeri, 2020), issues a signed token upon login, which is included in subsequent requests. The server validates the token to grant access to authorized routes, services, and resources.

Although the system integrates MongoDB as the database, the database will only be used to store metadata related to the files. The actual files are stored on the user's personal server, located within the backend code of the prototype. As such, the user remains the owner of their information. In the MongoDB database, the location of the files is stored, representing the API call to access the information. Using this structure, also visualized in Figure 5, a federated information system is created. While the prototype currently uses a centralized backend for demonstration purposes, the vision is to distribute data storage across multiple personal servers. This federated approach decentralizes control and storage, giving users ownership over their data. In comparison to the IDS-RAM 4, the blue section of Figure 5 illustrates the data space concept as proposed by the IDSA. This research contributes to the field by focusing on developing the user interface, represented by the orange section, and the decentralized data storage structure, represented by the green section.

Using the present system architecture, each user has autonomy over their personal data and the ability to access or modify its visibility. The centralized MongoDB database serves as a centralized consensus mechanism linking information across nodes. Although a fully distributed P2P network, where nodes communicate autonomously without central consensus, is feasible (Brandín and Abrishami, 2021), implementing such a system would require an architecture that integrates shared ontologies and policies as well. The IDS-RAM 4 and linked data system architectures utilizing ontologies (e.g., in the Vocabulary Hub) are good examples of this. However, this is beyond the scope of this research.

## Results

This section presents the prototype. The code and a demonstration video of the prototype can be found on GitHub<sup>3</sup>.

The prototype starts with a login screen where users can create an account and log in. Once logged in, the homepage displays three main components. First, a profile overview shows personal information, including the user's name, companies, roles, and involvement in projects and teams, as well as projects where they are registered as a client. Second, users can post text, images, or both, which are shared with all users in the data space. This feature facilitates discussions about projects, highlights published data, or requests missing information. Finally, the homepage lists the user's friends, with the option to add new

<sup>3</sup><https://github.com/KristavanZandwijk/GraduationProject>

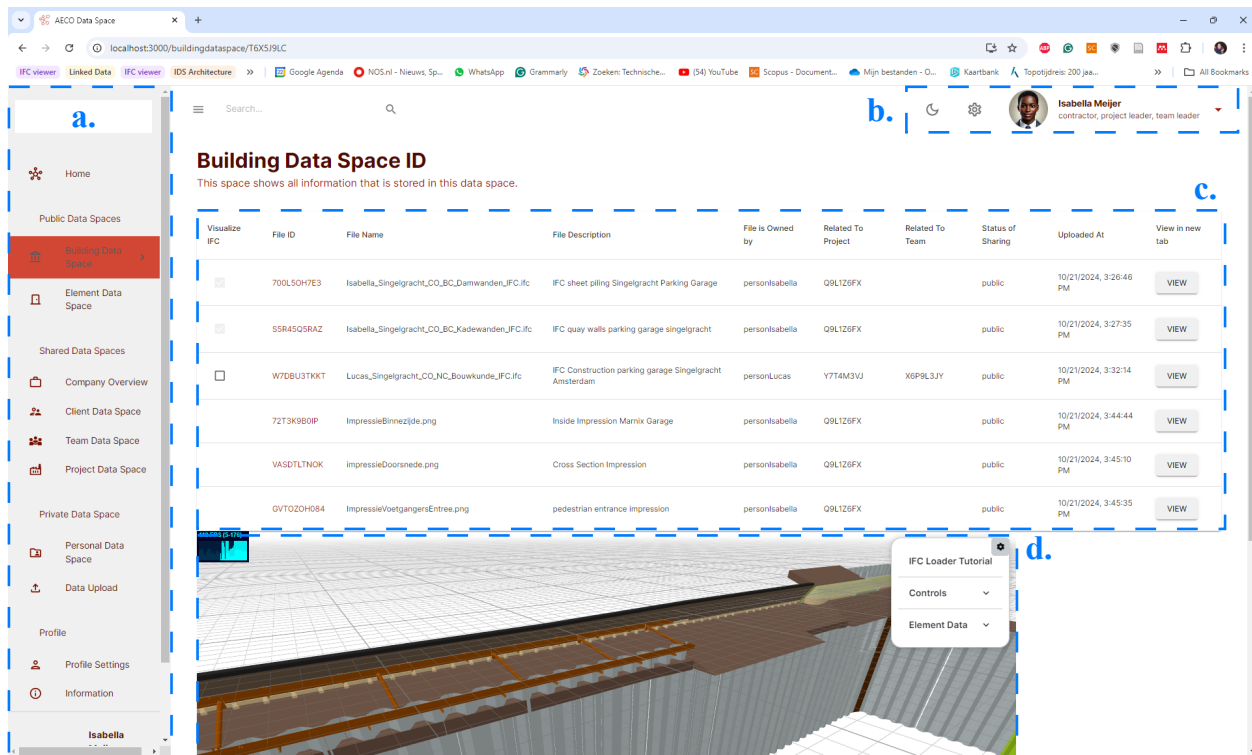


Figure 6: User Interface of the Building Data Space, With Main Components Highlighted in Blue: (a) Navigation Bar, (b) User Information, (c) File Overview Including Metadata, and (d) IFC Viewer

connections. Clicking on a user shows their personal information and involvement. Next, users can upload files through the data upload tab, which is accessible via the navigation bar on the left-side of the UI. During the upload, users must provide metadata about the file. After uploading, the file appears in the personal data space, where users can edit its metadata, including file status, which controls its visibility to others. The navigation bar provides access to various data spaces, such as project, team, client, element, or building data spaces, each with the same UI but displaying different information. An example of a building data space is shown in Figure 6. It consists of two components. First, a table listing all visible files along with their metadata, enabling users to access file details without opening each one. For each individual file, the table provides a ‘view’ button, allowing the user to view the file. For IFC files, the second component, an IFC viewer, enables visualization of one or more files simultaneously. In addition, the system includes a profile settings page and an admin page. The profile settings page allows users to edit personal information. Role management is restricted to the admin page, where administrators can control user roles and permissions for managing companies, projects, teams, buildings, and elements.

### Prototype Validation

The validation process involved assessing the system’s performance against established requirements and incorporating user feedback gathered through the validation survey. The results indicate that many user and system re-

quirements have been met, though some areas still require attention. For user requirements, several key expectations have been successfully fulfilled, such as addressing core functionalities. However, advanced search capabilities and version control are still areas where improvements can be made, particularly by incorporating linked data and enhancing data management features. On the system side, the performance meets several foundational requirements, but there are notable gaps in areas like decentralized operations and metadata management. Currently, metadata is stored centrally, and the files are stored on local servers, requiring further testing to evaluate online functionality and achieve a more distributed approach. Additional system improvements are necessary in areas like version control and simultaneous editing, which were identified as key user demands. Moreover, enhancing machine readability, interoperability, authorization, and access control are essential to fully address user needs.

Considering the survey results, the participants responded positively to the prototype, although some aspects for further improvement were also noted. The participants appreciated the prototype’s clear, structured design and user-friendliness, noting its alignment with the ISO 19650 standard. They valued the system’s ability to manage file access based on roles, and the easy modification of file access by file owners. However, participants raised concerns about the metadata entry, considering it as a time-consuming workflow. To improve this, drop-down menus with pre-defined options were added. For example, when

selecting a project, the menu displays only the projects the user is involved in. Suggestions for further improvement include stronger integration and linking of data with geometric models, and the integration of automated workflows for tasks such as quality assessments. As expected, the participants also emphasized the importance of integration with existing tools like MS Teams, the Autodesk Construction Cloud, or Autodesk Revit to avoid duplication and version control issues.

The survey results also highlight issues related to version control issues. Currently, the data spaces allow users to download files, which can lead to version control issues, especially if the file owner withdraws the file after it has been downloaded. This creates limited control over data reuse, potentially causing problems like plagiarism, unauthorized versions, and loss of oversight of reusability. Such uncertainty may discourage file sharing unless clear data retention and usage policies are established. Future research should focus on implementing fine-grained access controls, withdrawal mechanisms, and access tracking to improve oversight and protect shared files.

Participants did not provide specific feedback about the decentralized data storage, raising questions about their awareness of data storage location and its implications for protection and ownership. However, they expressed positive feedback on the ability to adjust access rights and the system's transparency about who can access files. While unaware of the federated backend storage, participants appreciated the centralized data access, valuing the convenience of accessing all personal, project, team, client, and building information through a single platform. According to the participants, this centralized access strengthens collaboration, streamlines communication, and improves project tracking.

## Conclusion

Currently, the AECO industry is dependent on centralized information systems, hindering collaboration across and between industries. Data spaces can facilitate the transition to a federated information system, improving data sharing throughout the building life cycle and enabling more effective collaboration, and more informed decision-making. Although research on data spaces exists, practical implementations remain scarce, highlighting a research gap between conceptual frameworks and real-world applications. This study bridges this gap by addressing both user-focused frontend design and backend development, focusing on federated data storage while prioritizing end-user control and ease of use.

This paper presents a prototype for AECO data spaces, which incorporates a nested structure consisting of several data spaces to manage file access based on their sharing status. In essence, the AECO data spaces are conceptually one data space, in which different users have different access rights and thus see different files. All files are stored on the file owner's personal server, while a centralized database manages all metadata, resulting in a feder-

ated system architecture. For end-users, this setup provides visibility and control over what data is shared and who can access it under which conditions, ensuring transparency and trust.

The key difference between the AECO data spaces and existing solutions relying on regular web-based exchanges lie in its federated architecture, which fundamentally changes how data is managed, stored, and accessed. Unlike traditional centralized systems where all data is saved on a single server, the data space uses a decentralized model in which users retain ownership of their data. While the current prototype allows users to save their files in their personal data space folder located within the backend of the prototype, the ultimate goal is to implement distributed data storage across personal servers. Such a federated structure would allow more granular access control, where data would be dynamically visible across the nested data spaces based on their sharing status. By decentralizing control and storage, this approach improves transparency, giving users a clear overview of their access rights and data-sharing relationships.

Future research should focus on storing data on personal servers, and creating a fully operational data access in a fully decentralized environment. This research should also include addressing security concerns such as data encryption, secure transmission protocols, and protection against potential vulnerabilities in a federated system, going beyond the currently used JWT-based access control. Additionally, an analysis of how the federated architecture scales with increasing data volumes and users is crucial. Integrating shared, machine-readable inter-industry standards is essential for enabling data exchange across data spaces. Furthermore, future research should extend beyond building-related disciplines to also include other sub-domains, such as infrastructure and urban planning, addressing their unique data-sharing needs and contributing to a comprehensive AECO data space framework. Moreover, exploring the integration of technologies like blockchain could enhance data provenance, integrity, traceability, trust, transparency, and collaboration (Brandín and Abrishami, 2021), which are key for the future evolution of the AECO data spaces.

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