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Bridging the Gap: A Socio-Technical Framework for Enhancing Application Interoperability in the AEC Industry

A design research exploring digital innovation through technical and organizational strategies

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Foreword

Working on this thesis has been quite the adventure, filled with plenty of ups and downs. It's amazing how much I've learned along the way, from figuring out complex technical problems to managing the whole project on my own. While there were definitely some tough moments, each challenge taught me something new and helped me grow. This thesis has been the hardest project I've tackled during my academic journey. The difficulty came from the open-ended nature of the work—figuring out where to start, what direction to take, and how to maintain a solid plan throughout the process. While I stumbled through some hurdles along the way, each challenge taught me valuable lessons about project management, perseverance, and self-guidance. Despite the difficulties, I definitely learned a lot from the experience.

I stumbled upon this project when Olivier from Semmtech reached out. I would have never thought of this subject myself, but it turned out to be a great opportunity to dive into something completely new. Working at Semmtech was not only about learning technical stuff like linked data and ontologies; I also enjoyed getting to know the people in the company, which made the experience much richer. The supportive environment and collaborative culture added a personal dimension to my professional growth. I especially want to thank Utku for his supervision and the entire Semmtech team for their support and guidance. So many people helped me that it's hard to name them all, but each contribution was invaluable.

I also want to extend my gratitude to my supervisors at TU Delft. Sometimes I wasn't the best at communicating, but Marcela's support throughout the entire process made a huge difference. Her encouragement kept me motivated and on track, which I greatly appreciate. I'm also thankful to Carlos for his valuable feedback, which helped refine my ideas and improve the overall quality of the thesis.

Since readers of this thesis will likely start with the same level of knowledge I had at the beginning of the project, I hope I've made the topic understandable and enjoyable to read. It's been quite the journey for me, and I'm excited to share what I've learned.

Abstract

The Architecture, Engineering, and Construction (AEC) industry is grappling with the growing challenge of improving communication and collaboration. As projects become more intricate, the need for seamless interoperability—where systems and teams can easily exchange and understand information—becomes even more critical. This research delves into a socio-technical approach designed to address both the technical and non-technical obstacles that hinder seamless integration and interaction across various systems and stakeholders. By conducting an in-depth review of existing literature and engaging with industry professionals, the study identifies key challenges such as fragmented information sources, misaligned organizational strategies, and complex contractual relationships.

The framework proposed in this research aims to bridge these gaps by combining ontology development and semantic web technologies with middleware integration, which should enhance data exchange and improve standardization. On the non-technical side, the framework emphasizes the importance of collaboration across organizations through coalition-building, the development of standardized contracts, and ensuring strategic alignment. Ultimately, this research not only presents a practical solution to the interoperability challenges in the AEC industry, but it also contributes to the larger conversation on digital transformation within the sector. By aligning technical innovations with organizational strategies, the proposed framework has the potential to improve productivity by encourage innovation. The study highlights the importance of integrating both technical and organizational perspectives in order to create scalable and effective solutions.

Keywords: Interoperability, Socio-technical framework, Ontology, Semantic web, AEC

Contents

1 Introduction

The increase in demand for infrastructure projects plays a significant role in the challenges faced by the Architecture, Engineering, and Construction (AEC) industry, which is experiencing a workforce shortage and slow productivity growth (Infrasite, 2024; Mischke, Stokvis, & Vermeltfoort, 2024). Studies indicate that construction productivity growth lags compared to other industries, primarily due to the ongoing reliance on document-based work processes and insufficient adoption of digital solutions (Mischke et al., 2024). Labor-intensive practices not only hinder productivity but also limit firms' ability to adapt to the complexities of modern projects. Consequently, there is a pressing need for innovative approaches that can reduce manual effort in data management and enhance communication among project teams. Achieving interoperability within the AEC information landscape is therefore a crucial step toward improving project efficiency, aligning stakeholders, and meeting demands in a tight labor market.

To tackle interoperability challenges, collaborative efforts within the industry have given rise to innovative initiatives. The BuildingSMART community developed Building Information Modeling (BIM) and the Industry Foundation Classes (IFC) vocabulary. BIM provides a framework for project collaboration, enabling various disciplines to work together within a shared digital model instead of being confined to data silos. Studies highlight that BIM can enhance communication, coordination, and information sharing across project phases, which supports both internal and external interoperability (Poirier, Staub-French, & Forgues, 2015; Balkhy, Sweis, & Lafhaj, 2021). For example, BIM enables the use of open standards like the IFC standard, which offers a structured description of building components to improve compatibility between software tools (Laakso & Kiviniemi, 2012). While BIM shows promise for enhancing interoperability, it has notable limitations. Research indicates that BIM implementation in the AEC sector remains fragmented, relying heavily on proprietary software systems, which creates barriers such as "vendor lock-in," where participants must use compatible applications. Although the IFC standard aims to mitigate this issue, it is not universally adopted, and data stored in IFC format is not always compatible across different systems (Patsias, 2019). The IFC standard primarily focuses on project-specific data, limiting its broader applicability for connecting various project types or aligning with requirements management systems in multi-stakeholder environments.

Other research has explored the use of semantic web technologies to address interoperability challenges (Pauwels, Zhang, & Lee, 2017; Pauwels, 2014; Pauwels, De Meyer, & Van Campenhout, 2011; Svetel & Pejanovic, 2010). These technologies, arising from the development of the internet, focus on connecting information in a uniform, machine-readable format, allowing for the mapping between different data sources. This is achieved through interconnected knowledge graphs and standardized vocabularies such as RDF and OWL. Semantic web technologies have the potential to improve data sharing and reusability across platforms (Simperl, 2009; Aßmann, 2005). However, while this technology holds significant promise, its application within the AEC industry remains largely conceptual, with limited real-world adoption (Kurteva, McMahon, Bozzon, & Balkenende, 2024). The fragmented information landscape in the AEC domain, characterized by proprietary software and diverse data models, continues to pose challenges for integration and collaboration.

Beyond technical considerations, other research highlights the broader dimensions of interoperability, encompassing organizational, institutional, and social contexts. These dimensions involve aligning business processes, enhancing collaboration, and addressing legal and contractual barriers (Grilo & Jardim-Gonçalves, 2010; Linderoth, Jacobsson, & Elbanna, 2018; Criado-Perez et al., 2022). Studies that leverage the European Interoperability Framework emphasize the need to combine technical innovation with strategies that manage human and organizational factors influencing data exchange and collaboration. Similarly, (Jacobsson, Linderoth, & Rowlinson, 2017) stresses the critical role of the socio-technical environment in adopting new information and communication technologies (ICT).

While current design research has primarily focused on developing technical solutions, such as ontology development and semantic frameworks, there has been comparatively less emphasis on how these solutions interact with broader organizational and institutional structures. This imbalance often leads to a gap between conceptual academic advancements and their real-world implementation in the industry. A critical aspect of this gap is application interoperability, which is essential for enabling different software systems used by various stakeholders to exchange and interpret data models seamlessly. In the AEC industry, where complex projects involve numerous participants using diverse tools and platforms, the ability to share and integrate data models—such as building information models or project requirements—across applications is vital. Without robust application interoperability, data silos persist, leading to inefficiencies and errors in information exchange.

The lack of widespread adoption of these technical systems suggests that challenges within the non-technical layers—such as governance, stakeholder alignment, and standardization—significantly hinder effective deployment. By focusing on application interoperability, this research specifically targets the ability of different software applications to exchange and use data consistently. The framework designed here aims to broaden the interpretation of interoperability to not only cover technical functionalities but also to address the social dynamics, including organizational policies and collaborative practices, that influence the successful implementation of these application-level solutions.

The main research question addressed in this study is: *"How can a socio-technical framework for application interoperability, aimed at improving model-based exchange, be designed to tackle both technical and non-technical challenges in the Architecture, Engineering, and Construction (AEC) domain?"* This question seeks to bridge the gap between technological innovation and practical application in real-world scenarios. By exploring this question, the research contributes to developing solutions that meet the technical requirements for interoperability while also considering the organizational and institutional context necessary for successful adoption and long-term viability.

This research aligns closely with the objectives of the CoSEM master's program by addressing the socio-technical complexities within the AEC domain. It adopts a typical CoSEM approach by integrating engineering design with institutional, economic, and social considerations to create a socio-technical framework for interoperability. By addressing both the challenges of technological integration and stakeholder management, the research emphasizes process management strategies and systems engineering principles. The design leverages digital technologies, including semantic web frameworks and linked data, to enhance the broader information landscape of the AEC industry. Additionally, the study examines public and business values by exploring organizational and institutional dynamics related to the framework's long-term applicability. Through its multidisciplinary methodology and focus on public-private collaboration, this thesis aims to contribute to CoSEM's goal of analyzing and proposing solutions for contemporary socio-technical challenges.

The structure of this report is organized as follows: Chapter 2 outlines the research methodology, detailing the design science approach and the specific methods employed. Chapter 3 reviews the existing literature on interoperability, emphasizing key technical and socio-technical challenges. Chapter 4 analyzes the information landscape within the AEC domain. Chapter 5 presents the methodology and findings from interviews conducted with industry stakeholders, offering insights into current practices and existing barriers. Chapter 6 describes the functional and non-functional requirements derived from the research. Chapter 7 introduces the proposed socio-technical framework, elaborating on its design and implementation. Finally, Chapter 8 evaluates the framework, and Chapter 9 concludes with a discussion of the findings, their implications for the field, and suggestions for future research.

2 Methodology

This section describes the methodology of the research and the reasoning behind it. Firstly the Design Science Research approach is discussed, followed by a description of the methodology that is used to answer the subquestions. Finally, two schematic overviews are given that illustrate the sequence and flow of the research.

2.1 Research approach

2.1.1 Design Science Research

This project adopts a design science research (DSR) approach. According to A. Hevner and Chatterjee (2010), DSR is particularly effective for creating socio-technical artifacts within a relevant application domain. This type of research aims to integrate the pertinent problem domain with the existing knowledge base (Hevner, March, Park, & Ram, 2004). The relevant problem domain is discussed in detail in sections 3, 4, and 5. The existing knowledge base will be examined by reviewing related literature and conducting interviews with key actors in the domain. These two components are outlined in sections 3 and 5, respectively.

The goal of this research is to develop a socio-technical artifact—a framework for addressing interoperability issues within the architecture, engineering, and construction (AEC) domain—that confronts both technical and social challenges. Ultimately, the design will undergo an evaluation process, which will provide feedback to refine the artifact and validate the credibility of the research. This evaluation will critically reassess the assumptions made during the design cycle.

Peffers, Tuunanen, Rothenberger, and Chatterjee (2007) identified six distinct phases in a typical design science research process: (1) Problem identification, (2) Objectives for the design, (3) Design and development: creating the artifact, (4) Demonstration: illustrating how the design functions within the specified problem situation, (5) Evaluation: an assessment that may necessitate returning to phase three for revisions to the design, (6) Communication: this step entails conveying the importance, added value, and limitations of the design.

To ensure a coherent research process, the subquestions will be addressed in conjunction with the research phases outlined by Hevner et al. (2004)

2.1.2 Architectural design

The primary goal of this research is to develop a framework that addresses the critical need for enhanced interoperability among proprietary software applications within the AEC domain. The artifact aims to fulfill the needs for interoperable systems that can be identified within the application domain. These needs are constructed by studying relevant related works and interviewing actors active within the problem domain.

The success of the artifact hinges on both technical functionalities and social dynamics within the environment. The requirements for the design will be split up into technical and non-technical aspects. This means that the evaluation of the framework will also be based on these different dimensions.

2.2 Research question

The main research question, already shown in the introduction, is as follows:

How can a socio-technical framework for application interoperability, aimed at improving model-based exchange, be designed to address both technical and non-technical challenges in the AEC domain?

To answer the main question, four subquestions are construed. These questions follow the six steps of a DSR approach broadly.

2.2.1 Subquestions

The first subquestion aims to identify the problem context, the second questions formulates the objectives, the third question guides the design and development and also the demonstration. The last question handles the evaluation and the communication.

1. How does the socio-technical problem context for application interoperability in the AEC-domain look like?

This question explores the problem context of the socio-complex system at hand. Information is gathered from two main sources: scientific literature, whitepapers, and semi-structured interviews with relevant stakeholders. The literature review consists of a structured search that is conducted using the scientific database Scopus. Adjacently, documents on regulation and standards are collected and white papers and policy papers of stakeholders are reviewed.

The interviews are conducted with participants who can be categorized under three different groups of stakeholders: project owners, clients, and experts. These roles were identified in a paper on requirements management of (Jallow, Demian, Baldwin, & Anumba, 2014). The collection of participants will be done via the professional network of the company Semmtech, which helps clients with their requirements management and cooperates with other organizations active in the field to improve interoperability between various information systems.

The content of the literature review determines the topics that will be discussed during the interviews. How these two are linked can be found in the fifth section which contains the methodology and analysis of the interviews. However, both outputs are used to answer the first sub-question.

By combining these various viewpoints, we can develop a thorough understanding of the system. This question is analyzed through two different lenses, a technical and non-technical dimension. This is a simplified version of the interoperability model presented by Shehzad et al. (2021), which applies the European Interoperability Framework (EIF) to the building environment, encompassing four dimensions.

The content of the literature analysis and interviews are used as inputs to answer this question. Consequently, the output is the overview of the landscape based on the four different dimensions. Thereafter, this will serve as an input for the second and third subquestions.

2. What are the requirements for a design aimed at improved application interoperability within the AEC industry?

This question formulates the objectives of the design. These objectives are embedded within the socio-technical environment of the system. Understanding the definition of interoperability is important for this question. "The possibility to exchange information between two or more systems and consequently use that information" (Grilo & Jardim-Gonçalves, 2010) is a comprehensive definition that will be used during the research. However, this interoperability still has more dimensions. In light of this, the research will concentrate on specific topics: exchanging data models and their requirements, reusing these models, and effectively storing and managing this data. These three processes were identified as challenges in a previous study (Jallow et al., 2014)

Furthermore, the analysis of the first subquestion will provide a foundation for addressing the second subquestion. The deliverables for this question consist of both functional and non-functional requirements, which will be classified into the four dimensions identified in the previous subquestion: technical, semantic, institutional, and organizational.

3. How can solutions for better application interoperability be integrated into a framework for managing and exchanging data models within the systems environment?

This question is tackled by developing a design that incorporates design options derived from the requirements. Thus the first step in answering this question is constructing those design options. This was done by brainstorming with colleagues at Semmtech, and consulting white papers, literature, standards, and other relevant sources. The construction of these design options is an iterative process, where feedback is elicited and the options are changed accordingly. During the next step, a selection of those options is integrated into a comprehensive enterprise architecture. The evaluation of these options is done on a requirements-based analysis.

After evaluating the design options, the ArchiMate language is used to create an enterprise architecture, providing a high-level view of the system that incorporates the design options. The paper of Kurnia, Kotusev, Taylor, and Dilnutt (2020) describes design as one of the main purposes of an enterprise architecture. This third question delves into incorporating solutions into this landscape. An enterprise architecture using the ArchiMate standards is ideal for this purpose as it allows to depict how different components of the system interact and support the overall business objectives.

After the high-level architecture design, a more detailed design is constructed that shows how the information flows through the system. This will consist of a data flow diagram, which describes the different processes the information undergoes. This detailed representation will illustrate how data moves through the system, ensuring clarity on integration points and data management practices. Thereafter, a use case is shown as an example of an implementation of the design.

This structured approach aims to develop a solution architecture that not only meets the immediate technical requirements but also supports long-term goals by ensuring efficient system interoperability and data governance.

4. How does stakeholder feedback inform the identification of opportunities and limitations in the design of the proposed framework for application interoperability in the AEC domain?

To evaluate the proposed socio-technical framework, a structured methodology was employed to gather and analyze feedback from key stakeholders in the AEC domain. The evaluation focused on collecting qualitative insights from industry experts through structured interviews and a stakeholder meeting. The selected participants, recognized as specialists in linked data and model-based data management, were chosen for their expertise and direct relevance to the framework's components.

The evaluation process consisted of several steps: (1) Participant Selection: Experts f were selected based on their extensive experience with data models, linked data technologies, and interoperability challenges in the AEC industry. (2) Feedback Session Design: The sessions were structured to allow participants to review the framework's design and provide detailed feedback on both its technical and non-technical aspects. Open-ended questions encouraged participants to discuss the practicality, scalability, and potential barriers to adoption of the framework. (3) Data Collection: The sessions were recorded and transcribed to ensure accurate capture of the feedback. (4) Thematic Analysis: The qualitative data were analyzed using thematic coding to identify common themes and insights related to the framework's effectiveness, strengths, and areas for improvement. This systematic approach ensured that the evaluation was both comprehensive and reflective of the real-world challenges and opportunities in implementing the framework.

2.3 Research Flow Diagram

Figure 1 represents the flow of the research concerning the research questions. The figure visualizes which part of the design cycle is covered and which sub-questions are answered. The output of the four subquestions eventually leads to the answer of the main research question. Green arrows indicate when knowledge of the outputs is used as an input for another question. Black arrows indicate the flow of the research through the different steps of the design cycle.

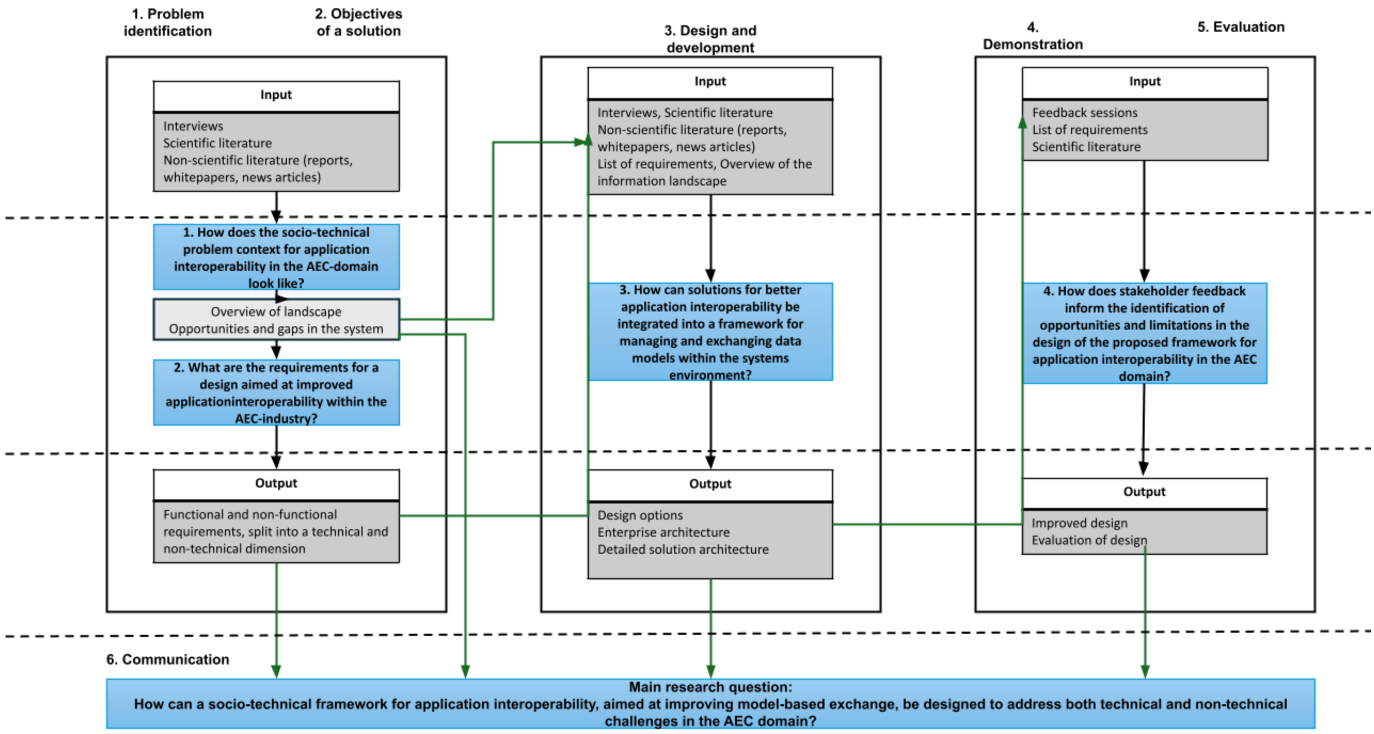


Figure 1: Research Flow Diagram (RFD)

3 Related work

This section presents a systematic approach to reviewing the current scientific literature. The first subsection describes the methodology used for the literature review and provides an overview of the relevant studies that were identified. The second subsection provides a detailed analysis of the literature, highlighting and discussing key themes and insights.

3.1 Methodology

The literature search is conducted systematically to identify various types of articles relevant to the research. Given that the research adopts a socio-technical approach, it is important to include both technical and socially focused-articles.

Table 1 presents the search queries used and the number of results retrieved from each respective database. The first query was broad, yielding a relatively large number of results. The second query focused specifically on requirements management, resulting in a smaller set of relevant articles. The third query further refined the search to target literature on the principles of linked data and the semantic web, aligning with a key focus of the research. The final query sought to identify articles exploring the process of digitization in the AEC industry and its general impact on organizations. The articles were first screened for relevancy, later on, the relevant articles were read and the ones that were useful for the analysis were selected. Eventually, 26 articles were included in the literature review.

Articles were excluded from the literature review based on several criteria. First, articles were excluded if they had an irrelevant focus, meaning they did not discuss overlapping topics or were entirely unrelated to the socio-technical framework for application interoperability in the AEC domain. Second, articles with a narrow scope were excluded if the relevant topic was discussed in such a limited context that it didn't contribute meaningfully to the broader research question. Third, articles were excluded if they merely mentioned the relevant topic in passing, without providing substantial analysis or insights. The "articles" column indicates the number of articles that were initially reviewed based on their titles and abstracts. The "screened" column shows the number of articles that were reviewed after a full reading and assessment of the entire text. The "selected" column indicates the number of articles that were eventually selected for the literature analysis.

Search query	**Database**	**# Articles**	**# Screened**	**# Selected**
interoperability AND aec AND information	Scopus	250	24	16
("linked data" OR "semantic web") AND aec	Scopus	77	8	6
(digitization OR "digital transformation") AND aec	Scopus	114	8	6
Total number of articles		**441**	**40**	**28**

Table 1: Search queries

3.2 Literature analysis

Table 2 gives an overview of the articles that are included in the literature analysis. These are broadly categorized into the four dimensions of the EIR. However, in most of the articles, there is an overlap between two or more dimensions. If the article takes a very broad view of the interoperability concept, the article is categorized in the overview category. One can see that most of the articles are focused on the technical and semantic layer, while fewer of the articles are focused on the organizational and legal aspects. To find relevant concepts for those two categories, the broader concept of digitization within the industry was included.

nr.	Reference	Technical	Non-technical
1	(Shehzad et al., 2021)	✓	✓
2	(Turk, 2020)	✓	✓
3	(Fürstenberg, 2020)	✓	✓
4	(Deng, Xu, Deng, & Lin, 2022)	✓	✓
5	(Hu, Corry, Curry, Turner, & O'Donnell, 2016)	✓	
6	(Scherer & Schapke, 2011)	✓	
7	(Laakso & Kiviniemi, 2012)	✓	
8	(Malsane, Matthews, Lockley, Love, & Greenwood, 2015)	✓	
9	(Niknam & Karshenas, 2017)	✓	
10	(Chen et al., 2005)	✓	
11	(Venugopal, Eastman, & Teizer, 2015)	✓	
12	(Kovacs & Micsik, 2021)	✓	
13	(Kukkonen et al., 2022)	✓	
14	(Rasmussen, Lefrançois, Pauwels, Hviid, & Karlshøj, 2019)	✓	
15	(Pauwels, Costin, & Rasmussen, 2021)	✓	
16	(Pauwels et al., 2017)	✓	
17	(Pauwels, 2014)	✓	
18	(Patsias, 2019)	✓	
19	(Ferguson, Vardeman, & Nabrzyski, 2016)		✓
20	(Criado-Perez et al., 2022)		✓
21	(Grilo & Jardim-Gonçalves, 2010)		✓
22	(Jin, Hancock, Tang, Chen, et al., 2017)		✓
23	(Jin, Hancock, Tang, & Wanatowski, 2017)		✓
24	(Linderoth et al., 2018)		✓
25	(Klein, Stelter, Oschinsky, & Niehaves, 2022)		✓
26	(Liao, Teo, & Chang, 2019)		✓
27	(Ma, Chan, Li, Zhang, & Xiong, 2020)		✓
28	(Jacobsson et al., 2017)		✓

Table 2: Articles categorized by dimension

3.2.1 Overview

The literature often emphasizes Building Information Modelling (BIM) as a key tool for improving interoperability. However, the underlying concepts and technologies can also be applied to other fields. The use of standards, common semantic systems, and process alignment can enhance interoperability across various software tools and application domains beyond just the BIM context. Some articles adopt a holistic view of interoperability within the AEC industry. For instance, Shehzad et al. (2021) utilizes the European Interoperability Framework, which categorizes interoperability into four dimensions: technical, organizational, semantic, and legal. While these dimensions are presented as distinct in the model, they often overlap in practice. Technical systems rely on specific semantic frameworks and are shaped by organizational decisions, which, in turn, are influenced by the relevant institutional and legal frameworks. Despite these interconnections, examining each dimension separately can still provide valuable insights. Turk (2020) argues that to effectively address the persistent challenge of interoperability, it is crucial to consider levels beyond the technical. He classifies the semantic and technical layers of interoperability as "computer-to-computer" interactions. In contrast, the organizational and legal layers involve human interactions with each other and with IT systems. Despite this broader perspective, current scientific research predominantly focuses on the technical and semantic layers (Fürstenberg, 2020; Turk, 2020). This emphasis on technical and semantic layers creates a knowledge gap, especially as the growing complexity of systems makes "person-to-computer" and "person-to-person" interoperability increasingly critical. This gap is also evident between academia and industry (Deng et al., 2022). While technical systems are often developed at a conceptual level in academic settings, they are not fully implemented within the industry. This suggests that challenges within the non-technical layers may be contributing to this disconnect.

3.2.2 Technical layer

Table 3 provides an overview of the themes identified in the literature focusing on the technical aspects of interoperability. A substantial body of literature focuses on the technical and semantic layers of interoperability, with most studies being exploratory and proposing conceptual frameworks or designs (Fürstenberg, 2020). This section gives insights into the main technical aspects relevant to the AEC domain, including challenges such as fragmented information landscapes, the role of standardization, ontology development, and the application of semantic web technologies.

nr	Theme	Reference Numbers
1	Fragmented Information Landscape	5, 6
2	Standardization	7, 8, 10, 12, 18, 19
3	Ontology	9, 11, 13, 14, 18, 19
4	Semantic Web	15, 16, 18

Table 3: Themes within technical layer

Several articles focus on the technical and semantic layers of interoperability, where most studies are exploratory and propose conceptual frameworks or designs (Fürstenberg, 2020). This section first discusses key concepts within the technical layer. The literature highlights several concepts, such as standardization, model-based approaches, ontology development, and the application of semantic web technologies and linked data. Another key area of focus in the literature is Building Information Modeling (BIM) and its ability to enhance interoperability. Semantic web technologies can be used together with BIM standards, but are not the same. BIM is primarily focused on integrating different disciplines in AEC projects. Interoperability also encompasses concepts such as data exchange, reusability of data, and compatibility. The difference between BIM and semantic web technologies will be discussed and how they both can play their role within this problem context.

Fragmented information landscape

A core challenge in the AEC domain is the wide range of different applications and stakeholders. Most of these have different data models that are used in different software environments, which makes data exchange difficult (Hu et al., 2016). These data models are created and maintained separately in proprietary software models (Scherer & Schapke, 2011). As a consequence, the main part of the literature searches for solutions to make these data models compatible.

Standardization

Most communication in the AEC industry is done through proprietary software tools, which can lead to vendor lock-ins where stakeholders are encouraged to use the same or compatible software (Laakso & Kiviniemi, 2012). Open standards offer a potential solution by enabling different software systems to communicate effectively. A key example is the IFC standard, widely used in BIM software applications, which provides a standardized description of building objects. Some studies delve into how they can apply this standard to different use cases (Malsane et al., 2015; Niknam & Karshenas, 2017; Chen et al., 2005; Venugopal et al., 2015; Kovacs & Micsik, 2021). These studies mainly focus on the possibility of coupling the IFC standard to other ontologies. The coupling of these semantic systems eventually has the goal to achieve interoperability between the data models of different stakeholders. The theoretical advantage of this method is the ability to translate information to one open standard, which means you are open to all the other systems that support this standard (Laakso & Kiviniemi, 2012).

The article by Laakso and Kiviniemi (2012) takes a socio-technical perspective to examine the IFC standard. According to Laakso and Kiviniemi (2012), the IFC standard primarily adopts an anticipatory stance, focusing on future trends rather than addressing the current demands of the industry. This approach is one of the factors of its limited adoption in practice. In addition to the IFC standard, there are several other data standards designed to enhance system interoperability. The success of IFC depends on the adoption rate throughout the industry, and this is also linked to the alignment with the needs of the socio-cognitive and institutional environment (Jacobsson et al., 2017). Linked data is another technology that offers a potential solution by enabling connections between various data silos (Pauwels et al., 2017). Despite this, the practical implementation of this technology remains limited. Achieving broader adoption requires addressing not only the technical challenges but also the non-technical factors involved (Jacobsson et al., 2017).

Ontology

When we talk about standards, we talk about a standardized ontology that is used industry-wide. An ontology is a formal way to describe concepts that represent things in the real world (Niknam & Karshenas, 2017). Niknam and Karshenas (2017) describe three different ways to create an ontology in a multi-domain environment:

1. Creating a single ontology that covers all domains.
2. Domain independent ontology development. These domains have to be aligned for information exchange.
3. Domain-independent ontology development with a foundation ontology.

The article argues that the third way is the preferable way of creating a domain-wide ontology. Venugopal et al. (2015) argue that by using ontology building, the consistency of IFC implementation can be enhanced. The research of Kukkonen et al. (2022) uses the third method for creating a new ontology. By extending several ontologies to a domain-specific ontology concerning flow devices. This way, multiple ontologies can be created that refer back to a shared ontology. This ensures that different domain ontologies can understand each other by referencing back to the same core ontology. The research of Scherer and Schapke (2011) uses a similar method. Multi-models are integrated by a central model that shares the basic elements. This kernel ideally should contain no real-world objects, but make abstractions such that more domain-specific interpretations can be given. Rasmussen et al. (2019) explain that such ontologies in semantic web technology are formal, explicit, and shared. In this context, formal refers to machine-readable. Explicit refers to the explicitness of the concepts and constraints that are used. Shared means that it aligns with the knowledge of the specific domain. Applying these three criteria to the IFC standard, we can see the IFC standard is an ontology (Pauwels et al., 2021). There exist other ontologies throughout the industry. The core of these ontologies lies in the Building Topology Ontology (BOT). The more domain-specific ontologies are far less standardized than the shared foundational ones. Thus indicating that the third method described by Niknam and Karshenas (2017) is common practice in research and practice. Another advantage of making ontologies is making the knowledge available more explicit, which is easier to interpret (Patsias, 2019). By creating semantic links between instances and classes, the querying of data sets becomes less complex and depends less on implicit information (Patsias, 2019).

Semantic web

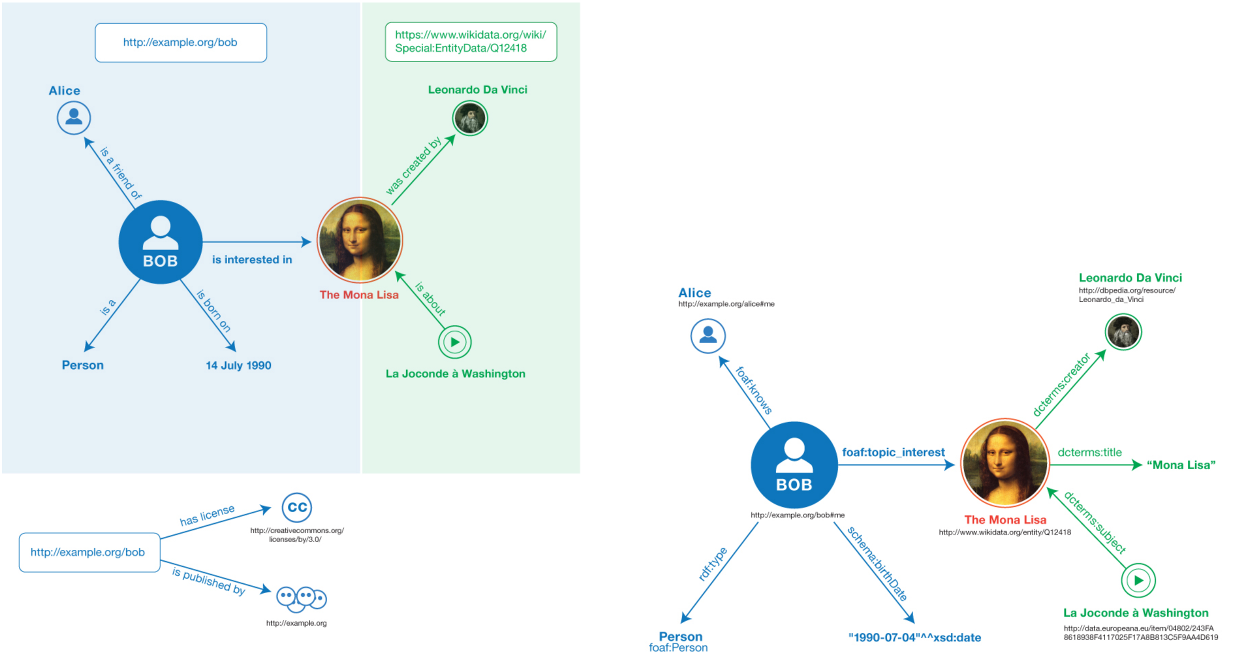
The concepts discussed above are part of semantic web technology. This covers both the semantic and technical part of interoperability.Pauwels et al. (2017) describe three different topics that are mentioned for the usage of semantic web technologies. Interoperability is mentioned first. Mainly this covers the machine-readable format, thus making it possible for computer systems to interact with each other. Another article argues in the same way against the file exchange focus that is currently in place (Pauwels et al., 2021). This should eventually lead to vendor-neutral model exchange. This promise could solve vendor lock-ins and promote easier communication between varying stakeholders. The second topic that is mentioned is the linking across different domains, although one can also categorize this in the same box as interoperability. Finally, the semantic web can be used for compliance checking and checking the completeness and consistency of models.

The semantic web offers a promising solution to interoperability challenges by using web technology to create interconnected knowledge graphs. Just as the World Wide Web connects websites through machine-readable identifiers known as URIs, the semantic web uses a similar approach where data is linked and represented in a structured format. All the information in this web is described in the Resource Description Framework (RDF), a vocabulary that should make information reusable and interpretable for both humans and computers (Pauwels et al., 2017). Within this framework, ontologies' formal representations of knowledge are expressed using RDF and adhere to the OWL (Web Ontology Language) standard, which is a standard managed by the W3C (World Wide Web Consortium). According to Pauwels et al. (2017), the semantic web's approach of providing a unified vocabulary (RDF), combined with the logical structure of OWL and the interconnection of knowledge graphs, could be an ideal solution for achieving interoperability. This approach not only supports the integration of diverse datasets but also allows for flexibility in extending and adapting new ontologies as needed.

The W3C organization gives an example of a simple knowledge graph, that uses the RDF language. Figure 2 illustrates how the structure of a knowledge graph. The core of this vocabulary exists of a *subject, predicate, and object*. The predicate describes the relation between the object and the subject in a directional way. These three elements are always present in an RDF statement and are called triples. The resources are then identifiable via an IRI, which can be seen in Figure 2b beneath the resources. These IRI's can then be reused to point to the same things and are similar to URI's of the internet.

This figure is a simple version of a knowledge graph, that is here to illustrate the concept of a knowledge graph. However, knowledge graphs can get much more complicated in practice.

Differences BIM and linked data



(a) Informal way of illustrating a knowledge graph (b) Using the language of RDF triples in the same graph

Figure 2: Illustration of a representation of a knowledge graph, made by the W3C (*RDF 1.1 primer*, 2014).

BIM and linked data represent two different approaches that can complement each other in managing and integrating information. BIM is specifically designed for the construction industry, providing a standardized structured digital representation of building assets. In contrast, linked data comes from broader information management principles, enabling the mapping of patterns, concepts, and diverse data formats (Ferguson et al., 2016). A major drawback of BIM, particularly with tools like IFC, is its reliance on formats tailored to specific software, which can make interoperability across platforms difficult. Linked data offers another solution that allows for heterogeneous data to be integrated in a computer-readable way, while also enabling connections between disparate datasets (Ferguson et al., 2016).

Another strength of linked data lies in its flexibility, making it easier to extend data models to other domains or adopt additional standards. However, these two approaches are not necessarily alternatives; they can also work together. For instance, BIM information encoded in IFC standards can be linked and made more interoperable through the use of linked data technologies (Pauwels, 2014). This demonstrates how both approaches can serve distinct purposes while complementing one another in advancing data management practices in the AEC industry.

3.2.3 Non-technical layer

Table 4 provides an overview of the themes identified in the literature focusing on the non-technical aspects of interoperability.

Nr.	Theme	Reference numbers
1	Value Creation	1, 4, 20, 21
2	Obstacles in the Industry	4, 21, 22, 23, 24
3	Strategies to Overcome Obstacles	21, 23, 24, 25, 26
4	Institutional Factors	22, 23, 25, 27

Table 4: Themes within the non-technical layer

A substantial aspect of interoperability lies within the non-technical layer. Grilo and Jardim-Gonçalves (2010) argue for this extended view on interoperability, highlighting the importance of business processes, employees, culture, and management. While the topic of semantic web technologies is primarily focused on the technical layer, some articles discuss digitization and the implementation of BIM technologies in the non-technical layer. Given that many of these discussions center on interoperability and digital change management, an overlap between these topics is to be expected. Thus discussing these articles is relevant to other technological innovations.

This subsection explores the various topics deemed essential for the successful implementation of digital technologies. Three different questions will guide this part of the literature review: What can digital innovation deliver, why is it difficult in the current environment to innovate and what are strategies to improve?

Value creation

A key factor in the successful implementation of new technologies is ensuring alignment with business needs. As Criado-Perez et al. (2022) point out, many digital transformation efforts fail because their goals are not closely aligned with the overarching business objectives. In the context of BIM implementation, Grilo and Jardim-Gonçalves (2010) highlight the significant value that organizations can gain, including enhanced communication, coordination, cooperation, and collaboration—each contributing to improved internal and external interoperability. However, the full impact on external interoperability is still largely contingent on how widely BIM is adopted across the industry. According to Jin, Hancock, Tang, Chen, et al. (2017), practitioners often cite cost reduction as a primary benefit of improved interoperability, alongside a better understanding of the project, shorter construction times, and fewer design errors. A study on BIM practitioners in China reinforces this perspective, though with a slight shift in emphasis. While cost and time reduction are still recognized, the most valued benefit among Chinese practitioners is the enhanced collaboration and communication that BIM enables, underscoring its role in fostering deeper, more effective partnerships across project stakeholders (Jin, Hancock, Tang, & Wanatowski, 2017).

Obstacles in the industry

A frequently made observation in the literature is the lack of implementation of new technologies in the industries. Linderoth et al. (2018) observe that there is a short-term focus, where the completion of daily tasks is prioritized. When new technologies are implemented, short-term results are then expected. A study by Criado-Perez et al. (2022) highlight the burden that bureaucratic tasks have on the overall workload. Additionally, the industry has a conservative stance and is risk-avoidant. This is also caused because smaller firms can't afford investment failures. As a result, innovation throughout the industry is limited, which hurts productivity. Without organizational support, employees within these firms are less likely to accept new technologies (Klein et al., 2022). This creates a gap between available technologies and implementation. Furthermore, the cost of innovation (Klein et al., 2022) and the uncertainty that comes with these investments (Jin, Hancock, Tang, & Wanatowski, 2017) reinforces the conservative approach. Another factor, that is adjacent, is the lack of long-term strategies to achieve business goals (Criado-Perez et al., 2022).

Linderoth et al. (2018) note in their research that the heterogeneous nature of the client side is another obstacle to digital innovation. Often, requirements are difficult to clearly articulate and make understandable to contractors. When these processes are not standardized and communication varies from project to project, interoperability becomes more challenging. This issue is further compounded by the fragmented nature of the industry, which leads to a lack of understanding of what other stakeholders need or are doing (Linderoth et al., 2018). Criado-Perez et al. (2022) also observe that this fragmentation can result in contradictory or overlapping digital applications, ultimately undermining the collaboration they are meant to enhance. There is also another consequence of the fragmented nature of the AEC domain. The difficulty is to get all the stakeholders to agree on innovation. As the study of Liao et al. (2019) shows, stakeholder alignment is one of the key hindrances to the acceptance of BIM.

A final hindrance observed is the limited knowledge available within firms (Linderoth et al., 2018). This lack of knowledge is a consequence of the other factors previously mentioned. The conservative nature of the industry, coupled with a lack of top-down support, prevents the establishment of effective learning trajectories within these firms (Liao et al., 2019). As a result, the acceptance and implementation of innovative solutions suffer. From a bottom-up perspective, this knowledge gap leads to a focus on day-to-day operations, with little consideration given to new ICT solutions that do not directly impact daily activities (Linderoth et al., 2018).

Strategies to overcome the obstacles

Not only are obstacles identified, but strategies are also proposed to overcome them. The study by Liao et al. (2019) outlines six managerial strategies. Three of these strategies emphasize the need for strong top-down support, which should foster a learning environment and provide sufficient resources. The other strategies focus on enhancing collaboration with stakeholders during projects by standardizing contracts and aligning business interests. These managerial approaches address the barriers posed by the fragmented AEC domain and the lack of knowledge. Moreover, the acceptance of new technologies heavily depends on their ease of use (Klein et al., 2022). Since people often prefer familiar working methods, offering specialized training during the early phases of implementation can demonstrate the benefits of new technologies and increase their acceptance.

However, these strategies all assume a level of executive commitment that, as previously discussed, is often lacking within the AEC domain. This means that the root of the problem is not fully addressed. Criado-Perez et al. (2022) recognize this in their article, noting that training alone is not a complete solution. They propose four thinking schemes designed to shift the business environment: (1) "Advance future thinking by imagining futures and scenario planning," (2) "Embed strategic thinking," (3) "Install capability thinking," and (4) "Ingrain experimental thinking." They argue that these schemes should serve as stepping stones, with each one building on the previous, allowing firms to progressively advance from one schema to the next. Although they acknowledge the challenges leaders may face in incorporating these different ways of thinking into the industry, when implemented it could yield results.

One of the last aspects that is not often discussed, is the institutional aspect of interoperable systems. Ma et al. (2020) recognize institutional governance as the key factor from a principal component analysis. A strategy falling under this factor is government policy and incentive to promote BIM implementation. Although this factor is ranked differently in the countries that were researched. Another institutional factor that is described in multiple studies is the contractual environment. Liao et al. (2019) sees a role for local governments to standardize multi-party contracts and incentivize stakeholders to share data openly. However, this sharing of data has implications for legal aspects of interoperability. Data ownership, liability, and model ownership could be barriers to exchanging information openly (Turk, 2020).

Conclusion

The literature on interoperability in the AEC domain highlights several findings. On the technical side, standardization, semantic web technologies, and ontology development are recognized as key to improving data exchange and interoperability. But there still are various technical solution directions, with no single approach universally established as the best for achieving interoperability. Additionally, the fragmented information landscape, vendor lock-ins, and the complexity of coupling data models and standards persist. Other research points out that the interoperability challenge must be seen from a broader non-technical perspective, such as forming long-term strategies and better collaboration between stakeholders. Several benefits are found within the literature regarding improved interoperability—while some studies emphasize cost reduction and time savings, others highlight the importance of enhanced collaboration and communication. Despite these insights, there is still a gap in how the technical and non-technical dimensions of interoperability can be fully integrated. The literature also reveals a disconnect between academic research and real-world implementation, which suggests that the impact of developed conceptual models remains limited. This leaves a gap between the alignment of technical development and non-technical issues.

4 Overview of the information landscape

This section gives an overview of the information landscape. This is done by addressing the stakeholders, their relations, interests, and needs. Thereafter, the technical landscape is sketched: the data that is transferred, which technologies are used, and which standards are relevant within the problem area.

4.1 Stakeholder overview

The stakeholders relevant to the problem context can be seen in the Power-Interest (Figure 3). This Power-Interest grid sheds light on which actors have an interest in how the information system is set up and how much power they have to shape the system. This doesn't necessarily mean that they have to shape it one way or another.

Project owner. The project owner is the main player in the project. Project owners can be split up into multiple departments, such as engineering, project management, and facility management departments. They are the center of the information and exchange it with other partners. They can primarily shape the Exchange Information Requirements and structure the data in OTLs or other databases. The amount of power also depends on the supply and demand of the market they operate in. If there aren't a lot of contractors capable of executing the tasks, contractors get more power within the contract discussions. Adjacently, they have a lot of interest in how the information landscape looks like. It plays a major role in their performance. With the current market conditions, it has become pivotal to increase efficiency and accuracy.

Contractors. The contractor receives information from their client (the project owner), has to use that information for construction, and reports back to their client. As was found in chapters 3 & 4, usually they do not concern themselves with how the data is stored and exchanged. They mainly want to have clear instructions on the job. Thus their interest is lower on the PI grid, although one can argue that they have much to win with better information systems. This will also improve their performance on projects, be it on consistency or efficiency. Generally, they have less power than the project owner, because the project owner comes up with the requirements and has more power within the contract discussions. As discussed in the project owner paragraph, when the supply of services is low contractors' power may increase. Collaboration between contractors may also increase their general power within the problem context.

Software vendors. Software vendors that provide applications for AEC projects have a significant influence over the information landscape. They can establish the internal logic and languages of the applications, design application interfaces, and control the degree of openness to other software providers. This gives them considerable power within the system. Vendors can be incentivized to create a vendor lock-in, compelling clients to rely exclusively on their proprietary software. Although standards and semantic web technologies hold the potential to increase interoperability and open up these applications, software vendors still have the power and the incentive to shape the system to their interests.

Regulatory authorities. Relevant regulations in this context include building and safety regulations, but also possible regulations for information management. More efficient requirements management could improve compliance with these rules. However, the influence of regulations on how these processes are implemented remains limited. While there is potential to mandate the use of certain technologies and standards, this approach is not commonly used because it may have contra-productive outcomes when there are new technologies and standards available.

Standardizing bodies. Examples of such organizations within the AEC industry are buildingSMART, which propagates the use of open BIM standards, and W3C, which focuses on linked data standards. These organizations consist of a collaboration of multiple stakeholders that promote the adoption of these standards. However, their power is tied to the number of stakeholders involved and the degree of adoption within the industry. Therefore, their success largely depends on how these standards are perceived and implemented by the industry.

Advisory firms. These consultancy firms help stakeholders enhance various aspects of information management and related topics. Their primary goal is to maintain client satisfaction, thereby securing ongoing and future assignments. Their power mainly comes from shaping the information landscape by introducing innovative ideas and strategies. However, their influence is reliant on the willingness of contractors and project owners to invest in and adopt these strategies and technologies. The influence of consultancy firms can be further strengthened through examples of projects that demonstrate additional value for clients.

There can be different initiators of innovation. Also coalition of stakeholders can be made that have similar interests.

Industry Standards Organizations. Industry standards organizations (e.g., buildingSMART, ISO) play a crucial role in defining and promoting standards that can facilitate linked data adoption across the industry. These organizations are often responsible for setting technical standards and frameworks that ensure interoperability and integration across various systems and stakeholders. By developing and endorsing standards for linked data, these bodies can drive industry-wide adoption and provide a structured approach for implementation.

Regulatory Bodies. Regulatory bodies, such as government agencies or industry regulators, can influence the adoption of linked data by mandating its use through regulations or policies. These bodies can require compliance with linked data standards for certain types of projects or applications, effectively driving industry-wide adoption.

Industry Coalitions and Consortia. Industry coalitions and consortia, such as collaborative groups or alliances within specific sectors, can facilitate the adoption of linked data by bringing together key stakeholders to develop shared strategies and best practices. These groups can work collaboratively to pilot linked data initiatives and demonstrate their benefits, encouraging broader adoption.

Leading Companies and Innovators. Major companies or industry leaders who adopt linked data and integrate it into their systems can set a precedent and demonstrate the benefits of the technology. By showcasing successful implementations, these organizations can influence other stakeholders to follow suit.

Individual Stakeholders. Within an organization, specific stakeholders, such as project owners, IT managers, or data architects, can take steps to integrate linked data into their systems. They can advocate for the technology within their organizations and participate in industry discussions to drive broader adoption.

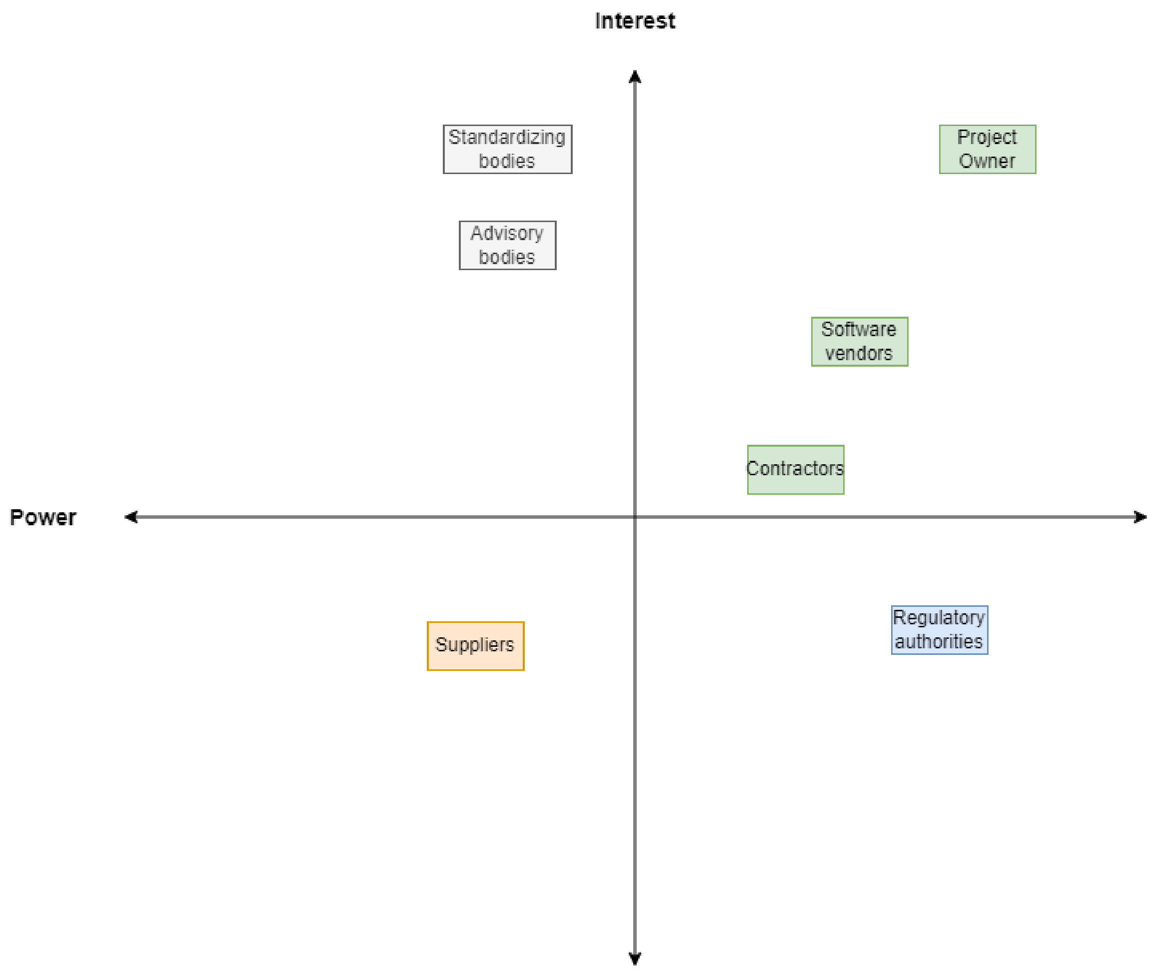


Figure 3: Power-Interest grid of the stakeholders

4.1.1 Aligning and conflicting interests

In this stakeholder landscape, potential coalitions and conflicts arise from varying interests, priorities, and levels of digital maturity. Coalitions can be formed between project owners in infrastructure and government institutions, who share goals of compliance, sustainability, and public accountability. This also comes from the fact that project owners, such as grid operators, rail operators, or other owners of infrastructure, are linked to governmental bodies. Similarly, regulatory agencies and advisory bodies may align with infrastructure project owners in ensuring adherence to standards and stimulating innovation. However, conflicts frequently emerge between project owners and contractors due to differing perspectives on requirements and execution. Project owners have a stronger focus on long-term interoperability and compliance, whereas contractors focus on short-term deliverables and operational efficiency. Misunderstandings also occur when regulatory agencies impose data-sharing protocols that contractors find restrictive, or when subcontractors lack the knowledge or resources to adapt to new digital workflows. Power imbalances can further complicate collaborations, with larger contractors or software vendors sometimes dominating negotiations, and smaller stakeholders will have to follow. These dynamics underscore the need for frameworks that bridge knowledge gaps, align incentives, and establish clear, mutual agreements on responsibilities and data-sharing practices.

4.2 Flow of requirements information within AEC-projects

Building on the analysis of the previous subsection, this section describes the flow of requirements information between stakeholders.

The process starts with the creation of the construction design by architects and/or engineers. Depending on the type, scale, and contract form of the project, this can be carried out by the project owner, external engineering firms, or primarily by the contractor. During this phase, a model of the construction is developed, and the requirements for various elements within the model are defined. Essential is that the requirements are then linked to the model of the construction. This model is then handed over to the project management team on the owner's side, who are responsible for overseeing the project's execution.

The project management team collaborates with the contractor, managing and exchanging the relevant data of the model. Also depending on the type, scale, and contract form of the project, the model is partly or fully exchanged to the contractor. This data needs to be integrated into the applications used by the contractor, such that it can be used for the execution of the project. Subsequently, the contractor must communicate the specific requirements to the subcontractors, who typically only need portions of the model relevant to their scope of work.

As the project progresses, the fulfillment of these requirements must be described and linked back to the overall model, ensuring that the information is communicated to the project owner. When a project is finished, the information is transferred to the asset management team of the project owner, who will use it for building maintenance, compliance checks, and ongoing management.

4.2.1 Bottlenecks

Analyzing the flow of Figure 4, some bottlenecks within this flow can be found. This section gives a short overview of these bottlenecks.

Reusable information

Reusing information from previous projects in future ones can significantly improve efficiency throughout project lifecycles. While projects may vary in scope and objectives, certain components—such as methodologies, processes, or data models—often share similarities, creating opportunities for reuse. As earlier noted, data models based upon ontologies, enable more reusable project information. However, the reusability of these ontologies still depends on how much agreement there is within the industry to use certain ontologies (Simperl, 2009).

Viewpoints

For the owner, it is important that different disciplines can communicate and understand each other effectively. As illustrated in Figure 4, the design, project management, and asset management departments are involved during different phases of the life cycle. They also have different tasks and thus look at the data from a different perspective. The same applies to the transfer of data between project management and the contractor. If these parties use different data models or request information inconsistently, it can lead to inefficiencies and inconsistencies throughout the project. This observation was both found in the interview section and the scientific literature.

Integrating information.

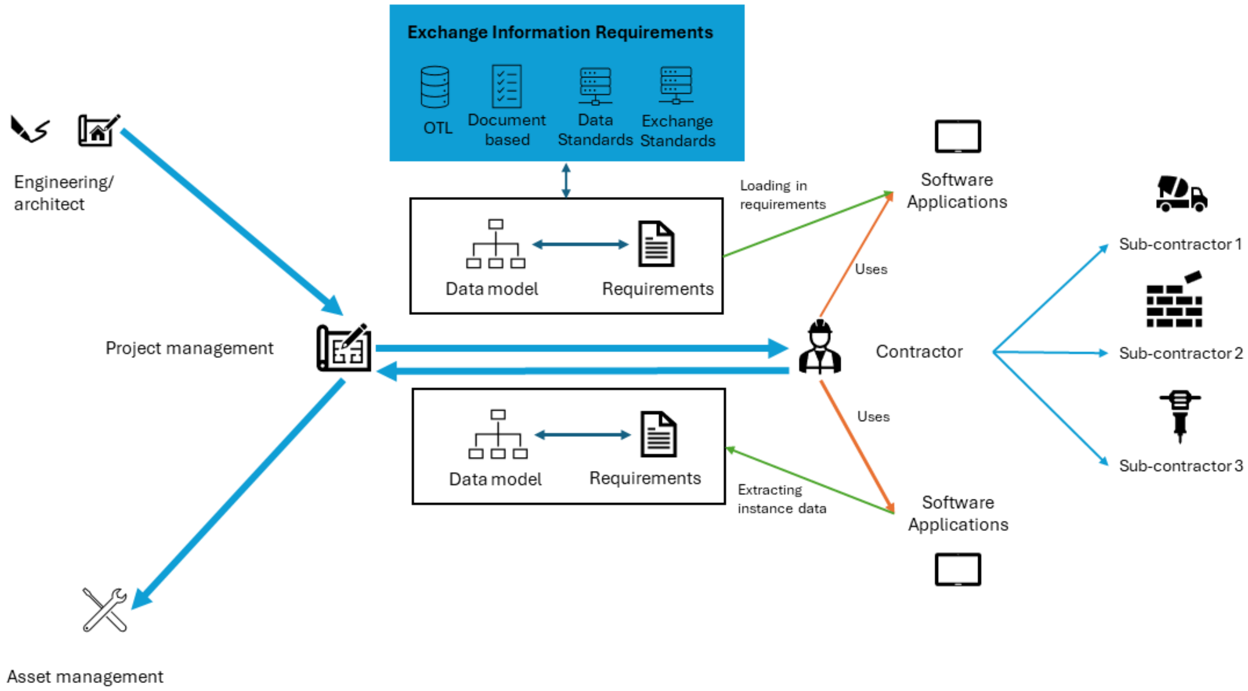


Figure 4: Flow of information within projects

When the data model, along with its requirements, is transferred to the contractor, it must be loaded into the contractor's applications. These proprietary applications can vary in structure, format, and interface, posing a challenge in efficiently integrating the project owner's data model into their information environment. Ensuring efficient transfer and compatibility between the owner's data model and the contractor's tools is one of the core challenges to maintaining efficiency, consistency, and avoiding errors.

Automation.

While it is possible to manage these processes manually using document-based methods, this approach is labor-intensive and prone to errors. Ideally, communication should be automated as much as possible to improve consistency, accuracy, and efficiency, reducing the likelihood of mistakes and streamlining the workflow across stakeholders. To achieve this a main hurdle observed in the interview section is to make information explicit instead of implicit. Computer systems are otherwise not capable of interpreting the information. This hurdle is apparent because some information is hard to make explicit and the current processes are not focused on explicit information.

4.3 Use of standards and vocabularies

Standards play a critical role in addressing interoperability challenges by giving a common framework for data representation, protocols, and processes for data handling and exchange. They enable stakeholders to communicate and collaborate in the same language, ensuring that information is better accessible and reusable across different platforms and domains. However, enforcing standards within the fragmented AEC industry is challenging. Stakeholders often operate with proprietary tools and their workflows, leading to resistance against adopting standards due to concerns about the disruption of established processes. The literature shows that this is a problem within the AEC industry (see Chapter 3).

Additionally, the adoption of standards is heavily influenced by the network effect—a known concept in the field of economics. A study of Zhu, Kraemer, Gurbaxani, and Xu (2006) shows that experience with older standards creates a barrier for conversing to newer and possibly better standards. The network effect also significantly impacts software vendors, who gain a competitive edge when their proprietary standards become the industry norm. Vendors compete to establish their standards as the default. This strategy often leads to vendor lock-in, as adopting a particular standard increases switching costs for users, further reinforcing the network effect. By making it costly or complex to transition to alternative solutions, vendors not only secure their market position but also increase the value of their products. This dynamic creates a self-reinforcing cycle of adoption, where the dominance of a particular vendor's standard can shape the entire industry landscape (Lee & Mendelson, 2007).

An overview of the relevant standards and vocabularies for the problem context can be found in Appendix C. The vocabularies of the semantic web, standards of the BuildingSMART organization, NEN, and ISO are explained.

5 Interview analysis

5.1 Types of participants

This research's main aim is to develop a framework to improve interoperability in information management throughout the AEC industry.

The main perspective in this research is from the problem owner, who has the main responsibility to manage data models and exchange information with the involved partner. Therefore the selected participants for the interviews are those who have direct involvement with the project owner. The stakeholders who are involved in creating legislation, software vendors, and regulatory bodies are left out of the scope of this section. While this creates a more narrow perspective, it ensures that the most relevant stakeholders contribute to the design.

5.1.1 Project owner and contractor

To identify relevant participants, it's essential to provide an overview of the key stakeholders. According to Scherer and Schapke (2011), these stakeholders can be categorized into two main groups: the client side and the contractor side. Within each group, there are different levels of involvement, from top-level management to lower-level and on-the-ground personnel. These stakeholders interact mostly in the middle management, where both sides have project management teams. The client is responsible for initiating the project, while the contractor executes the tasks. Getting input from both sides contributes to getting an overview of what stakeholders need and shedding light on possible conflicts between the different viewpoints.

5.1.2 Expert in digital innovation

However, the literature highlights a knowledge gap within construction firms (Linderoth et al., 2018). Azzouz and Papadonikolaki (2020) address this gap by focusing on digital agents who take responsibility for innovation within their firms, stepping across the boundaries of organizations and disciplines. Therefore, a key participant in this research are experts who are involved in driving digital innovation within the industry across different boundaries.

5.1.3 Excluded stakeholders

While the focus of this research is on participants directly involved with the project owner, it's important to acknowledge the stakeholders that were left out of the interview scope. These include software vendors, regulating bodies, and sub-contractors.

Software vendors play an important role in shaping the information landscape, by providing tools and platforms with specific vocabularies and technologies. However, their perspective was excluded from this section to maintain the focus on the end-users of these systems and in which ways they can shape and transform the landscape.

Regulating bodies is essential for setting standards and ensuring compliance within the industry. The decision to exclude them was based on a focus on the operational aspects of interoperability rather than the regulatory framework, which, while important, falls outside the immediate scope of this research.

Sub-contractors, who often play a significant role in the execution phase of construction projects, were also left out of the interview scope. Although their input could provide valuable insights into on-the-ground challenges, the research prioritized participants more closely aligned with the project owner's strategic management and decision-making processes.

5.2 Interview participants and protocol for interviews

For the research, five participants were interviewed that covered the three perspectives explained in the previous subsection. Appendix A provides an overview of the interview participants, representing different roles within the Architecture, Engineering, and Construction (AEC) industry. Each participant brings expertise from a different viewpoint essential for understanding the interoperability issues. The roles are categorized into project owners, contractors, and experts in digital innovation, each playing a distinct part in the AEC ecosystem. Project owners, such as information managers, are primarily responsible for defining project goals, managing data environments, and ensuring compliance with organizational standards. Contractors focus on implementing project requirements and managing the flow of information with project owners, often dealing with on-the-ground challenges of data integration and real-time collaboration. Meanwhile, experts in digital innovation bring specialized knowledge of advanced data management practices, such as linked data and ontology setup, which are increasingly crucial for achieving interoperability across systems. This combination of technical, organizational, and strategic expertise from different project types and organizational backgrounds provides a comprehensive perspective on the challenges and needs within the requirements information landscape in the AEC industry.

The participants for the interviews were selected through my internship company, Semmtech, which facilitated access to a network of industry clients involved in requirements management and data interoperability projects. The selection aimed to ensure a balanced representation of various roles within the AEC domain, focusing on stakeholders such as project owners, contractors, and digital innovation experts. This diversity was intended to capture a broad range of insights relevant to the research's objectives. However, given the limited number of interviewees, the analysis predominantly reflects perspectives from infrastructure projects. Consequently, while the findings offer valuable insights, they may not fully generalize to other types of AEC projects, where contextual factors might differ. A larger pool of participants could have provided a wider variety of responses, potentially enriching the overall analysis.

The initial set of questions used during the interviews can be found in Appendix B. These questions were designed to explore the perspectives and expertise of the participants, with a particular focus on their roles in the information landscape. The questions were tailored to each participant group—project owners, contractors, and experts—to gather specific insights into their approaches, challenges, and priorities in managing and exchanging project data. However, these questions served only as a starting point for the conversation. Each interview lasted approximately one hour, during which various topics were explored in depth. The direction of the conversation was influenced by the knowledge, expertise, and viewpoints of the interviewee. Before the interview, all participants provided their consent for the content to be recorded, transcribed, and analyzed. They were also asked for permission to use their job title and experience, though their names were omitted from the report as this information was deemed unnecessary. This approach reflects the semi-structured interview method, where the discussion is guided by specific topics, but allows for flexibility, ensuring that the content is not limited to predefined questions and can evolve based on the input from the participants.

5.3 Results

This section is the analysis of the interviews. Common themes were extracted and discussed in light of the literature findings. These themes will eventually guide the development of the framework.

5.3.1 Methodology of analysis

The analysis of the interview data was conducted manually without the use of specialized software. Each interview was transcribed and thoroughly reread to identify recurring themes and patterns within the responses. These themes were abstracted based on their frequency and relevance across the interview population. To draw meaningful conclusions, I examined the prevalence of these themes across different participants, considering factors such as role, expertise, and context. This allowed for an in-depth understanding of why certain themes emerged more frequently in some interviews and were less prominent in others. The analysis was iterative, with the findings continually refined through a process of comparing and contrasting the themes across interviews to ensure a comprehensive interpretation of the data.

5.3.2 Theme 1: Misunderstandings in communication

One theme that came up in the interviews was misunderstandings. These misunderstandings can be seen as misunderstandings between computer-to-computer communication, person-to-computer communication, and person-to-person communication. Different aspects of these misunderstandings are standardization, differing viewpoints of stakeholders, and explicit and implicit working. These themes were extracted from different questions from the questionnaire.

Subtheme	Questions	Participant
Standardization	(1.6;1.8); (2.6;2.7.1); (3.6;3.7;3.10;3.11;3.12)	[1,2,3,4,5]
Different viewpoints	(1.9); (2.8); (3.8)	[2,4,5]
Explicit vs Implicit	(1.6;1.8); (2.6;2.7.1); (3.6;3.7)	[3,5]

Table 5: Subthemes and their corresponding questions and participants

Standardization

Standardization of processes, formats, and language is used such that there are fewer misunderstandings between stakeholders. All five participants underscored the value of standardized work and standardized formats. The goal is to use standardized language, such that it becomes understandable and translatable for anyone who has access to this standard. The difference and advantage of using an open interoperability standard is visualized in Figure 5.

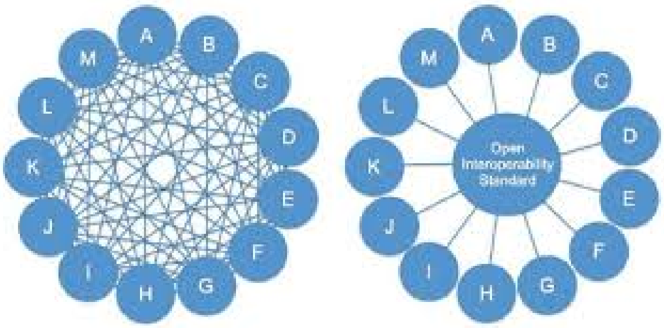


Figure 5: The use of open standards for interoperability. A diagram used from the article of Laakso and Kiviniemi (2012).

"The key advantage of publishing is using an open standard rather than a tool-specific one. In theory, any tool can be used to load the data." [1]

The use of specific standards has the promise of automating processes. Three of the five participants [1,2,5] mention the use of linked data standards and ontologies as a way to increase the efficiency of information exchange. These standards should also lead to easier integration of other systems.

"Here, our goal is to ensure that the information adheres to linked data standards, allowing for the integration of various systems. Having a common ground based on these standards facilitates interoperability." [2]

Another advantage of using linked data principles is the ability to map relationships between data points in different databases. This was explained by participant 1.

"Computers can't just interpret two datasets on their own, but Linked Data can create links between different datasets, enabling you to query them as if they were one large dataset." [1]

Different viewpoints

The advantage of using standards to avoid misunderstandings is clear. However, some participants [4,5] indicate that another cause of such misunderstandings is the differing viewpoints from the main stakeholders: the contractors and project owners. They look at the requirements set from a different perspective, which leads to interpretation errors and requirements that are not workable in practice for contractors.

"*For example, in 2gWatt, we received a reference design from TenneT, developed by Arcadis. They said, "You just need to create a UWO." But then you find many small issues in those models—how they handled the requirements, little things that don't quite fit. Then we essentially have to redo the DWO because we can't proceed with what we've been given. So, you end up redoing everything."* [4]

These different viewpoints are also identified by [2]:

"...if I'm talking about an asset from a requirement management perspective, and the designer is talking about it from a design perspective, we might not be on the same page. Or, from a project management perspective, they might be focused on cost and delivery time." [2]

Streamlining these different viewpoints within organizations is easier, but this also depends on the organization. Where the organization of [5] has fragmented strategies per department, [2] has a unified strategy to streamline digital communication within the firm. Streamlining communication with external partners is even more difficult and requires more effort in collaboration. Aligning interests is seen as a way to stimulate innovation and collaboration [2,5]. Adjacently, [4] mainly wants clear agreements on how and what has to be done.

"If you only define information requirements that are important to us, there's a risk that execution will suffer. However, if you ensure that the data exchange benefits both parties, the quality improves for everyone. For example, optimizing the data exchange with subcontractors and suppliers can lead to a higher quality outcome for both sides." [5]

Explicit vs Implicit

Another hurdle that was noted by two of the five [3,5] participants was implicit reasoning versus explicit reasoning. Computer-readable formats, such as the RDF language, require explicit reasoning. However, current communication via documents is more implicit. Implicit reasoning requires more interpretation, which leads to more inconsistencies when data is used or exchanged. The limitation of implicit and explicit reasoning in project requirements is formulated by [3]:

"Whether a requirement is met can be very easily made explicit (yes/no). For some requirements, it can be difficult to make the explanation explicit. Take, for example, a housing requirement for the municipality: whether it fits into the streetscape, and the explanation of this is hard to make explicit, as it is more of an implicit reasoning. Certain parts of a project will therefore never be made fully explicit. This is a limitation for automation." [3]

This is congruent with observations of participants [5]:

"Full automation is not our goal because it is not entirely feasible. Our work package is responsible for ensuring quality, and the technical requirements can sometimes be open to interpretation or even contradictory, which is something the contractor needs to identify and clarify." [5]

5.3.3 Theme 2: Organizational awareness

Another theme discussed was the awareness of interoperability issues and how they are addressed within organizations. As noted in the literature, there is a tendency within the industry to prioritize short-term benefits, potentially hindering innovation. Additionally, the literature highlights the importance of strategic thinking and developing a clear vision for addressing these challenges. The following subsection discusses if and how these themes are represented in practice.

Strategic thinking

All participants were asked how within their organizations interoperability issues were dealt with. This aspect of interoperability differs between project owners and contractors, as their roles are also different. From a project owner perspective, [5] explained:

"TenneT has seven different project organizations, and not all of them are as advanced. Some are still focused on working with documents [...] Therefore, we needed to change how we work with contractors. This strategy was established at a high level, focusing on making implicit data explicit, implementing BIM, and adopting new contract forms that place more responsibility on the contractors." [5]

Another observation by [5], was the variance in how contractors operate:

"There's a wide range of capabilities among contractors. Some, like Siemens, are highly advanced, with their own OTL and knowledge graphs, allowing them to maintain their working methods while still collaborating effectively. Others are not as far along and may not fully grasp what we're asking for initially, though they often catch on later. We need to create development paths and collaborate closely with contractors to ensure success." [5]

From a contractor perspective [4], it was argued that there could be more collaboration between contractors such that the variance in work methods could be less. By creating such a collaboration, clients (project owners) would be incentivized to use methods that align with theirs. [3] argues in congruence with the literature, that the view of contractors is mainly project-based:

"A key aspect within contractors is that much is viewed on a project basis. They often do not look further than a week ahead to arrange everything. When there is a large project, they are often conservative in exploring new ways to organize data systems. Especially with large projects, they prefer to use the programs they are familiar with." [3]

Participant [2] notes that they have different ways to tackle their interoperability issues internally and externally. For the internal part, the different disciplines are integrated:

"Yes, part of our goal, which is tied to our digital strategy, is ensuring that the system engineering team, project management team, and other design disciplines communicate in the same way. Even if they use Different platforms, those platforms need to communicate effectively based on established processes. At Arcadis, we've gone beyond just internal management between different disciplines." [2]

For external parties, they try other methods to convince them to adopt their standardized methods:

"At Arcadis, we often support pilot studies to demonstrate value. Once the client sees this, they're more open to managing their projects this way." [2]

Short term vs long term

An aspect that was identified in the literature, was the short-term focus of the industry mainly on the contractors' side. This is also represented by participant [3]:

"They often do not look further than a week ahead to arrange everything [...] For certain changes, there may also be more urgency, as they provide significant short-term benefits. Think about integrations between different systems used within a company (design, 3D, finance, requirements, etc.).

But we can see that there are initiatives that have more long-term effects. Such as the replacement of a document-based system with a database system and OTLs [5]. However, during such large-scale processes, there is a tendency to fall back on old methods when the new system is not performing optimally.

"Moving from specification documents to a database was technically challenging as well. The performance of the database deteriorated as it grew, leading people to create shadow databases." [5]

Shadow databases exist when employees are using other files where they keep and update their data, instead of using the central data environment. However, such large data migrations are usually coupled with system errors. This can be seen more as an in-between-state which will eventually diminish when implementation is fully operational.

5.3.4 Theme 3: Institutional aspects

Contractual agreements

The digital exchange usually is established in the tendering process for projects. Different contractual frameworks can be used, where Exchange Information Requirements [5] or Information Delivery Aspects [4] are established to ensure how information is transferred.

"Information Delivery Specification: if you create a drawing, it must have this layer structure, it must be delivered in this format, with an OTL, references, etc. There are always requirements for how you should create the model, how to deliver the information, and what file types." [4]

However, participant 3 notes that it is not always the case that these specifications are worked out, and in practice, the specifications are not feasible for a project.

"Initially, the requirement stated: we want the data to be transported in a linked data format. Eventually, they could not specify this and removed it from the requirements. This was likely due to a lack of time, vision, or knowledge, and they reverted to the old approach. Now, the requirements are shared with TenneT again via Word or PDF documents." [3]

[5] mentions that there are clauses within the contractual environment that ensure improvements in digital exchange and information management.

"We included a clause in our contracts that allows us to implement improvements over time. For example, instead of continuing to use Excel sheets per object, this clause enables us to develop a roadmap that benefits both us and the contractors. It serves as a powerful tool to ensure progress in our data management strategies." [5]

[1] also underscores the importance of collaboration between the stakeholders:

"That's why they need to encourage and learn from each other. The partnership in the contract is crucial. There have been instances where the first projects didn't go well, and we had to revert to the old way of delivering the dataset." [1]

The power dynamics also play a role in forming the contracts and information requirements:

"One of our core challenges is that only a few contractors can meet our requirements, giving them significant leverage. For example, we have a specific philosophy for identification, which we consider crucial, but we haven't always been able to achieve what we want due to the limited number of capable contractors." [5]

[1] gives an example of how digitization processes can be guided by structuring the tendering process in a certain way:

" Over the next 10 years, we know 600 projects are coming up. So, we tender a framework contract in advance. Contractors must bid on a fictitious project, which includes a digitalization component, where it must be demonstrated that the contractors can work with the standards. From that framework contract, the assumption is that contractors are capable. How they achieve this is up to them." [1]

Ownership and Security

When data is exchanged or opened up to other parties. It remains the question of who owns the model or data, who can access certain data and how secure are different ways to manage the data.

Participant [2] notes that openness and security is a trade-off for parties.

Security is one of the factors slowing down the adoption of linked data or open standards. Not everyone is comfortable sharing how they manage their data, so defining what is open and what isn't is crucial. [2]

Complementary, [2] notes that sharing OTLs and using agreed-on standards is an industry-wide problem, where common action is needed:

the question is whether the client is comfortable making their object type libraries publicly available. This is a broader issue for the construction industry—do we come together and agree on a shared standard? [2]

[5] notes that security is important when managing large databases, however, just like [2] noticed, the instance data isn't shared. Thus sharing data models in an open available format isn't a security issue:

Security is a critical issue with such large databases [...], Most data used for maintenance is at a C2 security level, which means it can be public. However, some data must be secured, especially information related to systems. We are working to ensure that sensitive data is protected accordingly. [5]

5.4 Conclusion

The findings of this chapter highlight some challenges in managing and exchanging data models during construction projects, which align with the broader interoperability issues found in the literature. A recurring theme is the misunderstandings among stakeholders, which result in inefficiency, inconsistency, and inaccuracy. These misunderstandings do not only come from the characteristics of the information being exchanged but also from differing viewpoints and expertise levels among stakeholders. While standardized data models and explicit representations of data can improve communication, participants noted that not all the project information can be made explicit, creating barriers to further automation of exchange processes.

An important contradiction found during the interviews was the varying organizational awareness and strategic alignment. Project owners generally focused more on long-term strategies for digital innovation, also driven by a limited workforce and an increasing workload. In contrast, contractors tended to prioritize short-term benefits and project-specific goals, creating a misalignment that was also found in the literature. As noted in the literature, the AEC industry is characterized by a project-driven approach, which leads to short-term collaborations. This short-term focus among contractors is somewhat in contrast with the project owners' longer-term digital strategies, although this sample size is far too small to make statements for the whole industry. Additionally, within firms themselves, digital innovation initiatives were sometimes compartmentalized. This reflects limited coordination between different disciplines, an issue also found in the literature. Collaboration between the disciplines is important to prevent information silos and achieve better progress in digital transformation.

The contractual environment adds more complexity to the system. Participants noted the importance of establishing data management and exchange agreements upfront. However, these agreements face challenges during implementation, when the practical realities of projects differ from the contractual agreements. These findings align with Chapter 3, which found that the AEC industry has a fragmented information landscape where it is difficult to standardize agreements across stakeholders with varying priorities and levels of digital maturity. While participants generally didn't see large security concerns associated with sharing object model data, they highlighted higher risks with instance data, which can be important for the functioning of infrastructure. There is also a difference between critical infrastructure and other infrastructure, which translates to different levels of security needs.

The interaction between communication and misunderstandings among stakeholders plays a crucial role in the challenges of interoperability. Misunderstandings often become apparent during communication, as different stakeholders may interpret data models or processes differently due to implicit assumptions or varying technical backgrounds. These miscommunications underscore the need for more explicit and structured communication strategies that can highlight and address these differences early, ensuring that all parties are aligned in their understanding and expectations.

The adoption of newer technologies, such as standardized ontologies, can help streamline communication by providing a common framework that reduces the likelihood of misunderstandings. These technologies facilitate a more uniform representation of data models, making it easier for stakeholders to interpret and use shared information correctly. However, successful adoption relies heavily on effective strategies that encourage stakeholder engagement and alignment. Additionally, well-defined contractual environments can formalize these expectations and responsibilities, ensuring that each party understands their role in maintaining data integrity and communication standards. By integrating these strategies, stakeholders can reduce miscommunications and enhance the overall efficiency of data exchange.

6 Requirements

6.1 Requirements

This section defines the requirements that the design aims to fulfill, specifying the core functions and characteristics necessary for successful implementation. These requirements come from the analyses presented in previous sections, where the technical and non-technical issues and needs were identified. In alignment with the previous sections, the requirements are split into technical and non-technical dimensions. Thereafter, they are split into functional and non-functional categories. Functional requirements outline the key functions the system must support, addressing "what" the system must achieve, while non-functional requirements specify "how" these functions should be achieved to meet quality and performance standards.

Further, the requirements are classified by their level of importance: "must-have" requirements represent foundational aspects essential for the project's success, while "should-have" requirements provide added value without being strictly necessary for core functionality. Additionally, potential conflicts or trade-offs between requirements are examined to anticipate and manage challenges in balancing various objectives effectively.

6.1.1 Functional requirements

The table below outlines the functional requirements identified for the system, categorized into technical (T) and non-technical (NT) components. Each requirement addresses specific needs derived from the system's objectives and aligns with key themes, such as standardization, data ownership, interoperability, and collaborative workflows. These requirements were developed by analyzing the system's goals, as discussed in previous sections, and are designed to ensure that both technical capabilities and organizational needs are met.

Functional requirement number	Description	Explanation and Origin
T.1.	The system should provide mechanisms for storing and structuring project requirements in a way that data is reusable	Standardization; Explicit vs Implicit.
T.2.	The system must provide access to project data in a way that allows multiple stakeholders to view and interact with it.	Different viewpoints
T.3.	The system should ensure compatibility with multiple vendors	Standardization; Data ownership and security
NT.1.	The system must ensure that data ownership is clearly defined between all parties involved	Contractual agreement; Data ownership and security
NT.2.	The system should encourage collaboration between different organizations	Different viewpoints; Contractual agreements; Strategic thinking; Value creation
NT.3.	The system must ensure that contractual agreements include the processes for data management and exchange.	Contractual agreements; Strategic thinking
NT.4.	The system should support knowledge sharing between stakeholders	Strategic thinking; Different viewpoints

Table 6: Functional Requirements related to the themes of chapter 4. "T" stands for technical and NT for non-technical

6.1.2 Non-functional requirements

Table 7 gives an overview of the non-functional requirements. These originate from the functional requirements stated in the previous section. The non-functional requirements are answers to how the system is going to achieve the functional requirements.

Number	Description
T.1.1.	Project data must reference to an ontology, facilitating structured relationships between data entities.
T.1.2.	Knowledge must be stored in a knowledge graph.
T.2.1.	There should be role-based access control
T.2.2.	Modification and verification based on your role must be possible.
T.3.1.	The design must take into account open standards.
T.3.2.	The design should be able to connect open standards with proprietary formats.
T.3.3.	Data must be queriable by involved stakeholders.
NT.1.1.	The design must specify the different responsibilities for data ownership and exchange upfront.
NT.2.1.	Regular stakeholder meetings must be agreed upon.
NT.2.2.	A roadmap must be created for the adoption and implementation of the data model and project standards.
NT.3.1.	Contracts should be standardized,
NT.3.2.	Standards compliance should be included in the EIR
NT.3.3.	Data models should be specified in the contracts
NT.3.4.	Information requirements for different phases should be included in the contract
NT.4.1.	Interdisciplinary teams should be formed
NT.4.2.	Inter-organizational teams should be established

Table 7: Non-Functional Requirements related to their Functional requirements

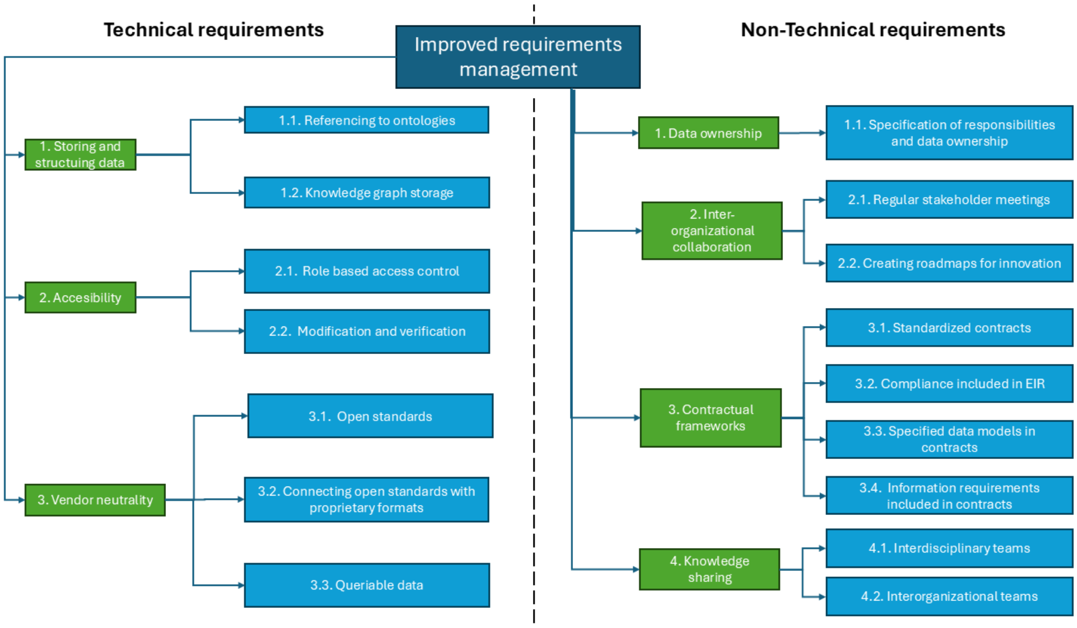


Figure 6: Requirements diagram with the functional requirements in green and the non-functional requirements in blue.

6.2 Conflicting and reinforcing requirements

Table 8 highlights key areas where the fulfillment of certain requirements may compromise others. For instance, the tension between standardized contracts and compliance(NT.3.1 & NT.3.2) might conflict with modification and verification functions in the technical systems(T.2.2). This is a conflict between flexibility and rigor standards within the system. Similarly, adopting open standards (T.3.1) may conflict with proprietary system integration (T.3.2), creating challenges in aligning competing approaches. However, both are needed to achieve vendor neutrality in the current landscape. Lastly, while knowledge sharing (NT.2.2) is essential, it could conflict with realistic roadmaps (NT.4), especially when planning relies on estimating stakeholders' understanding or readiness.

Conflicting Requirements	Reasoning
NT.3.1 and NT.3.2 vs. T.2.2	Standardized contracts (NT.3.1 and NT.3.2) emphasize fixed agreements to protect intellectual property and responsibilities, but this may reduce the flexibility needed to make relationships between information highly visible (T.2.2). Rigidity in contracts can hinder the adaptability required for transparent data sharing.
T.3.1 vs T.3.2	Open standards (T.3.1) enable interoperability and inclusivity, but their integration with proprietary data structures (T.3.2) can be challenging. Balancing openness and compatibility with existing systems often leads to trade-offs.
NT.2.2 vs. NT.4	Effective knowledge sharing (NT.2.2) is crucial to address knowledge gaps in the industry, but it might interfere with the feasibility of roadmaps (NT.4), as overly optimistic assumptions about knowledge dissemination could result in unrealistic planning.

Table 8: Conflicting Requirements and Their Trade-Offs

Table 9 illustrates how certain requirements support and enhance each other when fulfilled together. For instance, structuring data in knowledge graphs (T.1.2) makes the data better queryable (T.3.3), which can be done with the SPARQL language. Similarly, the Accesibility of data for involved stakeholders (T.2) improves collaboration (NT.2), enabling stakeholders to communicate effectively. Using ontologies (T.1.1.) also reinforces standardized agreements (NT.3) by using clearly defined models, which can be incorporated more easily into standardized contracts.

Reinforcing Requirements	Reasoning
T.1.2 and T.3.3	Knowledge graphs (T.1.2) are highly queriable and make explicit relationships between data.
T.2 and NT.2	Accessible information for involved stakeholders (T.2) directly enhances collaborative potential (NT.2), as stakeholders can more easily understand, share, and act on linked information.
T.1.1. and NT.3	Structuring your data conforming ontologies (T.1.1.) align with creating standardized agreements (NT.3), as both aim to make use of standardized models or agreements.

Table 9: Reinforcing Requirements

7 Design

This chapter presents the proposed socio-technical framework designed to address interoperability challenges in the AEC domain. It begins by exploring various design options, evaluating their feasibility, and selecting the most suitable solutions. Both technical and non-technical dimensions are considered, ensuring a holistic approach to the problem. The chapter then introduces an enterprise architecture, outlining its strategy, roadmap, and layered structure, which provide a high-level view of the system's integration and alignment with project objectives. Next, the middleware architecture is detailed, including a data flow diagram that illustrates how information is managed and exchanged. Additionally, potential bottlenecks in the design are identified, and strategies to address them are discussed. The chapter concludes with a use case, demonstrating the practical application of the framework and showcasing its relevance through a real-world scenario.

7.1 Design options

The design options will be examined across three distinct dimensions. The first dimension involves exploring various routes to achieving the eventual system, with a focus on comparing and contrasting different paths to innovation. This includes evaluating the feasibility and effectiveness of the routes. The second dimension addresses the available technical solutions, detailing each option and applying pre-determined criteria for evaluation. A comparative analysis will assess their effectiveness and practicality. The third dimension focuses on non-technical solutions, describing and evaluating them based on specific criteria to understand their role and potential benefits. Finally, the insights from the technical and non-technical evaluations will be integrated to propose an architecture made from the viewpoint of project owners. Additionally, the broader industry impact of these solutions will be analyzed, considering how they influence overall practices and interoperability within the sector.

7.1.1 Non-technical solutions

This subsection will look into options that are situated on the non-technical part of the system.

Regulation by standards

One non-technical option to address interoperability challenges and stimulate innovation is the use of formal standards. This approach offers advantages and disadvantages and is a subject of ongoing debate in economic literature. The study Blind, Petersen, and Riillo (2016) makes a distinction between regulation and the use of standards and the effectiveness of these options in stimulating innovation. In markets with low uncertainty, regulations tend to be more effective as they provide clear guidance, whereas standards can act as barriers. Conversely, in **highly uncertain** markets, standards are often more favorable as they offer flexibility, while rigid regulations may stifle innovation.

Determining the level of uncertainty in the AEC IT market remains challenging. Studies, such as those by Jacobsson et al. (2017), suggest that technology adoption in the AEC sector is predominantly project-based, with limited focus on long-term strategies. This project-centric approach results in a slower innovation rate, positioning the market closer to a low-uncertainty classification, where regulations might be more appropriate. However, the high degree of heterogeneity in systems, an indicator of market uncertainty, complicates this classification. Heterogeneity reflects that it is uncertain what the effect of innovation is, which increases the chance of information asymmetry between a regulator and the market. This creates the potential for market makers to form further lock-in dynamics.

In light of this, the AEC IT market's heterogeneity indicates that standards may serve as a more effective tool for stimulating innovation. Standards provide more flexibility thereby avoiding the potential misalignment associated with regulations. Instead, collaboratively developed standards, which can adapt to a changing market, are better suited to support innovation in such a fragmented and uncertain environment. These conclusions align with the empirical findings of Jacobsson et al. (2017), highlighting that the appropriate balance between regulation and standards depends on market dynamics and stakeholder behavior.

Coalition forming: Aligning Interests for Collaborative Innovation

Coalition forming plays an important role in addressing interoperability challenges that exceed the capacity of individual stakeholders. When there is a common-action problem, coalitions can result in breakthroughs. The study of Jacobsson et al. (2017) shows that to establish new technologies during projects, it is important to build alliances with clients. Cause adoption of new technologies is not only influenced by the market and institutional actors but also by the socio-cognitive environment that is created. Therefore, the environment and the actors within influence each other and the perception of technologies (Jacobsson et al., 2017). Coalitions, which bring together large clients, contractors, consultancies, regulatory bodies, and standardization organizations, can use their overall influence within the industry to set industry-wide standards and practices. The analysis in Chapter 3 shows that industry fragmentation, coupled with varying levels of digital maturity across organizations, limits the efficacy of unilateral efforts. Therefore, a coalition-based approach is a good method for collaboration, aligning interests, and setting shared goals, particularly around innovative technologies and developing standards.

There are multiple examples of coalitions within the AEC industry that have achieved some of these things. One of them is buildingSMART. As noted in Chapter 4, buildingSMART is an influential coalition focused on advancing open BIM (Building Information Modeling) standards to facilitate better interoperability across software systems in the construction sector. Its members include a wide variety of stakeholders, from software vendors and large engineering firms to government entities and educational institutions. By developing and promoting standards like IFC (Industry Foundation Classes), buildingSMART tries to increase interoperability across different systems and stakeholders.

Another collaborative initiative is W3C's Linked Building Data Community Group. The Linked Building Data (LBD) Community Group is organized by the W3C, which promotes the application of Linked Data principles to building information. As highlighted in the literature (see Chapter 3.2), this coalition enables shared ontologies and standardized data handling methods. This coalition addresses the challenge of integrating data across domains, aligning stakeholders who recognize the value of scalable data sharing through open standards.

Coalitions can only be formed when interests between stakeholders within the landscape align. The interests that typically align among coalition members include:

Reducing Redundancies and Costs: For both large clients and contractors, redundant data entry and inconsistent data formats lead to inefficiencies and increased costs. Coalitions aim to create shared protocols and standards that reduce the need for redundant data management across project phases and stakeholders.
Enhancing Compliance and Reducing Risk: Regulatory bodies are motivated to ensure compliance with safety and building codes, while contractors and clients aim to minimize risks associated with non-compliance. Coalitions can address both goals by standardizing data formats and protocols that meet regulatory requirements, as seen with buildingSMART's efforts to incorporate regulatory compliance into BIM standards.

By aligning these interests, coalitions create a foundation for more significant and far-reaching accomplishments in the industry. Some of the key achievements of well-aligned coalitions include:

Development of Interoperable Standards: Coalitions are instrumental in developing industry standards and adoption of technologies like the IFC model in BIM and RDF vocabularies for Linked Data. As discussed in Chapter 5, these standards enable better data exchange between software applications, addressing interoperability between proprietary systems.
Pilot Projects for Digital Innovation: Coalitions can run pilot projects to demonstrate the benefits of new interoperability frameworks, helping stakeholders understand their practical value before broader implementation. For example, large consultancies like Arcadis have partnered with clients in pilot studies (as per Chapter 4's interviews) to validate the interoperability benefits of standardized data handling.
Training and Knowledge Sharing: Coalitions can promote training programs to bridge skill gaps across organizations or within organizations. Standardization bodies like buildingSMART frequently offer certification programs for BIM and interoperability skills. This collaborative training aligns with the literature findings observed in Chapter 3, which noted that knowledge sharing improves the adoption of innovative standards.

Training and Education
Aligned with coalition efforts, training and education programs across organizations increase the knowledge throughout firms. An important finding of Lavikka, Kallio, Casey, and Airaksinen (2018) was that boundary agents are important for firms to think of strategies to implement new technologies. These boundary agents can be people who have sufficient knowledge of the context of the industry and available technologies. There is a role for consultancy firms that work across boundaries of organizations, or inter-organizational cooperations that work together in coalitions. Training is crucial for both project manager-level and technical staff, as observed in interview results from Chapter 4, where participants noted a gap in technical familiarity across organizations. This learning environment could stimulate long-term strategic planning of AEC stakeholders concerning " data openness, use of digital technologies, interoperability, and technical standards." (Lavikka et al., 2018).

Most importantly, when it is coupled with coalition forming, this could create a less conservative industry. This conservative attitude is one of the causes of a lack of innovation. The effectiveness thus depends on the

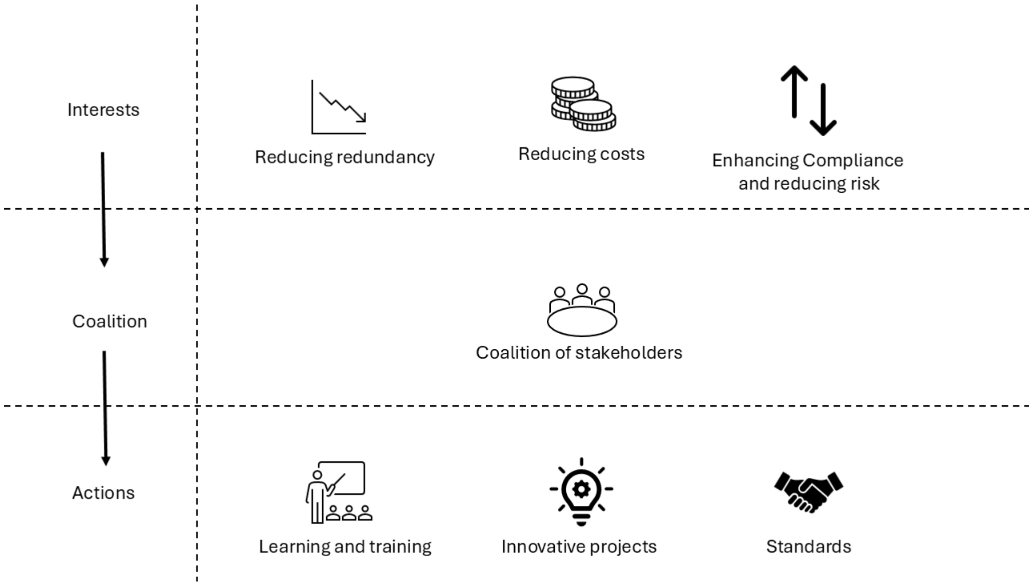


Figure 7: Illustration of the process of forming coalitions and coming up with actions

effectiveness of boundary agents and the effectiveness of coalitions throughout the industry.

Contractual agreements

In the context of the AEC industry, contractual agreements are foundational for setting information standards and expectations between project owners and contractors. Exchange Information Requirements (EIR) play a crucial role in these contracts by specifying data formats, standards, and the structure of information. As discussed in Chapter 5, the larger the client organization, the more leverage it holds in defining these standards (such as ISO 19650 and other BIM-related protocols). This leverage allows larger clients to enforce comprehensive EIRs, which, in turn, supports improved interoperability across projects. Abdirad (2015) found that there was still a lack of standardization in contracts for BIM agreements, although this study was conducted in 2015. This can be explained by a falling behind of the legal part to the technology (Ashcraft, 2008), or by the fast adaption of smaller firms who manually construct their contracts. Although this design option is not a proposition of BIM specifications in contracts, these studies show that legal parts tend to fall behind on the technology. This can be detrimental to innovation, as the institutional environment is an important factor within innovation (Jacobsson et al., 2017).

The use of established EIR frameworks enables consistent data handling, encouraging alignment in data structuring and format across contractors. As evidenced in Chapter 5's interviews, contractors often find alignment with client requirements beneficial yet challenging when EIRs lack clarity or fail to account for practical implementation limits. Therefore, to improve the efficacy of EIRs, a balance must be struck between detailed specifications and room for practical limitations of agreements upfront.

For more long-term contracts, it can be useful to include long-term goals in the tender process(Lenderink, Boes, Halman, Voordijk, & Dorée, 2022). This is also congruent with the findings of Chapter 4, where a level of digitization is a part of the tender process and a roadmap is established with milestones for each half-year.

Evaluation of the non-technical solutions

Table 10 gives an overview of the strengths and limitations of the non-technical solutions.

Non-Technical Solution	Strengths	Limitations
Regulation by Standards	Provides clear guidance in low-uncertainty markets, stimulating innovation by reducing ambiguity in workflows. Facilitates alignment across stakeholders through collaboratively developed standards that adapt to changing needs.	May stifle flexibility and innovation in markets characterized by high heterogeneity and uncertainty. Information asymmetry between regulators and market participants can lead to misaligned regulations and potential lock-ins.
Coalition Forming	Promotes collaborative standardization and innovation by aligning diverse stakeholder interests, including clients and contractors. Develop shared standards like IFC and RDF, enabling better data exchange and interoperability.	Varying levels of digital maturity among coalition members can hinder effective implementation. Smaller firms may lack the resources to adopt coalition-driven standards, requiring targeted support mechanisms.
Training and Education	Addresses knowledge gaps by improving technical skills and understanding of interoperability standards across organizations. Encourages a learning culture, fostering long-term adaptability to evolving standards and technologies.	Relies on executive support and sustained resources to ensure comprehensive and ongoing training programs. Without sufficient industry-wide commitment, training efforts may fail to achieve meaningful adoption of new practices.
Contractual Agreements	Formalizes interoperability expectations through mechanisms like EIRs, ensuring consistent data handling across projects. Larger clients can enforce data standards effectively, driving compliance and standardization across projects.	Rigid contracts may not account for real-world implementation challenges, creating inefficiencies or conflicts. Smaller clients and contractors may struggle to meet detailed specifications, requiring adaptable or tiered contractual approaches.

Table 10: Evaluation of Non-Technical Solutions for Interoperability

7.1.2 Technical solutions

The technical solutions will be made by keeping in mind that they must fulfill the requirements that were construed in Chapter 6. Different solutions will solve different issues and may have some trade-offs when implemented.

Ontologies

As discussed in Chapter 3, an ontology is a formalization of knowledge. In the context of knowledge modeling, ontologies allow for the formalization of various elements of physical objects like buildings and roads, or more abstract entities like rules and workflows. These elements are systematically described in a way that captures not just what they are, but also how they relate to each other. For instance, in a building ontology, concepts such as "rooms," "floors," "windows," and "doors" can be represented, along with the relationships between them (e.g., "a room is located on a floor" or "a door connects two rooms").

To ensure that ontologies can be shared and understood across different systems, various standards have been developed for ontology creation. One prominent organization that defines such standards is the World Wide Web Consortium (W3C). The W3C has developed the Web Ontology Language (OWL), which is widely used to represent ontologies for the Semantic Web. OWL provides a formal way to specify classes, properties, individuals, and their relationships in a domain.

Advantages

One of the primary advantages of using ontologies is that they offer a structured representation of knowledge. This means that the data is organized in a way that is both logical and machine-readable, allowing for automated processing and interpretation. Ontologies represent entities (objects or concepts) in well-defined classes and provide a clear description of the relationships between these entities. This structured format opens up the possibility of making data interoperable across different systems.

Another key advantage of ontologies is that they enable querying through languages like SPARQL (SPARQL Protocol and RDF Query Language). SPARQL is designed to query RDF (Resource Description Framework) data, which is one of the ways graph databases are represented. This query language allows users to retrieve and manipulate data stored in RDF format, based on the logical structure of the ontology (Patsias, 2019).

For instance, a building management system could use SPARQL to query an ontology to find all rooms on a specific floor that are equipped with projectors. SPARQL enables users to query complex relationships and structures within the data, making it an essential tool for accessing and analyzing information in ontology-based systems.

Another valuable aspect of ontologies is their ability to make knowledge reusable (Pauwels, 2014). Once an ontology is created, it can be reused across different systems, applications, or contexts. For example, an ontology developed for modeling railway infrastructure can be reused by multiple rail companies or transportation agencies, saving time and effort in knowledge creation. Furthermore, ontologies can be easily extended and scaled. As new concepts or relationships are identified, they can be added to the existing ontology without disrupting the overall structure.

Limitations

To make ontology truly reusable, there has to be an agreement between stakeholders across the industry (Simperl, 2009). Thus the technology in itself doesn't solve the problem in itself. Another adjacent problem is all the domain-specific information, and it can be hard to make an industry-wide ontology's (Niknam & Karshenas, 2017). However, this could be mitigated by extending broader ontologies to more domain-specific ones, by referencing a core ontology.

Publishing Data Models in Linked Data Format

Publishing data models in linked data format is a critical step in enhancing interoperability across different applications within the AEC industry. Linked data leverages web standards such as RDF (Resource Description Framework), OWL (Web Ontology Language), and SPARQL (SPARQL Protocol and RDF Query Language) to make data more accessible, interoperable, and reusable. By converting data models into linked data format, information is structured in a way that allows for seamless integration and interaction between disparate systems.

This approach not only standardizes the way data is stored and queried but also enables the creation of rich, machine-readable links between data points. Publishing data models as linked data ensures that data can be accessed through uniform protocols, reducing the dependency on proprietary formats and fostering a more open ecosystem. Additionally, this method supports the integration of diverse datasets, allowing for more complex queries and analytics across different domains.

Limitations

However, this approach is not without limitations. One significant challenge is the initial effort required to convert existing data models into linked data formats, which can be time-consuming and resource-intensive. Additionally, the complexity of maintaining consistent and accurate semantic relationships across vast datasets can pose difficulties, particularly in ensuring data quality and coherence. Despite these challenges, the benefits of linked data, particularly in improving long-term data integration and accessibility, make it a valuable tool for enhancing interoperability in the AEC industry.

Mapping standards in linked data format

Mapping different standards and their semantics in linked data format is a crucial design option for enhancing interoperability within the AEC industry. By using linked data, standards like IFC (Industry Foundation Classes) and NEN (Dutch Standards Institute) can be semantically mapped to create more cohesive and reusable data structures. Linked data enables the construction of knowledge graphs, where entities and their relationships are defined in a machine-readable format, making it easier to connect disparate datasets and reuse information across various applications.

One of the primary advantages of using linked data for mapping standards is its ability to facilitate more dynamic and scalable integration of diverse data sources. Knowledge graphs inherently support linking data from multiple standards, allowing for more flexible and adaptive data management practices. This interconnected nature of knowledge graphs ensures that once standards are mapped, the data can be more readily accessed and utilized, fostering greater efficiency in data exchange.

Additionally, linking widely used standards such as IFC and NEN through linked data can significantly enhance their adoption. Since these standards are already well-integrated within the industry, connecting them using linked data frameworks can reduce the barriers to implementation and encourage broader acceptance of new technologies. This approach addresses the adoption challenges by creating a more intuitive and streamlined way to integrate and apply standards.

Limitations

However, there are limitations to this approach. Creating mappings between standards is a time-consuming and resource-intensive process, requiring careful attention to ensure that semantic relationships are accurately represented. Each standard must be analyzed and translated into the linked data format, which can delay the implementation and increase the complexity of data management. Furthermore, maintaining these mappings over time as standards evolve can add another layer of complexity, necessitating continuous updates to ensure relevance and accuracy.

Middleware: Plug-ins via API

Since the adoption of Linked Data is still relatively limited, it is unlikely that all organizations will adopt it immediately. The adoption rate depends on factors such as ease of use and how well Linked Data interacts with the systems and practices already in place within companies.

One approach to increasing the adoption of Linked Data is to connect Linked Data libraries to existing applications commonly used in the industry. This connection can leverage the functionalities of these established applications. Currently, the adoption of linked data is not a high priority for any single actor within the industry. However, it will become more attractive to use Linked Data when it can integrate with other applications. In the future, a scenario could emerge where Linked Data becomes essential for communication between stakeholders and the network effect described in Chapter 4 will enhance the adoption of this technology. In such a situation, the more widely the technology is adopted, the greater its value in facilitating communication. However, the challenge lies in reaching this point of widespread adoption. Therefore, encouraging early adopters and demonstrating the value of Linked Data is crucial.

One way to foster this adoption is by implementing middleware that links Linked Data libraries with existing applications that don't have linked data imports. Currently, most applications in use do not support Linked Data imports directly. One can think of plug-ins within applications, or plug-ins via a separate middleware. With the help of middleware, information can be transferred between applications without the user noticing any transformation. The middleware would enable information from the Linked Data ontology to be accessible to other applications.

This middleware would connect with these applications via APIs, transforming the queried Linked Data into the format required by the target application.

Advantages

This approach makes it easier for organizations to implement Linked Data technology and immediately benefit from its use. In the short term, this provides value for individual organizations. Over time, this could lead to a broader adoption of Linked Data libraries. As the use of these libraries grows, it will become more attractive for software vendors to support Linked Data imports, giving them a competitive advantage. Currently, the limited adoption of the technology discourages this development. However, as adoption increases, the need for middleware and plug-ins will diminish, and Linked Data technology will become integrated into core information systems.

An analogy can be drawn with web standards on the internet. Today, all developers use the same protocols because they benefit from the network effects of the internet. It would be nonsensical to use your standards and protocols. In the same way, once Linked Data adoption reaches a critical mass, its use will become standard across the industry because of this network effect.

Another advantage lies in that this route doesn't make use of top-down guidance. In this way, the system can develop in a more flexible way that suits the needs of actors.

Limitations

The first disadvantage is that the application landscape is very broad within the industry. This makes it difficult to make plug-ins for all the applications. One has to pick and choose the most used applications and focus on certain domains. This may slow down adoption throughout.

Adjacently, all these plug-ins require effort from developers. However, one may ask who's interests exactly align with developing and maintaining these plug-ins. Software vendors have an interest in keeping clients within their software environment. Project owners do not have the specific interest or knowledge to create these plug-ins. However, generally, it is in their interest to innovate. Thus it may be challenging to get all the actors together, when individually they don't have large stakes. There is some incentive gap here.

Evaluation of the Technical solutions

Ontologies play a foundational role in this process by formalizing knowledge into structured data models. These ontologies form the backbone of linked data, enabling machine-readable representations of complex relationships and entities within a domain. Once ontologies are developed, they can be published in linked data formats, which further enhances data accessibility and interoperability by adhering to standardized web technologies like RDF and OWL.

Following the publication of data models as linked data, the next step involves mapping standards such as IFC and NEN to these linked data formats. This creates semantic mappings that enrich the data's utility by linking it across various standards and domains, thus fostering greater data integration and reuse. Finally, middleware solutions act as a bridge to facilitate the adoption of linked data by connecting these formats to existing applications. By providing plug-ins and APIs, middleware helps ease the transition for organizations, enabling them to benefit from linked data without overhauling their current systems. This layered dependency—from ontologies to linked data publication, to standard mappings, and finally middleware—ensures that each component supports and amplifies the effectiveness of the others, creating a robust framework for interoperability.

Technical Solution	Advantages	Limitations
Ontologies	Provides structured and machine-readable knowledge representation, enabling data interoperability across systems.	Requires agreement across stakeholders to ensure reusability, which is difficult to achieve in fragmented industries.
	Facilitates querying through SPARQL, allowing better data retrieval and analysis.	Developing industry-wide ontologies is challenging due to domain-specific information and varying requirements.
Publishing Data Models	Enhances data accessibility, interoperability, and reusability through standardized web technologies like RDF and OWL.	Initial conversion of existing data models into linked data formats is time-consuming and resource-intensive.
in Linked Data Format	Supports integration and complex querying across diverse datasets, fostering open ecosystems.	Maintaining semantic consistency across large datasets can be challenging, especially in ensuring data quality and coherence.
Mapping Standards	Facilitates dynamic and scalable integration of standards like IFC and NEN, enhancing interoperability through knowledge graphs.	Creating and maintaining semantic mappings for each standard is resource-intensive and requires continuous updates as standards evolve.
in Linked Data Format	Promotes the adoption of Linked Data by linking widely used industry standards, reducing barriers to implementation.	Complexity in aligning multiple standards can delay adoption and increase management overhead.
Middleware:	Enables incremental adoption of Linked Data by connecting existing applications with Linked Data libraries, making technology accessible without extensive changes.	The broad application landscape complicates the development of plug-ins for all necessary software, potentially slowing adoption.
Plug-ins via API	Provides flexibility by avoiding top-down enforcement, allowing systems to evolve based on stakeholder needs.	Misaligned incentives may hinder the development and maintenance of plug-ins, as no single actor holds clear responsibility or sufficient stake.

Table 11: Evaluation of Updated Technical Solutions for Interoperability

7.2 Enterprise architecture

This section will come up with an enterprise architecture that incorporates some of the design options from the earlier section. The enterprise architecture will be made from the viewpoint of a project owner. This translates the business processes, to the application layer and eventually the technical layer. This should give an overview of how these processes can be translated into technical structures.

7.2.1 From strategy to actions

Figure 8 illustrates how the project owner's key drivers and objectives translate into actionable strategies and resource allocation. Forming such long-term strategies can help address long-term problems and creating clearer pathways to innovation (Lavikka et al., 2018). The industry's main drivers—rising workloads, a shrinking workforce, and increasing application complexity—make improving productivity and consistency critical goals. Productivity must rise to maintain efficiency, achieved through automation, knowledge sharing, and collaboration. Consistency, essential for managing the complex information landscape, can be enhanced via standardized formats, processes, and protocols.

Strategic outcomes, aligned with these goals, include increased automation, enhanced training, tool integration, and process alignment. Automation reduces manual tasks, improving productivity. Training equips workers to handle complexity, while tool and process integration simplifies workflows and fosters collaboration. These outcomes rely on implementing standards, developing ontologies, and adopting linked data. Standards ensure uniformity, ontologies structure complex data relationships for automation and linked data enhances tool interoperability.

Collaboration with partners supports training and aligns processes, addressing consistency challenges. A clear digital strategy underpins these efforts, providing focus and ensuring stakeholder alignment. Key enablers include explicit communication to align stakeholders, integrated tools for seamless workflows, collaborative platforms for real-time knowledge sharing, and management support to drive initiatives. Bottom-up innovation complements these efforts by ensuring practical, worker-driven solutions.

Existing resources, such as ontologies, industry standards, linked data technology, and organizational knowledge, provide a strong foundation for these efforts. Cross-boundary communication further fosters collaboration and knowledge sharing. Together, these factors enable the industry to achieve higher productivity, better training, and greater consistency across projects.

7.2.2 Roadmap

Figure 9 illustrates the five phases organizations can progress through in their digitization. The starting point is a document-based system for data storage and exchange. This is the most basic level, still common in some companies, and involves a high degree of manual processing. The first step towards modernization is the creation of ontologies, which help define and standardize the terms and concepts being used. This ensures clear communication between partners and makes sure more information is reusable. Ideally, these ontologies are stored in databases and align with industry standards, promoting consistency and interoperability across the sector.

The next phase involves storing these ontologies in a knowledge graph instead of a relational database to create a more interconnected and semantically rich dataset. This linked data allows for greater reusability, enabling connections between data sets and enhancing machine readability. Moving further along, a middleware that can import linked data and has ETL (Extract, Transform, Load) tools—to integrate these ontologies with other software tools that do not support linked data imports. In the final phase, middleware becomes obsolete as industry-wide software tools are designed to directly support linked data, enabling better interconnection between applications without the need for additional integration layers.

7.2.3 Layered view

Figure 10 presents an overview of how linked data and ontologies are integrated into the information environment of a project owner, particularly concerning object data model requirements. This implementation is organized into three interconnected layers: the business layer, the application layer, and the technology layer. The application layer (blue) enables the functions of the business layer (yellow), while the technology layer (green) underpins and supports the application layer.

Business layer

The "project owner" block involves three key stakeholders, which correspond to the roles outlined in Figure 4. Both the asset management and project management teams need to align their ontologies to ensure that the

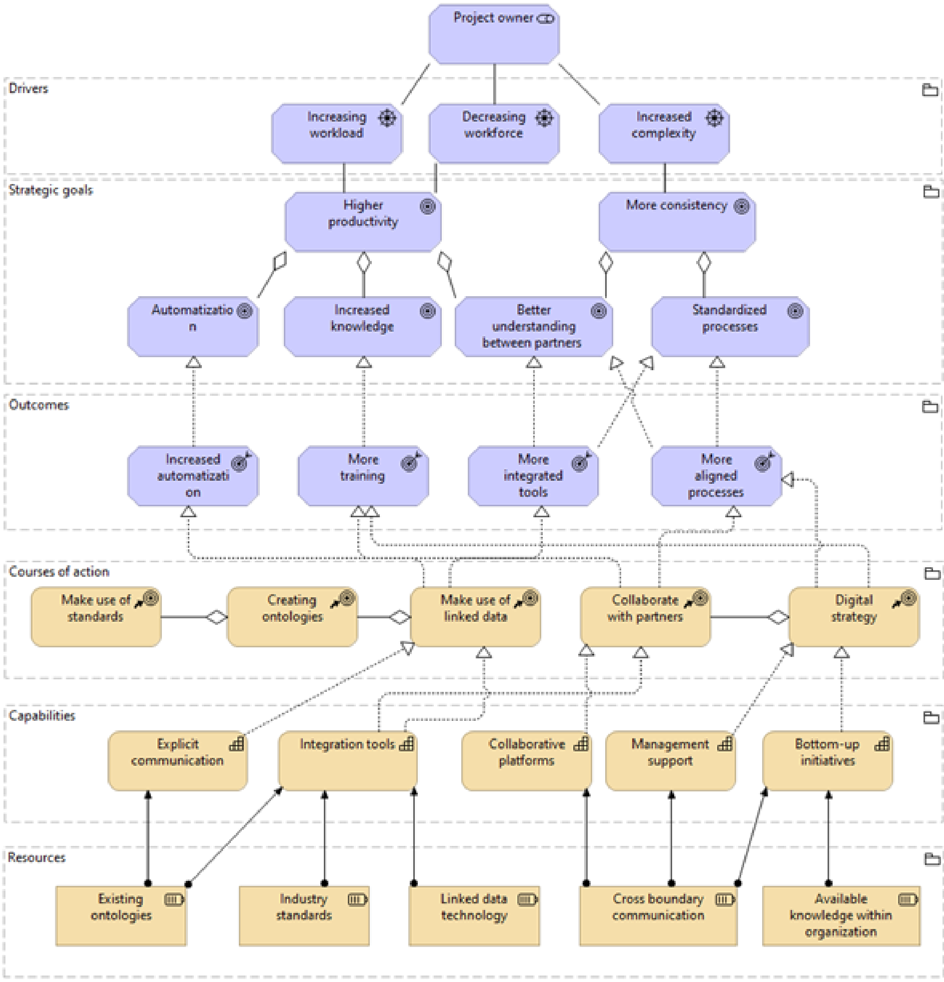


Figure 8: The flow from drivers at the top to resources at the bottom

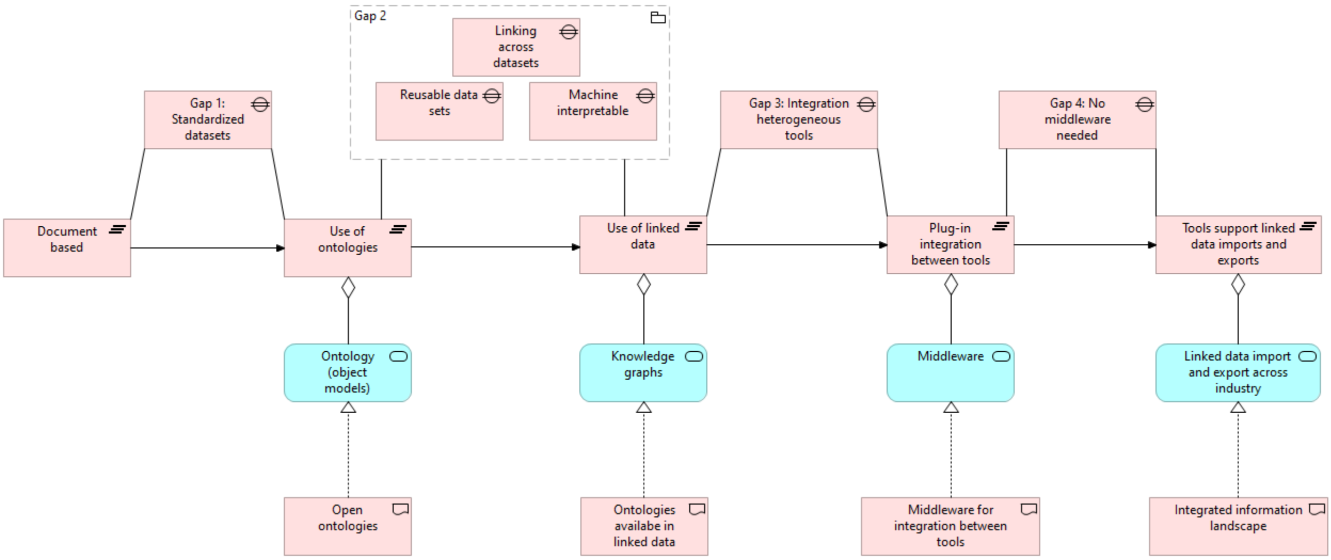


Figure 9: Roadmap that identifies four different levels of data integration.

information from the contractor can be incorporated into the asset management data model. The architect or engineers are responsible for developing the data model and defining the requirements. While these roles and their organizational affiliations may vary between projects, the underlying processes remain consistent, though coordination can be more challenging when these roles are spread across different organizations.

To establish ontologies, an object model must first be created, and this has to be connected to a reference ontology. This model does not yet contain instance data but instead defines objects at a conceptual level. The best practice is to base this model on widely used industry standards. Once the object model is finalized, it can be published to allow access by other parties.

The project owner is also responsible for preparing the Exchange Information Requirements (EIR) document. This document outlines the required data to be exchanged, the data formats, communication protocols, and the responsibilities for managing the data. This document then can be accessed by contractors, such that they can comply with these rules. This addresses several Functional Requirements, such as data accessibility and availability (T.3), interoperability through contractual frameworks (NT.3), and support for inter-organizational collaboration (NT.2). However, defining such a document in advance can be challenging, as it is difficult to anticipate all potential issues and differences in interpretation. This was one of the main findings of section 4.

Therefore, it is essential to incorporate lessons learned from previous projects and gather feedback from partners. These learning sessions can be integrated into collaboration agreements and internal business processes, promoting continuous improvement in managing data exchange and communication.

Outside of the project owner's block, collaboration with the contractor primarily involves establishing a contract through a tender process and exchanging data once the project begins. To facilitate data integration between the two parties, this architecture utilizes middleware. From the project owner's business process, data is published via web protocols, making it accessible and queryable by other stakeholders or machines.

However, many applications lack native import capabilities for linked data, necessitating the use of middleware. The middleware transforms the data into the required format and loads the data model into the appropriate software application. This process can also work in reverse, allowing contractors to extract information and send it back to the project owner.

The scope of this process excludes how contractors handle information internally. This workflow aligns with the fourth phase of the roadmap, though the final phase is currently unattainable and beyond the influence of individual project owners and thus left out of the architecture.

Application layer

The application layer consists of two key components that support business processes: the ETL (Extract, Transform, Load) middleware and the data storage. The data storage utilizes knowledge graphs, which rely on semantic web technologies and typically store information in triples using the RDF vocabulary, though other storage methods exist. By leveraging the properties of a knowledge graph, it becomes possible to establish links between the object model and the corresponding requirements, enabling machines to interpret these relationships. The data is eventually published via web protocols, from which it is extracted by the ETL.

Since these protocols use a universal language, ETL development can be relatively straightforward. However, the challenge arises when the ETL must target specific applications and interface with their APIs, which can vary widely. A transformation process is required when querying the necessary information, involving both semantic interpretation and format conversion. While the semantic interpretation between different models may need to be assisted by manual work, automation is possible if both sides make their data fully explicit. Alignment of models through standardizing and op ontologies improves this process. For successful machine-to-machine communication, the use of web protocols is essential.

The format transformation, however, can usually be automated. Still, for each application and communication protocol, a new integration protocol may need to be established. Once this transformation is complete, the middleware utilizes the target application's import function to deliver the necessary information. The technical details of this data provision will be covered in the following subsection.

Technical layer

The technical layer serves as the backbone of the architecture, providing essential support to both the middleware and application layers through a variety of services, nodes, and functions. This layer plays a critical role in ensuring efficient data storage, retrieval, and communication among the various components involved in the project.

At the heart of this layer is the database service, which is linked to the data storage application that utilizes a knowledge graph database. This service manages and stores data, allowing for clear organization of information and easy manipulation. By leveraging the capabilities of the knowledge graph, the database service enables a more meaningful representation of the data, facilitating better insights and data relationships.

Complementing the database service is the linked data web service, which acts as a bridge between the data storage application and the middleware application. This web service provides web-based access to the linked data, allowing stakeholders to query and retrieve information seamlessly. This can be done via platforms developed specially for managing data in a linked data format. An example of such a service is Laces. By enabling this interaction, the linked data web service ensures that all relevant parties have access to the necessary data when required.

Essential to the middleware's function is the query service, which is responsible for facilitating queries to the knowledge graph using the SPARQL query language. This service allows users and applications to extract specific data from the knowledge graph based, by using the semantic structure that the knowledge graph offers.

Another aspect of the technical layer is the export and import service. This service connects the middleware with proprietary software tools, enabling data exchange between different systems. The export function allows the middleware to send transformed data to proprietary software tools, while the import function retrieves data from these systems for further processing, ensuring a flow of information in both directions.

The architecture nodes play a crucial role in supporting these services. The linked data platform, which consists of a knowledge graph database, provides the technology function for the storage and retrieval of data. A cloud server serves as the infrastructure that supports both the linked data platform and the knowledge graph webpage, ensuring scalability and accessibility.

Access to the knowledge graph database is facilitated by SPARQL, which realizes the query service. This server acts as a gateway for executing queries against the knowledge graph, enabling the retrieval of structured data. Additionally, another cloud server is dedicated to hosting the databases of the proprietary software tools. However, these databases are outside of the scope of the design, as they are managed by software vendors. These tools themselves incorporate services for data import and export, comprising various nodes, including databases with their specific structures and formats, as well as APIs that enable the import function. These APIs are essential for the output of the middleware, as they determine how the connection with the proprietary tools can be made.

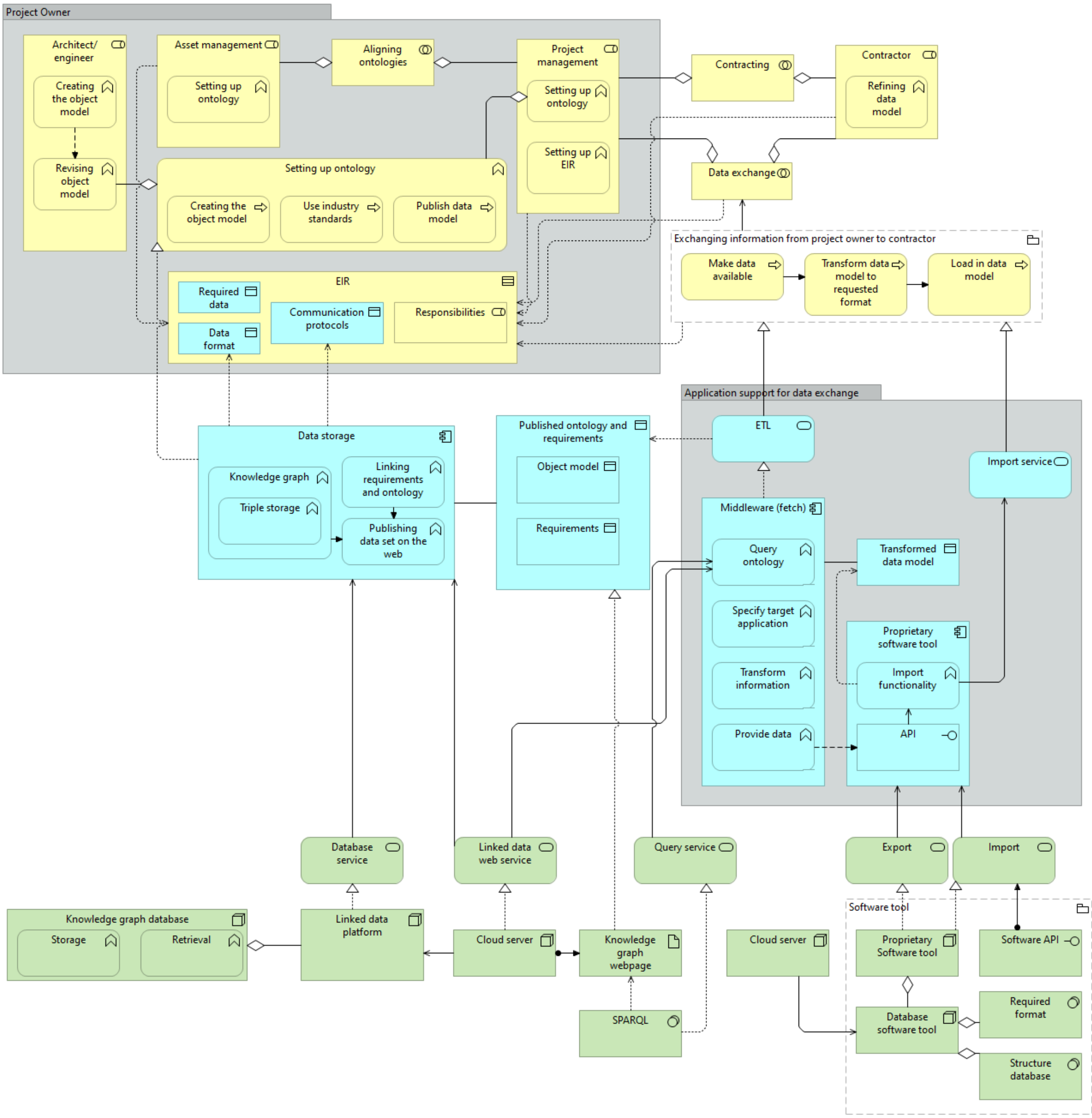


Figure 10: Enterprise architecture

7.3 Middleware architecture

This subsection expands on the middleware, which uses an extract, load, and transformation process to make a connection between linked data sources and target applications.

7.3.1 Data flow diagram

This section outlines the design and data flow within the middleware architecture, which enhances interoperability by ensuring better data exchange between linked data libraries and proprietary software tools within the AEC industry. The middleware system processes requirements data by extracting, transforming, validating, and distributing it, ensuring compatibility with diverse target applications. The following steps provide a detailed breakdown of each phase in the middleware's data flow, illustrating how data is standardized and prepared for secure access by external systems and users.

1. Data Sources and Initial Querying
The data flow begins with three primary sources: Requirements Data, Ontology Data, and Metadata Sources. This middleware design has a scope of importing published linked data libraries, such that the extraction part of the middleware can be generalized. This way it ensures that project owners can benefit from the use of linked data. This also has advantages for its scalability.

All three sources pass through the SPARQL Query Engine in the initial phase. This engine performs structured queries to retrieve the required information from each source, filtering only the necessary data for further processing. By using SPARQL endpoints, the system ensures data extraction and retrieves data in a format that can be mapped and transformed to meet the target application's requirements.

2. Transformation procedures

2.1 Schema mapping
Once the data is retrieved, it flows into the function Schema Mapping, where it undergoes initial schema mapping. This module translates the extracted data into a preliminary structure that aligns with the general requirements for the target application.

2.2 Data Transformation and Format Conversion.
Following ontology alignment, data enters the Data Transformation stage. Here, the data is converted from its native RDF format into the specific format required by target applications, such as JSON, XML, or another proprietary format. The structure was already transformed in the schema mapping process of 2.1. This step is essential for achieving compatibility with systems that cannot process RDF directly, which is the essential goal of the middleware.

2.3 Validate transformed data.
Upon completing the transformation processes, the data flows to the validation process. This stage performs rigorous validation to ensure data quality, verifying that the data meets defined schema requirements and is free from inconsistencies.

If any discrepancies or errors are detected, the data flows into the Error Handling and Logging module, where issues are recorded and flagged for reprocessing or manual review. This process helps maintain data integrity, ensuring that only accurate and consistent data is provided to the target applications.

3. Connecting to target application

3.1 Use interface of target application
Validated data then flows to the API Gateway, which manages external access and distribution to the target applications. The type of interface will depend on the target application that is chosen. The target application can be chosen by the project owner. In contrast to the extraction process, this is harder to generalize for multiple applications. Thus developing and maintaining the algorithms that have to ensure the transformation and interface alignment are managed individually. However, implementations of scripts that make use of RestAPI, SOAP-based API, or other interfaces, can serve as a base code for other implementations.

3.2 Authentication
Ensures that only authorized users or systems can access specific datasets. Rate Limiting and Load Balancing: Controls data request rates to optimize performance and prevent system overload. Format Conversion: Delivers data in the requested format (e.g., JSON or XML) for each external application, supporting compatibility with diverse systems. Through this managed API access, external systems like project management applications and compliance reporting tools can securely request and retrieve the transformed data as needed.

4.0 Data import to the target application
Finally, through the API Gateway, data can flow to target applications that have implementation within the middleware. Eventually, this should ensure that linked data can be leveraged by project owners and improve their communication with partners external or internal. By providing consistent, standardized data, the middleware enhances data interoperability, streamlines requirements management, and promotes more effective collaboration across the industry.

7.3.2 Bottlenecks

Several bottlenecks may affect the overall performance, scalability, and efficiency of the design. The first thing to note is, that if the input dataset grows, the SPARQL queries can become large and may be less efficient. For scalability issues, the SPARQL queries should be optimized such that the workload is still doable. Another

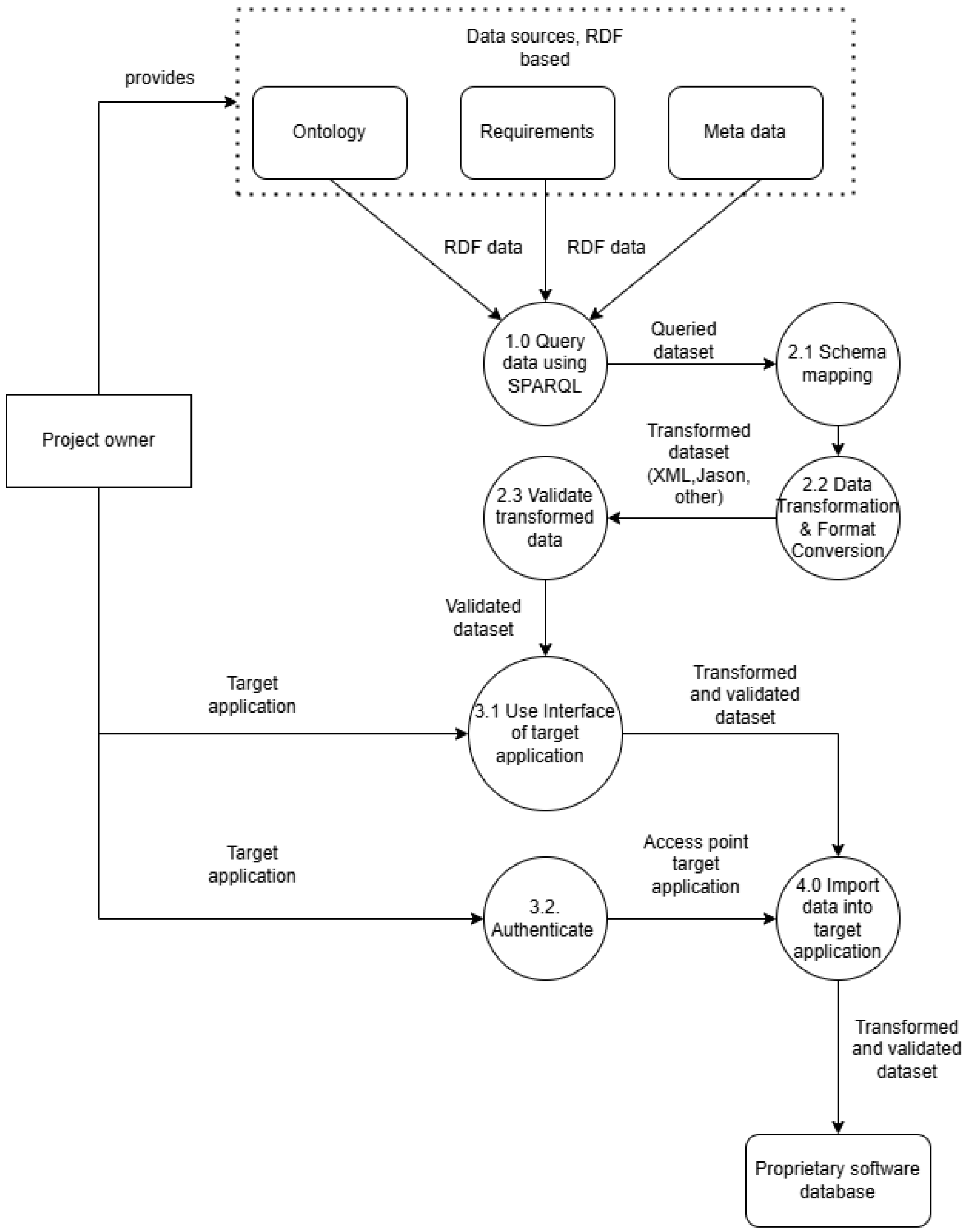


Figure 11: Data flow diagram of the middleware processes

solution could be to improve the structure of the ontology itself, such that queries from SPARQL become more efficient.

Following the extraction phase, the data transformation process poses additional risks of becoming a bottleneck. The conversion of data from an RDF format to other required formats, such as JSON or XML, introduces extra computational workload that could slow down the system, especially with larger datasets. Furthermore, the complexity of schema mapping from diverse sources may lead to processing delays if schemas are poorly defined or vary significantly. This can also lead to inconsistencies in the dataset. This is also a part of the process where human interpretation could be required if transformations lead to errors.

There are several options for how the linked data can be loaded into the target application. It is possible to give a new structure to the target application's dataset, such that new columns and rows are created within the target application. Another way is to load the transformed dataset into the existing structure of the target application. This creates more mapping problems but is a more lightweight option than the structured option. Another option could be to only link the existing structure in the target application to the ontology that has to be loaded in. This ensures the link between the two datasets, but it can be used immediately.

The validation process also warrants careful consideration, as it can be time-consuming and may lead to delays in data flow. The need for validation to ensure data quality can be a bottleneck, particularly if validation rules are complex or if errors are frequently encountered. These validation checks have to be done based on the ontology that was loaded into the middleware and the data that was loaded into a target application. In instances where discrepancies are detected, the subsequent logging and reprocessing of data can consume considerable time and resources, further slowing down the overall system.

Lastly, the API connection serves as a point of access for external systems, presenting its challenges. As a potential single point of failure, any downtime or performance issues within the API connection could disrupt access to the middleware and delay the flow of data to target applications. As the middleware architecture scales, ensuring the design and efficient management of these components will be essential to mitigate bottlenecks and maintain the effectiveness of the middleware. By proactively testing and validating the middleware before implementation, the performance of the middleware can be evaluated and improved iteratively.

8 Evaluation

The following chapter evaluates the proposed design by discussing the design on theoretical grounds and by evaluating it through the requirements outlined in Chapter 6. This evaluation examines in which ways the design meets the functional and non-functional requirements for interoperability within requirements management systems in the AEC industry. Additionally, the chapter considers the limitations of the design, links back to earlier identified problems in Chapters 3, 4, and 5, and discusses the overall goal and scope of the design.

8.1 Discussion of design

This chapter explored a range of design options aimed at increasing interoperability in requirements management within the AEC industry. These options included technical solutions, such as linked data standards, middleware architectures, and semantic web technologies, as well as non-technical solutions addressing organizational alignment, coalition forming of stakeholders, and strategic long-term planning.

8.1.1 Preferred Design Options and Justification

The selected options for this design integrate middleware architecture with linked data standards, prioritizing technical routes that enable better data flow and standardization across diverse systems. The middleware solution stands out because it enhances the benefit for project owners when using linked data technology, without the need for linked data compatibility for applications used in the industry. Linked data further enhances this setup by ensuring that data shared between systems remains consistent and is universally machine-interpretable (Pauwels et al., 2017). This technical combination was preferred due to its flexibility and ability to support a connection between existing software applications, achieving a more sustainable and vendor-agnostic approach to interoperability.

On the non-technical side, the design options were mostly construed from insights found in the scientific literature and interviews with relevant stakeholders. These elements address barriers to successful implementation, such as resistance to change or misalignment between short-term project goals and long-term digital transformation objectives (Turk, 2020; Jallow, Demian, Baldwin, & Anumba, 2010; Linderoth et al., 2018). One of the key contributions of this research is combining technical solutions with non-technical issues and different solution directions.

8.1.2 Interactions between Solutions

The technical and non-technical design options complement each other in important ways. Middleware architecture provides a technical opportunity or interoperability while using the technology of linked data and ontologies to ensure data consistency and interpretable data in data exchanges. Meanwhile, the non-technical strategies support the deployment and acceptance of these technical solutions by establishing a framework for collaboration and mutual benefit among stakeholders. As was found in the related scientific work and interviews, technical functionalities will not solve the problems on their own.

For example, the adoption of middleware is greatly facilitated by a non-technical focus on standardized collaboration, as organizational buy-in for such solutions depends on clear, shared benefits among stakeholders. Similarly, linked data technology, while essential for technical interoperability, is most effective when organizations recognize their value and commit to consistent, cross-functional data management and governance.

8.1.3 Interaction between Technical and Non-Technical Dimensions

The success of interoperability solutions within the AEC industry relies on the combined effectiveness of both technical and non-technical dimensions. Technical solutions require organizational and social processes for implementation, while non-technical strategies depend on technical tools to address the industry's challenges. This observation was found in multiple studies (Lavikka et al., 2018; Jacobsson et al., 2017; Shehzad et al., 2021) A key challenge is a common-action problem, which is connected to high entry barriers for the adoption of technology and network effects that can stimulate or impede the adoption of new technologies (Blind et al., 2016). This can lead to suboptimal outcomes even when adequate technology is available. Effective interoperability, therefore, depends on feedback loops where technical and non-technical solutions can reinforce or weaken each other. Positive feedback loops arise when collaborative efforts support the adoption of new tools, while negative feedback loops can emerge if misalignment and miscommunication hinder adoption. The AEC sector's conservative landscape and path dependence—the reliance on established workflows and tools—further complicate this interplay. While established practices offer stability, they also create resistance to change, especially when new technical solutions disrupt familiar workflows. This resistance is often intensified by a technical knowledge gap, where stakeholders lack the expertise to leverage advanced tools, highlighting the need for support and change management. The design proposed in this research addresses these challenges through a middleware architecture that enables data exchange across proprietary systems, supported by linked data and ontologies that ensure data remains interpretable and reusable across platforms. This technical setup is coupled with coalition-building by allowing stakeholders to collaboratively manage and access requirements information, streamlining data-sharing processes. On the non-technical side, the design includes clear contractual agreements and data-sharing protocols that align technical goals with stakeholders' organizational priorities. By formalizing roles and data exchange expectations in contracts, the design reinforces data interoperability both technically and institutionally, helping prevent misunderstandings and promoting a positive feedback loop. As stakeholders experience smoother, more reliable data exchange, their commitment to collaboration and the design standards strengthens. Finally, the design anticipates potential negative feedback, such as resistance from stakeholders with varying technical capabilities, by offering flexible adoption pathways. Stakeholders are encouraged to leverage linked data and ontologies through integration options via the middleware modules, allowing basic data sharing without overwhelming technical requirements. The design also emphasizes the importance of ongoing training programs and structured collaboration efforts to support long-term success. By recognizing that guidance and gradual improvement are essential, the design provides a foundation that helps stakeholders adopt the technical components at a realistic pace. This adaptive approach strengthens the positive feedback loop, promoting sustainable interoperability across the AEC industry.

8.2 Scope of the design

The framework designed focuses on providing a high-level framework that highlights the interplay between technical and non-technical aspects of interoperability, aiming to give organizations a clear understanding of the broader solutions and benefits. Consequently, certain specifics fall outside the scope of this design. For instance, while middleware integration is central to the solution, the actual implementation details—such as deployment, configuration, and testing of middleware solutions—are not covered here. Similarly, measurable metrics like scalability, system performance, and data throughput, which are critical for real-world implementation, are beyond this design's focus.

The design also does not delve into the technical infrastructure, such as the specifics of data storage solutions, server types, or configurations required to support these solutions. Additionally, the formation of new ontologies, improvements to existing ones, or methods for linking ontologies within the industry are excluded. Instead, the design provides a strategic overview that organizations can use to understand how technical and non-technical elements work together to address interoperability challenges. This approach enables firms to understand and use the potential of high-level solutions.

8.3 Evaluation by stakeholder feedback

This subsection evaluates the proposed framework based on feedback from stakeholders within the AEC industry. The feedback session was designed to gather expert insights on the framework's practical applicability, strengths, and areas for improvement. By engaging with industry practitioners, this evaluation aims to validate the framework's relevance and identify potential enhancements, ensuring it meets both technical and organizational requirements.

8.3.1 Methodology

Participant recruitment and rationale

The feedback sessions for evaluating the proposed socio-technical framework were conducted with four participants recruited through my professional network at Semmtech, where I completed my internship. These participants, including three colleagues from Semmtech and a researcher from TNO, were chosen for their expertise in linked data, model-based data management, and their active engagement with interoperability challenges within the AEC industry. The researcher from TNO brings additional perspective from his involvement with the Nationaal Groeifonds initiative, aimed at advancing model-based workflows in the industry. Their collective expertise provided a well-rounded critique that spanned academic insights and practical considerations.

The recruitment process focused on ensuring participants were directly engaged with the design and application of linked data and semantic web technologies. This expertise was crucial for aligning the feedback with the technical and non-technical requirements of the thesis framework.

Feedback session design

The feedback session, conducted via a one-hour Zoom meeting, began with a structured presentation of the framework of approximately ten minutes. I provided an overview of the thesis objectives, problem context, and proposed solutions, including the middleware architecture and strategies for coalition building. This presentation can be found in Appendix D. Key points for feedback were outlined to guide the discussion, but the session was designed to remain open-ended, encouraging participants to explore additional relevant topics. This format facilitated both structured evaluation and spontaneous insights, fostering a collaborative and interactive environment. The feedback session took one hour to complete.

To analyze the stakeholder feedback, the meeting was recorded and subsequently transcribed to ensure accurate capture of all discussions. Each point raised during the session was notated and contextualized within the framework of this research. This approach allowed for a systematic examination of the feedback, relating it directly to the research objectives and design components. However, this methodology has its limitations. The feedback session was structured around a short presentation of the design, which may have led to some design details being overlooked or certain points not being addressed due to time constraints. This limitation underscores the importance of complementary evaluation methods in future research.

8.3.2 Analysis

The analysis of the feedback is presented below, categorized into key themes that align with the thesis's requirements and research focus.

Coalition building and adoption strategies

Participants emphasized the importance of coalition building as a cornerstone for implementing the proposed framework. The feedback highlighted the need for a phased approach to forming coalitions, beginning with smaller, aligned groups of stakeholders. Sharing success stories emerged as a critical strategy for reducing perceived risks and encouraging broader participation. While the coalition-building strategy aligns with the thesis's non-technical requirements, the feedback suggests refining it by incorporating actionable steps for initiating and sustaining collaboration.

This aligns with the thesis's requirement to address organizational challenges and foster stakeholder alignment. By demonstrating early successes and creating structured collaboration pathways, the framework can effectively lower barriers to adoption.

Middleware Architecture and Technical Feasibility

The middleware architecture, designed to facilitate interoperability using linked data, was scrutinized for its technical feasibility and scope. Participants pointed out the need for detailed research into transformations and mappings between semantics and ontologies. The potential for integrating the middleware with existing standards, such as Building Smart and OSLC protocols, was discussed as a means of enhancing its usability.

Feedback also highlighted the challenge of achieving a network effect, with participants stressing the importance of creating a critical mass of stakeholders to ensure widespread adoption. Suggestions included narrowing the scope to focus on linked data within consistent technology environments, which could simplify implementation and increase its practicality.

These insights directly tie into the thesis's technical requirements, such as ensuring scalability and adaptability. Enhancing the middleware's design with detailed mappings and leveraging existing standards can strengthen its alignment with these requirements.

Data Transformation and Semantic Challenges

Participants recognized the potential of using a common ontology and semantic web applications within a federated system to address challenges in data transformation. However, they stressed the complexity of mapping diverse data models and ensuring semantic consistency across applications. Suggestions included exploring formal modeling approaches, such as notion theory, to simplify middleware and reduce integration complexity.

This feedback reinforces the thesis's emphasis on standardization as a key requirement for interoperability. Incorporating formalized modeling techniques can enhance the framework's ability to manage semantic diversity effectively.

Barriers to Adoption

Feedback consistently pointed to the need for lowering barriers to adoption, particularly for smaller industry players with limited resources. The discussion highlighted the importance of intuitive interfaces, simplified connectors for applications, and demonstrating the framework's value through practical implementations.

Addressing these barriers aligns with the thesis's goal of creating a user-friendly and accessible solution. Incorporating participant suggestions into the design can ensure the framework meets the practical needs of a diverse range of stakeholders.

8.3.3 Conclusion

The feedback sessions provided insights into the framework's strengths and areas for improvement. Key takeaways include the importance of coalition building and creating more actionable solutions to form these coalitions. The need for detailed technical mappings, and strategies to reduce adoption barriers. Table 12 gives a summary of the themes identified during the feedback session. Section 8.4 incorporates this analysis to evaluate the design concerning the non-functional requirements.

Table 12: Summary of Feedback Themes

Theme	Key Insights and Suggestions
Coalition Building and Adoption Strategies	Participants emphasized the importance of a phased approach to coalition building, starting with smaller, aligned groups. Sharing success stories was highlighted as a strategy to reduce perceived risks and encourage broader participation. Actionable steps for initiating and sustaining collaboration are needed.
Middleware Architecture and Technical Feasibility	The middleware requires detailed research into transformations and mappings between semantics and ontologies. Integration with existing standards (e.g., Building Smart, OSLC protocols) was suggested to enhance usability. Achieving a network effect and focusing on consistent technology environments could simplify implementation.
Data Transformation and Semantic Challenges	The complexity of mapping diverse data models and ensuring semantic consistency across applications was stressed. Suggestions included exploring formal modeling approaches, such as notion theory, to simplify middleware and enhance semantic diversity management.
Barriers to Adoption	Lowering adoption barriers for smaller industry players was a key focus. Recommendations included developing intuitive interfaces, simplifying connectors, and demonstrating the framework's value through practical implementations to ensure broader stakeholder engagement.

8.3.4 Fulfillment of Requirements

Building on the insights gathered during the feedback session (Section 8.3), this section evaluates the design's ability to meet the technical and non-technical functional requirements. The feedback session highlighted several critical areas for refinement, including the need for enhanced semantic mappings, improved adoption strategies, and clearer coalition-building processes. These perspectives are integrated into the analysis below.

Technical Functional Requirements		
Requirement	**Fulfillment**	**Reasoning**
T.1. The system should provide mechanisms for storing and structuring project requirements in a way that data is reusable.	+	The use of ontologies supports data reusability, enabling structured and consistent data management. However, feedback identified the need for more detailed research on semantic mappings and transformations to ensure domain-specific applicability.
T.2 The system must provide access to project data in a way that allows multiple stakeholders to view and interact with it.	+/-	Linked data publishing improves accessibility by offering a universal, platform-independent method for accessing data. Feedback emphasized simplifying connectors and enhancing user interfaces to make the system more accessible for smaller organizations and contractors.
T.3 The system should ensure compatibility with multiple vendors.	+	The middleware architecture enhances compatibility across vendors by bridging diverse systems. However, achieving full vendor neutrality depends on widespread adoption and network effects, as noted during the feedback session. Standardizing interfaces and promoting adoption among early stakeholders will be key to improving this requirement.
Non-Technical Functional Requirements		
NT.1 The system must ensure that data ownership is clearly defined between all parties involved.	+	The feedback reaffirmed the importance of embedding ownership definitions into contractual agreements. While the design aligns with this requirement, practical implementation may face challenges due to varying stakeholder priorities. Flexible contract templates, as suggested in the feedback, could address these concerns.
NT.2. The system should encourage collaboration between different organizations.	-	The design's focus on coalition building and standardized workflows strongly supports collaboration. Feedback highlighted the need for phased coalition-building strategies, starting with smaller aligned groups and sharing success stories to foster trust and adoption. This particular issue isn't addressed in detail within the design.
NT.3. The system must ensure that contractual agreements include the processes for data management and exchange.	+	The design incorporates contractual frameworks to enforce data exchange processes. However, feedback highlighted the rigidity of some contracts as a barrier. Incorporating iterative and adaptive clauses, as suggested during the feedback session, would enhance this requirement.
NT.4. The system should support knowledge sharing between stakeholders.	+/-	Centralized data repositories and standardized formats facilitate knowledge sharing. The feedback emphasized supplementing these with workshops, collaborative forums, and accessible "lessons learned" repositories to encourage active engagement and improve knowledge-sharing practices.

Table 13: Evaluation of Design Fulfillment against Functional Requirements

9 Discussion

9.1 Main Findings

The findings of this research demonstrate that achieving effective interoperability in the AEC industry requires a balanced integration of technical and non-technical solutions. While ontology development and semantic web technologies provide a robust foundation for technical interoperability (Pauwels et al., 2017), real-world implementation demands complementary organizational measures to address stakeholder alignment and collaboration challenges (Grilo & Jardim-Gonçalves, 2010; Niknam & Karshenas, 2017). This research highlights how a socio-technical approach, combining technical innovations with governance, coalition-building, and standardized workflows, can drive long-term adoption and impact.

The evaluation reinforced the importance of coalition-building, emphasizing a phased approach that starts with smaller aligned groups and uses success stories to reduce perceived risks. This refines the framework's strategy, making it more actionable for fostering alignment and overcoming organizational inertia. Additionally, the feedback identified gaps in semantic transformations and mappings, underlining the need for further research to enhance the middleware's ability to support heterogeneous systems effectively.

These insights, combined with the study's findings on the potential of ontology-driven data models for enabling data reuse and integration, highlight the value of integrating semantic web technologies with structured organizational strategies. The proposed framework demonstrates how socio-technical integration can address both technical and organizational challenges, offering a promising pathway for advancing interoperability in the AEC sector.

9.2 Contribution to the Field

This research contributes to the field of information management by proposing a socio-technical framework tailored to the interoperability challenges in the AEC industry. While situated in the specific context of the AEC sector, the framework's technical components, such as data standardization and ontology-based models, have broader applicability to other industries facing similar challenges. The research demonstrates how these technical innovations can be embedded within industry-specific organizational contexts, offering insights into the coordination of stakeholders, the management of diverse data systems, and the implementation of shared data standards.

Additionally, the study highlights the interplay between technical solutions and organizational strategies, emphasizing the importance of coalition-building, governance, and knowledge-sharing in achieving sustainable interoperability. By integrating design science research principles with a practical use case, the research provides a model for developing and applying information management strategies in complex, multi-stakeholder environments. This approach offers both theoretical contributions and practical tools for organizations seeking to enhance productivity and innovation.

9.3 Limitations

While this research presents a framework for improving interoperability, it has inherent limitations for generalizations into contexts of other industries. AEC-specific factors, such as the common use of BIM standards, the mapping of stakeholders such as contractors and project owners, and conservative industry, informed the design choices and may not directly apply to industries with different stakeholder structures or technical requirements. For instance, industries with other regulatory bodies, different role divisions, or different legacy systems may find some aspects of the framework less applicable or may need to adapt coalition-building efforts to be translatable to alternative organizational dynamics and standards.

Second, the lack of real-world implementation is a significant limitation. Without pilot projects or practical deployments, the framework's effectiveness remains untested in dynamic and heterogeneous environments. Such implementations could reveal unforeseen challenges, such as integration bottlenecks, stakeholder resistance, or variations in adoption outcomes across different organizational settings.

Additionally, the lack of a real-world implementation of the proposed framework limits the ability to fully evaluate its effectiveness. Practical deployment could give new unforeseen technical challenges and integration bottlenecks, especially in heterogeneous environments where systems and processes differ significantly across stakeholders. Also, the wide variety of contractor and project owner firms could give different outcomes. The participant pool in this research was also limited, potentially excluding perspectives from key stakeholders such as software vendors and regulatory bodies, whose input could further refine the design for broader applicability. Finally, the success of this framework relies heavily on stakeholder commitment to shared standards and active governance. Evaluation of the success is a long-term project and can also rely on factors that are outside of this design. Thus a large cohort of projects should be evaluated to determine the factors that are influential on the outcomes.

Another key limitation of this research is the lack of a detailed roadmap for coalition-building, which is essential for fostering collaboration and standardization in the AEC industry. While the phased approach provides general guidance, it does not specify actionable steps for engaging stakeholders, resolving conflicts, or sustaining long-term collaboration. This gap could hinder the framework's ability to achieve widespread adoption, highlighting the need for future research into structured coalition-building strategies tailored to the sector.

This research does not delve into the low-level technical specifics of implementation, which leaves certain aspects of the design unexplained. In particular, the study does not address the detailed management of datasets within ontologies, neither does it provide a design for making these datasets accessible as linked data. While the relevant technologies are discussed, their concrete implementation is beyond the scope of this work. Although there are existing industry applications that perform some of these functions, the primary aim of this research is not to design such a platform, but rather to highlight its broader implications within the field.

9.4 Future Research Areas

Future research should prioritize pilot projects to evaluate the proposed framework in real-world AEC contexts. These implementations could focus on both the entire design and specific components, such as the middleware architecture or coalition-building strategies, to assess their effectiveness and identify key success factors. Empirical studies of this nature could also help refine the framework by highlighting practical limitations and opportunities for improvement.

A specific study on coalition-building strategies in industries with similar fragmentation challenges could provide actionable insights for stakeholders. Such research would explore the dynamics of stakeholder alignment, governance structures, and the role of regulatory bodies in fostering collaboration. This would address a critical gap identified in the current study and offer a more robust foundation for the framework's non-technical components.

Further exploration of semantic transformations and mappings is also necessary. Advancing technologies like AI and machine learning could be investigated for their potential to automate the creation of semantic links between datasets, reducing the labor-intensive aspects of ontology integration. Research into more advanced ETL mechanisms could expand the framework's applicability to a wider range of software applications, enhancing scalability and impact.

Finally, governance frameworks to support long-term coalition-building remain an important area of study. Expanding the range of stakeholder engagement to include regulatory bodies, smaller subcontractors, and software developers would enrich the understanding of interoperability needs and inform the development of more universally applicable solutions.

10 Conclusion

This study aimed to address the interoperability challenges in the AEC industry through a socio-technical framework integrating both technical solutions, such as ontology-based data models and linked data, with non-technical strategies like coalition-building and governance. This was done by answering the main research question: *How can a socio-technical framework for application interoperability, aimed at improving model-based exchange, be designed to address both technical and non-technical challenges in the AEC domain?* The findings highlight that achieving effective interoperability requires a balanced approach, where technical innovations are complemented by organizational measures.

The framework's design specifically incorporates a middleware architecture to facilitate data exchange across different software applications. Ontology-driven data models enable the structuring and reuse of information, while linked data technologies ensure accessibility and compatibility. On the non-technical side, the design emphasizes the importance of coalition-building and standardized workflows to align stakeholder practices and foster long-term collaboration. The evaluation process revealed that the coalition-building strategy while promising, needed a phased approach starting with smaller, aligned groups to foster trust and reduce perceived risks. Stakeholders highlighted the importance of using success stories to demonstrate early wins and encourage broader participation. Additionally, the evaluation underscored the need for more detailed semantic mappings within the middleware architecture to enhance its practicality in handling diverse data systems. These insights provided refinement points, ensuring the framework addresses both the technical feasibility and organizational alignment necessary for effective interoperability. These are interesting follow-up points for future research.

This research contributes significantly to both the practical field and academic discourse on interoperability. The practical contribution lies in providing a structured framework that stakeholders in the AEC industry can adopt to improve data management and collaboration. The academic contribution extends to demonstrating how socio-technical integration can address complex industry challenges. These issues can to a certain extent also be extrapolated to the more general field of information management.

While the proposed framework addresses key aspects of interoperability, the study also has several limitations. The evaluation revealed a need for more detailed research into semantic transformations and mappings, which are crucial for ensuring data consistency across heterogeneous systems. Additionally, the absence of a real-world implementation means that the framework's effectiveness remains untested in dynamic environments, potentially limiting its immediate applicability. Finally, a broader population for the interview section could give a more balanced view of the problem context. Moreover, the lack of a structured roadmap for coalition-building was identified as a critical gap. Although the phased approach provides a general strategy, a more detailed plan outlining specific steps for engaging stakeholders and sustaining collaboration is necessary for practical implementation.

Future research should prioritize pilot projects to test the framework in real-world settings. Such studies would provide empirical data on the framework's practical limitations and its impact on interoperability in the AEC sector. The evaluation also highlighted the need for further research into semantic transformations and coalition-building strategies, which could enhance the framework's scalability and adoption across different organizational contexts. Additionally, exploring governance frameworks to support long-term coalition-building and developing more advanced ETL mechanisms could expand the framework's applicability and effectiveness in managing complex data ecosystems.

The proposed framework offers an approach to tackling application interoperability in the AEC industry, mixing technical with organizational strategies. The evaluation not only confirmed the framework's relevance but also provided numerous points for refinement and future research opportunities. As the AEC industry evolves, this framework can serve as a guiding structure for enhancing collaboration, standardization, and data exchange, contributing to improved application interoperability and a broader implementation of digital innovations.

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A Interview participants

nr.	Role	Expertise	Type of projects	Years of experience
1	**Expert/ project owner**. Product owner. Consultant on project owner side at semmtech and TenneT.	Mostly technical. Linked data expertise.	Primarly converting project data into centralized libraries, transforming it into linked data formats, setting up ontologies.	5
2	**Expert**. Systems engineer, consultant at Arcadis	Technical and process focused.	Mostly model-based projects.	10
3	**Contractor**. Consultant on contractor side for semmtech and DuraVermeer	Technical. Information management	Improving communication between partners and internal communication.	3
4	**Project owner**. Information manager at TenneT	Technical and organizational	Setting up a central digital environment for requirements management	10+
5	**Contractor**. BIM manager and information manager at DuraVermeer	Technical and organizational	Integrating different software tools in projects. Managing information exchange with project owners	5+

Table 14: Interview participants

B Interview Questionnaire

B.0.1 Role 1: Project owners

nr.	Question	Theme reference
1.	How would you describe your role within your company?	
2.	Did you have other roles in the past concerning requirements management?	
3.	What is your expertise in this area?	
4.	How many years of experience do you have?	
5.	How do you come up with the project requirements?	Non-technical 1, 2 & 3
6.	How do you store and manage your project requirements?	Technical 2 & 3, Non-technical 2
7.	How are the requirements updated throughout the system?	Technical 2 & 3, Non-technical 2
8.	Are the requirements reusable for other projects?	Technical 2 & 3, Non-technical 1
9.	Who are the stakeholders you share your requirements with?	Non-technical 1, 3
9.1.	How are the responsibilities and tasks divided?	Non-technical 1 & 3
10.	What kind of agreements do you have with your partners concerning digital communication and their respective digital system?	Non-technical 1, 2 & 3
11.	Is interoperability high on the agenda of your organization?	Non-technical 1 & 2
12.	What are long-term strategies within your company to requirements management or digitization as a whole?	Non-technical 1, 2, 3 & 4
13.	What are your expectations for the coming years with respect to your data management?	Non-technical 1, 2, 3 & 4

Table 15: Questionnaire for project owners

B.0.2 Role 2: Contractors

nr.	Question	Theme reference
1.	How would you describe your role within your company?	
2.	Did you have other roles in the past concerning information management?	
3.	What is your expertise in this area?	
4.	How many years of experience do you have?	
5.	How do you come up with the project requirements/where do the requirements come from?	Technical 1
6.	How do you store and manage your project requirements?	Technical 2, 3 & 4
7.	Is it important for your company to be able to reuse data within the software tools you and your partners use?	Non-technical 1 & 2
7.1.	How is data currently reused?	Technical 2, 3 & 4 Non-technical 2
8.	Is it important for your company to be able to exchange data within and between the software tools you and your partners use?	Non-technical 1, 2 &3
8.1.	How is this coordinated from your company's viewpoint?	Non-technical 3 & 4
9.	Is it important for your organization/company to be able to have traceable data within the software tools you and your partners use?	Non-technical 4
10.	What are the most important factors for choosing a requirements management application?	Technical 1 Non-technical 1 & 2
11.	Is there a top-level strategy for managing your digital systems, or more specifically your requirements data	Non-technical 2 & 3
12.	Do you have a view on how your requirements management will look like in the future?	Non-technical 1, 2, 3 & 4

Table 16: Questionnaire for contractors

B.0.3 Role 3: Experts

nr.	Question	Theme reference
1.	How would you describe your role within your company?	
2.	Did you have other roles in the past concerning information management?	
3.	What is your expertise in this area?	
4.	How many years of experience do you have?	
5.	With what kind of clients/organizations do you work on requirements management?	Non-technical 1
6.	What are common strategies seen with your clients to overcome interoperability issues	Non-Technical 3
7.	What are common hurdles on a technical level that clients have to overcome?	Technical 1
8.	What are common hurdles on an organizational level that clients have to overcome?	Non-technical 2
9.	What are the main functionalities clients want from their requirements data system?	Technical 2, 3 & 4
10.	What would be technical functionalities you would say are essential for more interoperable systems?	Technical 2, 3 & 4
11.	What would be process functionalities you would say are essential for more interoperable systems?	Non-technical 3
12.	Could you give examples on the following questions?	
12.1.	How are requirements updated?	Technical 2, 3 & 4
12.2.	How are requirements exchanged?	Technical 2, 3 & 4
12.3.	How are requirements reused?	Technical 2, 3 & 4

Table 17: Questionnaire for experts

C Standards and Vocabularies

Standard	Owner	Related standards	Short description
ISO 19650	ISO	EIR	Agreements on how and why information is exchanged
	buildingSMART	IFC	Format for information exchange on building information for different disciplines throughout the building environment
	ISO	CDE	Project information in a common environment such that all different actors can access the data
	BuildingSMART	IDS	Defines the exchange requirements in a machine interpretable way, based on the IFC format
NEN2660	NEN	NEN2660-series	Standard for conceptual models within the building environment. Also has guidelines for exchange of data.
Linked Data standards	W3C	RDF	The language for the web that uses a triple format to represent relations between objects in a knowledge graph
	W3C	RDFS	Builds on top of RDF, used to describe taxonomies: specialization hierarchies
	W3C	SPARQL	The query language for RDF knowledge graphs
	W3C	OWL	Expanded version of RDF schemas that has more functions for defining relations between objects and has an internal logic
	W3C	SHACL	Similar to OWL, but expresses constraints on classes such that it is prescribed how individuals should be modelled.

Table 18: Standards, vocabularies and their respective owners

C.0.1 ISO 19650 standards

The ISO 19650 is an international standard for managing information management over the whole lifecycle of built asset using BIM. This also includes the **Exchange Information Requirements** (EIR) and a **Common Data environment** (CDE).

The **EIR** is a specification on what requirements the information has to fulfill. Questions such as: Why is there information exchange? How will the information be exchanged?Which format will be used during the information exchange? How is it ensured that other or future information complies?

All these questions come down to an agreed format for collaboration and a unified language for the project models. Within BIM, the **IFC** language is the standard for describing objects in a conceptual model. However, one can also use data models based on other standards or unstandardized models. How information is exchanged depends on the format, which technology is used to make the information available. The last questions delves more into agreements that are made between stakeholders outside of the technical dimensions. One could think of regular meetings, scheduling audits for compliance or

Another important standard that was developed by the buildingSMART group is the **Information Delivery Standard** (IDS). This defines how information of object models should be delivered, based on the IFC format. There could be other ways to deliver information, outside of the IFC format, or by using multiple models and connect them via semantic web technology (Pauwels, 2014). This is further explained in the next subsection.

One of the essential standards for the building environment in the Netherlands is the **NEN2660** standard, that gives a blueprint how object within the building environment must be described. It also offers guidelines on standardization for data exchange within the built environment

C.0.2 Semantic web

Linked data is a foundational concept within the Semantic Web, designed to enable data to be interconnected and easily accessible across the web. It relies on the use of Uniform Resource Identifiers (URIs) to uniquely identify resources, such as people, places, or concepts, ensuring that each entity is represented by a distinct reference. These URIs are accessible via the HTTP protocol, allowing resources to be retrieved using standard web technologies. The data is typically represented in RDF (Resource Description Framework) or similar machine-readable formats like JSON-LD, which structures the information as triples consisting of a subject, predicate, and object. A key principle of linked data is that resources are not isolated but are interconnected through links, enabling data from different sources to be easily combined and queried. This interlinking facilitates the discovery and integration of related data, creating a more open and accessible web of information.

RDF

RDF is a standard language for structuing and exchanging information on the web. It makes use of RDF-triples, the triple concists of a subject, predicate and object. The predicate relates the object to the subject, in a standardized logical format. In this way, an RDF-graph is construed. Where the edges are the relationship description between the subject and object, which are the nodes. These objects and subjects are made availalbe through URI's, literals or blank nodes. This makes it possible to access the objects through the web.

RDFS

In addition to RDF, there are other important standards that build upon or complement the foundation of linked data. RDFS (RDF Schema) extends RDF by providing mechanisms to describe the structure and relationships of data more semantically. It allows the definition of taxonomies or specialization hierarchies, where resources can be classified under broader categories or specialized terms. RDFS introduces basic constructs such as classes and properties that can be used to create logical structures for data, facilitating better data organization and interpretation within a knowledge graph. By adding these structural elements, RDFS enhances the ability to model complex relationships between resources.

SPARQL

SPARQL is a language that can query through RDF-graphs. Thus it uses the triple format described above and can find specific objects through search queries. This language uses the advantage of the knowledge graph, where objects are related to each other. Such that certain objeccan be found without the need for a unified description of a certain object (Pauwels, 2014).

OWL

The Web Ontology Language makes use of the same format as RDF schemas. However, OWL has a larger vocabulary to describe relations between objects in the graph. Also the OWL checks for internal logic of statements, such as an instant of an object can't be a class in itself. Within an RDF schema, you don't have limitations for describing relations.

Eventually, by using these standards, it becomes possible to describe and define objects and their relations in such a way that it is interpretable for machines and uses identifiers from the web. This ensures that data from one source can be linked to other data sources.

SHACL

SHACL (Shapes Constraint Language) is another standard that works alongside RDF and OWL to define the constraints on the data models in a more detailed way. While OWL focuses on the logical consistency of statements, SHACL allows users to prescribe how individual resources (or instances) should be modeled, offering a way to enforce specific shapes or structures on the data. SHACL is particularly useful for ensuring that data adheres to predefined rules and constraints, making it a valuable tool for validating the integrity of linked data. Together with RDF, RDFS, and OWL, SHACL provides a comprehensive set of tools for managing, querying, and validating the relationships and structures within a semantic web framework.