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Léon olde Scholtenhuis, Monica Pena Acosta,
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5th 4TU/14UAS Research Day on Digitalization of the Built Environment
Proceedings Volume 4

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Preface

The organizers of the 5th 4TU/14UAS Research Day on Digitalization of the Built Environment are pleased to present these proceedings. The Research Day took place at the University of Twente in Enschede on 16 April 2026, preceded by a pre-conference evening on 15 April. It brought together researchers, educators, practitioners and students working on the digital transformation of the built environment.

This fifth edition continued the collaboration between the 4 Technical Universities (4TU) and 14 Universities of Applied Sciences (14UAS), offering a shared platform for academic and practice-oriented research. The event focused on how digitalization can help address current and future challenges in the design, construction, operation and management of the built environment.

This volume includes 28 peer-reviewed contributions, selected and organized across seven thematic sessions: Demonstrations, Data Management, Parametric and Data driven Design, Process and Monitoring, Data Modelling, Scenarios and Simulation, and Data driven Prediction.

Together, the contributions reflect the growing role of digital methods, tools and data in research and practice. A recurring theme is the need for better data interoperability, reusable digital models and stronger links between research prototypes and real world implementation. The papers also show how digitalization can support more informed, efficient and adaptive ways of working across the built environment.

The organizers would like to thank all authors and presenters for sharing their work and insights. Special thanks are also due to the session organizers, reviewers, chairs and supporting institutions whose efforts made the Research Day and these proceedings possible.

We hope this volume will serve as a useful reference for ongoing collaboration between universities, universities of applied sciences and practice, and that it will inspire further research, education and innovation in the digitalization of the built environment.

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Table of Contents

Full Papers 1

Data Management

Exploring Data Spaces: Insights from the Eclipse Minimum Viable Data Space . . . 3
Krista van Zandwijk, Ekaterina Petrova, Rik Eshuis, Pieter Pauwels

Building Identifiers for Open Building Data and Long-Term Archival in the Netherlands 13
Britt van Hulst, Krista van Zandwijk, Ekaterina Petrova, Pieter Pauwels

A Two-Layer Framework for Digital Building Logbook Implementation as a Gateway in Federated Data Environments 16
Avinash Ramachandruni, Ravi Sharma, Ekaterina Petrova, Pieter Pauwels

Parametric and Data Driven Design

Automated Compliance Checking with SHACL-based Digital Building Regulations using GraphRAG 27
Alex Donkers, Ekaterina Petrova

Data Modelling

A comparative analysis of data requirements for Digital Building Logbooks and Building Renovation Passports in Europe 38
Daan Schlosser, Hiba Doi, Giorgio Agugiaro

Scenarios and Simulation

Development and verification of a method to evaluate energy grid effects of retrofit strategies at neighbourhood level 48
Quint Geerman, Twan Rovers

Extended Abstracts 60

Data Management

Automating IFC version control through geometry-aware comparison on building element level 62
Bahar Boroushaki, Arghavan Akbarieh, Pieter Pauwels

Parametric and Data Driven Design

Spatial Optimization of Subsurface Utilities: Case Study Amsterdam 66
Aleksandra Bratic, Léon Scholtenhuis, Farid Vahdatikhaki

Developing an Inventory-Responsive Matchmaking Framework for Reclaimed Component Integration in Architectural Design 69
Nikita Dhavale, Marc van den Berg, Torsten Schröder, Andreas Hartmann, Hans Voordijk

Process and Monitoring

AI for Value-Driven Bridge Renewal 73
Jasper Hofman, Hans Voordijk, Luca Vadacci, Giel Klanken

Retrieval-Augmented LLM Framework for Robust Automated Generation of HVAC Diagnostic Models 76
Chujie Lu

A Modular Digital Twin Architecture for Urban Flood Resilience 78
Özgün Balaban, Pieter Pauwels

Extracting Generalizable Robot World Models from BIM Models 81
Anish Sridharan, Koen de Vos, Pieter Pauwels, René van de Molengraft, André Borrmann, Elena Torta

Data Modelling

The Energy ADE 3.0: A CityGML Application Domain Extension for Urban Building Energy Modelling 85
Giorgio Agugiaro, Rushikesh Padsala

A glimpse of the CityGML Scenario Application Domain Extension 90
Frederick Auer, Camilo León-Sánchez, Giorgio Agugiaro

Ontology for Verified Test Trench Data in Underground Infrastructure Management . 97
Faith Tangara, Léon olde Scholtenhuis, Ramon ter Huurne

Scenarios and Simulation

Digital Platform 'Public Dialogues' as Enabler for Collaborative Climate Action in The Hague 103
Daniëlle Strydom, Rizal Sebastian, Lucas Mastenbroek, Roos Kollen, Jos van Leeuwen, Siavash Kazemzadeh, Kees Sommer

Simulation-based Evaluation of Tree Planting Strategies to Reduce Energy Demand of Buildings under 2050 Climate Conditions 106
Adhisye Rahmawati, Weixiao Gao, Camilo León-Sánchez, Giorgio Agugiaro

Comparative Study of Extreme Sustainable Energy Systems for the Netherlands in 2050 112
Ali Agha Zeeshan, Amir Hosein Babakhani, Berend Feldbrugge, Rima Mahmoud

Data Driven Prediction

Continuous Learning Digital Twin for Predictive Building Energy Management . . . 118
Joan Njoroge, Mila Koeva, Mahdi Farnaghi, Dessislava Petrova-Antonova, Mariya Pantusheva

Metamodel-based Temperature Sensitive Warm Mix Asphalt Compaction Modelling . 121
Qinshuo Shen, Faridaddin Vahdatikhaki, Seirgei Miller, André Doreé

Towards Human-Centred and Neuro-Symbolic AI-Based Digital Twins for Industrial Built Environments 124
Arghavan Akbarieh, Cem Ataman, Rui Jiang, Yavuz Eren, Elçin Sarı Öztürk, Lyssane Vermulst, Mirén Bravo Rivera, Jasper Ebus, Alper Sarıkan, Bige Tunçer

GreenVision: Classifying Green Roof Typologies from Aerial Imagery 127
Maarten Meijer, Joseph Alsahwi

Demonstrations and Posters 130

Demonstrations

PDF2GIS: from old blueprints to 3D city models 132
Gosia Wrzesińska, Jan-Mark Wams

Digital Twin For Improvement of The Sustainability of Neighbourhoods Through Scenario Planning 136
Rakibun Athid, Mila Koeva, Pirouz Nourian, Ulla-Britt Krämer and Margreet Schluter

Developing a Digital Twin for Watershed Restoration Scenario Analysis: A Case Study in Mujib Basin, Jordan 137
Nawwar Procheta, Mila Koeva, Rosa Aguilar, Mira Haddad

Early Warning System for Harmful Algae Bloom in Beautiful Indonesia (HABIBI) . . 138
Ishraque Bin Khalil, Philip Kramwinkel, Pleun Kuipers

Posters

Towards Human-informed Building System Resilience: Enhanced Whole-HVAC System FDD with Occupant Behavior 141
Martin Mosteiro-Romero, Nitant Upasani, Laure Itard

Author Index

Full Papers

Thematic session:

Data Management

Exploring Data Spaces: Insights from the Eclipse Minimum Viable Data Space

Krista van Zandwijk [1], Ekaterina Petrova[1], Rik Eshuis[2], Pieter Pauwels[1]

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Abstract

The Architecture, Engineering, Construction, and Operations (AECO) industry is hindered by fragmented lifecycle data and limited secure, interoperable data-sharing solutions. Decentralized data spaces offer a promising approach to enable sovereign, standardized, and trustworthy data retrieval across organizations. In doing so, data spaces have the potential to support the creation and continuous updating of Digital Product Passports (DPPs), thereby facilitating the transition toward a circular AECO industry. However, existing open-source data space initiatives, such as the Eclipse Minimum Viable Data Space (MVDS), remain technically complex and have not been adopted in AECO practices. This research conceptualizes the Eclipse MVDS to increase its accessibility and transparency for non-technical stakeholders. Use case, sequence, and entity-relationship diagrams are developed to analyse and understand the backend architecture, while a user-friendly frontend is designed to explore how the backend processes can be visualized to increase transparency for data space users. The results indicate that MVDS workflows may be difficult for non-technical users to understand and may be inefficient for simple data transactions. Nevertheless, when supported by an intuitive user interface, data spaces show strong potential to enable sovereign lifecycle data management within the AECO industry. However, to fully realize this potential, further research is required in industry-specific adaptation, usage policy templates and requirements, decentralized sovereign identity management, and semantic interoperability.

Keywords: Data Space, Eclipse Minimum Viable Data Space, Decentralization, AECO industry, Lifecycle Data Management

1. Introduction

The Architecture Engineering Construction and Operation (AECO) industry is hindered by fragmented inaccessible information and poor life-cycle data management (Yang et al., 2021). To address these challenges, recent literature points towards decentralized information systems that enable more secure, standardized, and sovereign data sharing across organizations while maintaining control and trust over access (Bucher et al., 2025). One emerging approach is the data space framework, which provides a standardized federated architecture for secure,

interoperable, and trustworthy data retrieval while preserving data sovereignty (International Data Space Association, 2024a). In the context of the AECO industry, the data space framework is expected to support the development of coordinated digital ecosystems to improve life-cycle data access and management and enable more transparent and circular practices within the AECO industry. For example, Çetin et al. (2026) argue that AECO data spaces could enable a coordinated, interoperable, and sovereign digital ecosystem aligned with European Union regulations, facilitating the integration of digital tools such as Digital Product Passports (DPPs) and Digital Building Logbooks (DBLs).

Instead of centralizing data, data spaces rely on certified connectors that act as gateways between data providers and their data sources and data consumers, enforcing usage policies that define who may access data, for what purpose, and under which conditions (Steinbuss et al., 2021). The International Data Space (IDS) Reference Architecture Model (RAM) 4[1] includes core components such as connectors for secure and standardized data retrieval, identity providers for trust and authentication, brokers for metadata discovery, and optional services such as vocabulary hubs, app stores, and a clearing house components to ensure interoperability, data processing, and accountability (International Data Space Association, 2024a). Data remains stored at the source and is exchanged directly between participants after identity verification and contract negotiation. By avoiding centralized storage and enabling fine-grained usage control, data spaces address fragmentation and trust issues, making them well suited for secure, scalable, and sovereign data sharing across complex, multi-stakeholder environments (Bader et al., 2020).

Within the AECO context, only a few studies have explored the adoption of data spaces. For instance, Cuno et al. (2019) proposed an urban data space model based on a German municipal case study, while Gil et al. (2024) developed a regulatory framework for digitizing building permit management using a building data space. Hagedorn et al. (2025) demonstrate how the Information Container for Linked Document Delivery (ICDD) can be integrated with the International Data Space Association (IDSA) data space framework and van Zandwijk et al. (2025) explored the design requirements for an AECO-specific data space user interface, emphasizing end-user needs and the unique characteristics of the industry. Despite these efforts and its potential, practical implementations of commercialized data spaces in AECO remain absent.

The European data space landscape is shaped by complementary initiatives building on the IDS RAM 4, and practical implementation is supported by projects like Gaia-X[2], FIWARE[3], and Eclipse Dataspace Components[4]. Gaia-X focuses on trust, interoperability, and compliance between organizations; FIWARE provides open-source tools for interoperable data platforms; and Eclipse Dataspace Components (EDC) offer building blocks for implementing federated data spaces. Recent analysis by Gabellini et al. (2025) shows that the IDSA RAM dominates European data space initiatives, used in approximately 64% of projects, while alternatives like Gaia-X (8.5%) and FIWARE (3.4%) are less common. At the implementation level, Eclipse Dataspace Components are the most widely adopted connector solution (approximately 20%), especially in open-source and federated architectures.

[1] https://github.com/International-Data-Spaces-Association/IDS-RAM_4_0
[2] https://gaia-x.eu/
[3] https://www.fiware.org/
[4] https://projects.eclipse.org/projects/technology.edc

To participate in a data space, AECO stakeholders must either deploy a compliant connector that enables their organization to join an existing data space or develop and launch a new data space themselves. Data space components must comply with IDSA's technical guidelines and can be implemented using open-source solutions such as the Eclipse Dataspace Components. The Eclipse foundation provides a Minimum Viable Dataspace (MVDS)[5] that demonstrates how two data space participants can use the Decentralized Claims Protocol (DCP) within Eclipse Dataspace Components (EDC) to exchange and verify credentials before initiating a Dataspace Protocol (DSP) message exchange (Eclipse Foundation, 2025). The MVDS is provided as open-source code with an installation guide, enabling users to deploy and run the system with minimal setup as a lightweight, core-component-based data space designed for experimentation, allowing stakeholders to explore workflows, requirements, and interactions without deploying a full data space stack.

However, the technical documentation and code complexity of the MVDS make it difficult for non-technical AECO stakeholders to understand and engage with the system, which may limit experimentation and adoption. This paper therefore aims to conceptualize the MVDS and its workflows to make its underlying technical code transparent and comprehensible for AECO stakeholders. To achieve this, the study first explains the MVDS code and its core components in Section 2. Section 3 then conceptualizes the system using use case, sequence, and entity–relationship diagrams. Building on this conceptualization, Section 4 presents a frontend prototype that demonstrates the key workflows through which data providers and consumers interact within the data space. Finally, Section 5 concludes the paper by highlighting the essential MVDS components and discussing implications for future research.

2. The Eclipse Minimum Viable Data Space

The Eclipse MVDS includes a demo of a data space setup between two organizations, which represents the provider and the consumer side as visualized in Figure 1. On the provider side, six components are deployed: one provider identity hub, two independently managed connectors, two connector-specific private catalog servers, and one shared catalog server. The catalog describes the data assets made available by a connector without storing or transferring the actual data. All connectors and catalog servers share the same digital identity via the provider's identity hub. Each connector manages its own assets and policies autonomously, while its individual catalog server is not exposed publicly. Instead, a shared catalog server

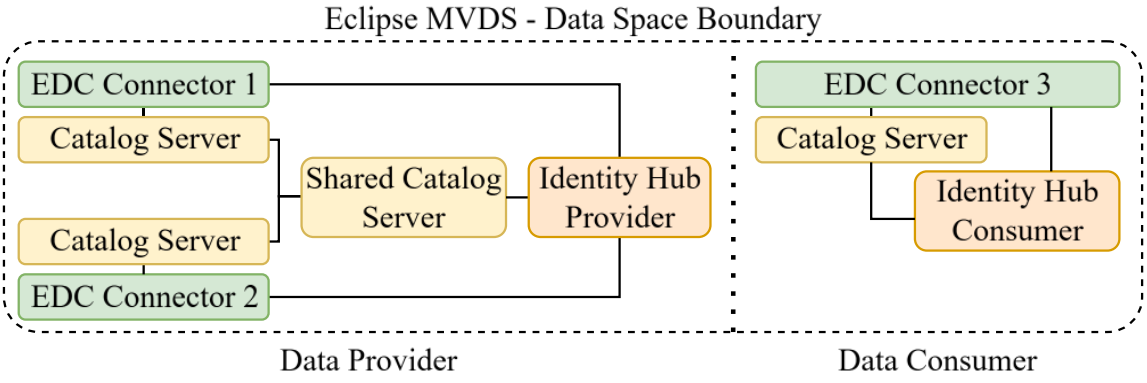


Figure 1. The set-up of the Eclipse Minimum Viable Data Space.

[5] https://github.com/eclipse-edc/MinimumViableDataspace?tab=readme-ov-file

distributes the connectors' catalog metadata to other verified participants within the data space, without hosting the actual data itself. The information provided through this shared catalog is accessible only to participants who have been explicitly authorized by the data provider, in accordance with the access policies associated with the shared catalog. On the consumer side, the setup consists of a consumer connector and a consumer identity hub. The consumer connector queries the provider's shared catalog server for asset discovery, and once an asset is selected, contract negotiation and data transfer occur directly between the consumer connector and the respective provider connector, with authentication and verification established through the participants' identity hubs.

Participant identifiers are implemented using decentralized identifiers (DIDs). These DIDs uniquely identify credential holders, reference their public key material, and expose important technical endpoint information, such as credential service endpoints. Access control in the data space is enforced through a combination of policies and verifiable credentials. Each participant must present a membership credential in every request, demonstrating that they are a verified member of the data space. This is evaluated against the relevant access policy, which defines who is authorized to access the shared catalog metadata. The participant's permitted processing actions are governed by a usage policy, which is linked to a data processor credential. This ensures that even authorized participants can only perform actions and access data in ways explicitly allowed by the data provider. For this demo, the participant identities and credentials are pre-created and seeded directly into the participants' identity hubs. This means that they are generated beforehand and manually inserted into each credential store rather than being issued dynamically. In a real-world dataspace, however, verifiable credentials would need to be issued by a trusted and verified authority during the onboarding process to ensure trusted governance and compliance. This simplification is one of the reasons why the Eclipse MVDS setup is not intended to serve as a production-ready foundation for a real commercial working dataspace, but rather as a technical demonstration of dataspace architecture and workflow.

3. MVDS Conceptualization

This section translates the technical backend implementation into a structured conceptual model using use case, sequence and entity relationship diagrams. Because of space limitations, only the most relevant diagrams could be included in this paper. The complete set of diagrams as well as the front-end's code are available in the GitHub repository[6].

3.1 Use Cases

Three core use cases structure the operation of the Eclipse MVDS. The first use case concerns data provisioning. A data provider makes resources available within the data space by creating structured data offers, including associated access and usage policies. These offers are first stored and managed on the data provider's internal catalog server, and if the provider intends to grant access to authorized data consumers, they are also published through the shared catalog server. To do this, the data provider should create a normal asset that is linked to the shared catalog server. This normal asset acts as a representation of the original asset without revealing sensitive or detailed information, allowing authorized participants to discover and request

[6] https://github.com/KristavanZandwijk/MVDS

access while preserving confidentiality. The second use case involves data discovery. A data consumer interacts via their connector with the shared catalog server to explore available data offers. Through this registry, data consumers can identify relevant datasets and obtain the necessary information to initiate further interaction. The third use case focuses on data negotiation and exchange. Once a relevant data offer is identified, the data consumer selects the asset from the shared catalog server and initiates a contract negotiation with the corresponding provider connector. The consumer presents the required Verifiable Credentials to satisfy the provider's access policies. Once the contract, including the usage policies, is agreed upon, the asset transfer is executed through the provider's connector, with the consumer presenting credentials again as required.

3.2 Sequence Diagrams

Next, sequence diagrams are used to visualize the order of actions between data space users, connectors, and catalogs. Within the MVDS, three main workflows can be distinguished: (1) data providers offering their data and setting their access and usage policies; (2) data consumers interacting with the catalogs via their connector to discover available data; and (3) providers and consumers negotiating a data agreement followed by the actual data retrieval.

To offer data within a data space, the data provider needs to interact with their data connector and shared catalog server following several steps. First, the data provider should create the data assed in their connector, specifying the metadata, a unique asset ID, and the data location, such as the HTTP endpoint. Next, the provider should create access policies that specify who can view the asset, as well as a usage policy that defines what authorized users can do with the data under which conditions. When these policies are formulated, the provider should link the asset to their access and usage policies using contract definitions, which govern contract negotiation and enforce policy compliance. This information is then stored in the connector's catalog. To share the asset with authorized data consumers, a normal asset should be created and registered to the shared catalog. Throughout this workflow, identity verification and trust establishment are continuously enforced. Participants' verifiable credentials, stored in their identity hubs, are checked by the connector against access and usage policies, allowing only authorized users to negotiate contracts or access assets and ensuring secure, policy-compliant interactions.

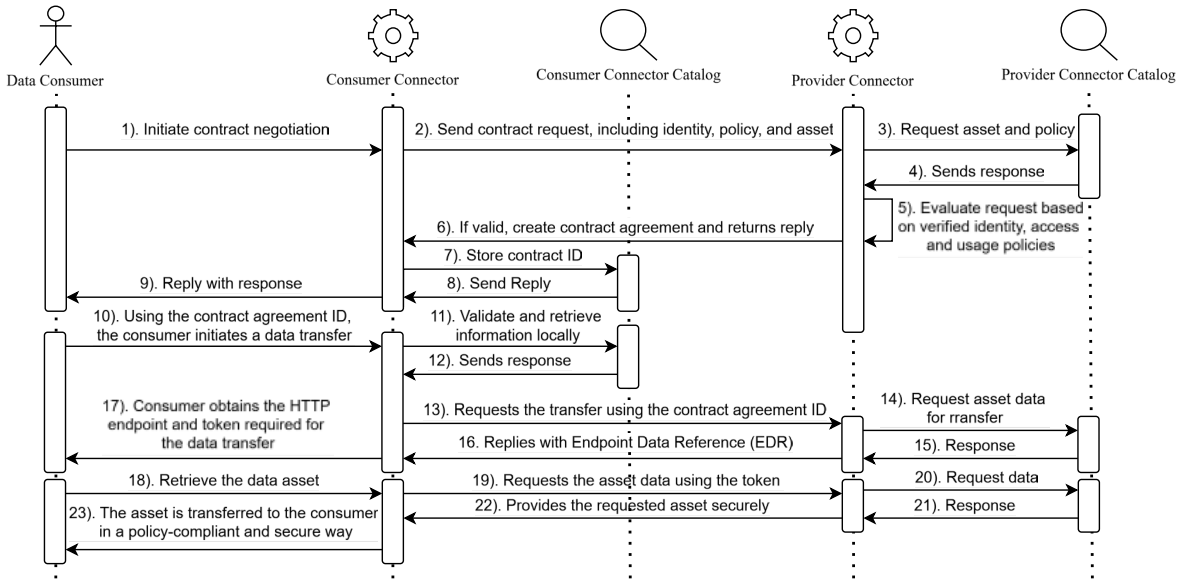


Figure 2. Sequence diagram showing data retrieval between data provider and consumer.

Next, data consumers use their connectors to interact with the data space, allowing them to explore shared catalogs and identify available data offerings. The data consumer first interacts with the data space by requesting their connector to retrieve available assets. This shows the data assets that are already available and where the data consumer already has access to. To explore assets, the consumer sends a catalog request to the shared catalog server, which responds with a root catalog containing references to specific connectors and their associated assets, along with relevant metadata. Based on this information, the data consumer can chose which data asset to obtain. When this decision is made, the consumer can query the cached catalogs to resolve individual assets and extract relevant metadata and the associated usage policies.

Finally, the data consumer and provider should reach a contract agreement, enabling the actual data retrieval, as illustrated in Figure 2. The consumer initiates a contract negotiation with the provider for a specific asset through their connector, which the provider evaluates against its access and usage policies. The negotiation is automatically accepted if it complies with the provider's predefined terms, and rejected otherwise. For now, this means that the negotiation process functions more as a contract validation mechanism rather than an interactive bilateral negotiation, which is something that should be explored in future research. Once an agreement is achieved, the consumer obtains a contract agreement ID, which is used to initiate the transfer process. The consumer then queries the transfer process to obtain the data access endpoint, including the data address and authorization token, and securely retrieves the asset from the provider's data endpoint.

3.3 Entity Relationship Diagrams

Figure 3 shows the entity relationship diagram showing the relationships between assets, catalogs, policies and connectors within the MVDS. Data is offered through assets and their corresponding normal assets each of which includes an asset ID, type, description, and URL

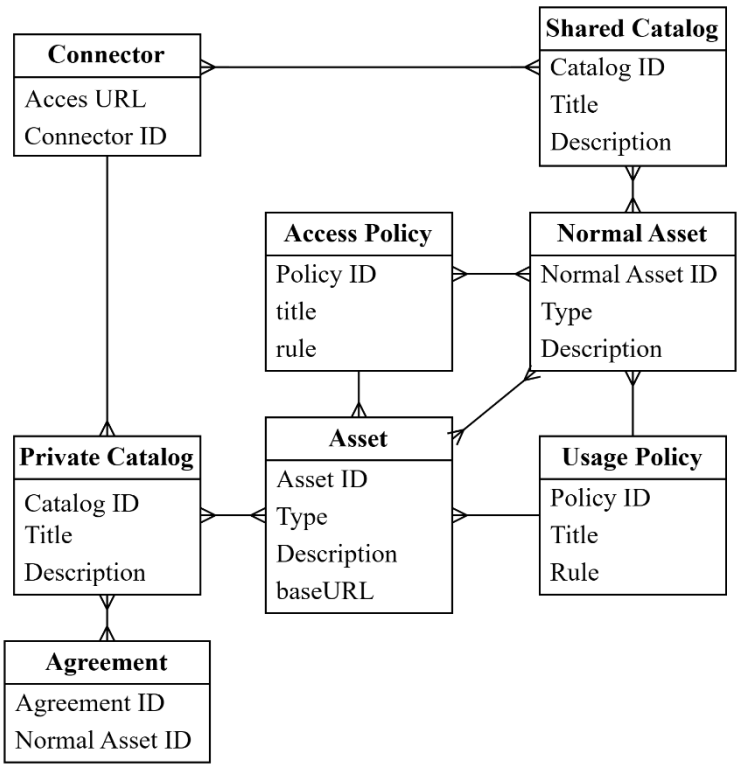


Figure 3. Entity-relationship diagram of a resource offer within the data space.

endpoint. Every asset, including normal assets, is associated with at least three core elements: an access policy, a usage policy, and a private or shared catalog. Assets in shared catalogs are available to all verified members of the data space who are covered by the access policy, whereas assets in private catalogs remain restricted to the data provider. Access policies specify which participants are authorized to access the catalog, while usage policies define the permitted actions on the associated data after authorized access, typically consisting of one or more enforceable rules. Although usage policies are beyond the scope of the present research, Steinbuss et al. (2021) provide an overview of the possibilities for usage policies within data spaces. When a data agreement is established, the associated asset receives an agreement ID that governs its usage and is stored in the related private catalog of the data consumer's connector. One of the main advantages of this system's structure is its scalability and reusability. The policies can be reused across multiple assets, and different data can be shared with distinct consumer groups via separate shared catalogs, each governed by its own access policy. These catalogs provide a structured and organized overview of the available data. While highly efficient for recurring transactions, this approach may be less optimal for one-off exchanges.

4. Front-end Development

The MVDS code includes only the backend and relies on JSON-based API calls executed in the Postman[7] environment to exchange data between connectors. For non-technical stakeholders, this can be perceived as a complex and non-transparent process, as the lack of a user-friendly interface makes it difficult to understand how data is shared and accessed. To address this, a mock-up front-end is developed, to explore how a visual representation of interactions and workflows, including data provisioning, discovering and retrieval, could improve transparency and comprehensibility of the data space for its participants.

Figure 4 shows a snippet of the data provider's interface, presenting an overview of the provider's assets and distinguishing between complete and incomplete data offers. Complete offers are highlighted in green, while incomplete ones appear in red; an asset is considered

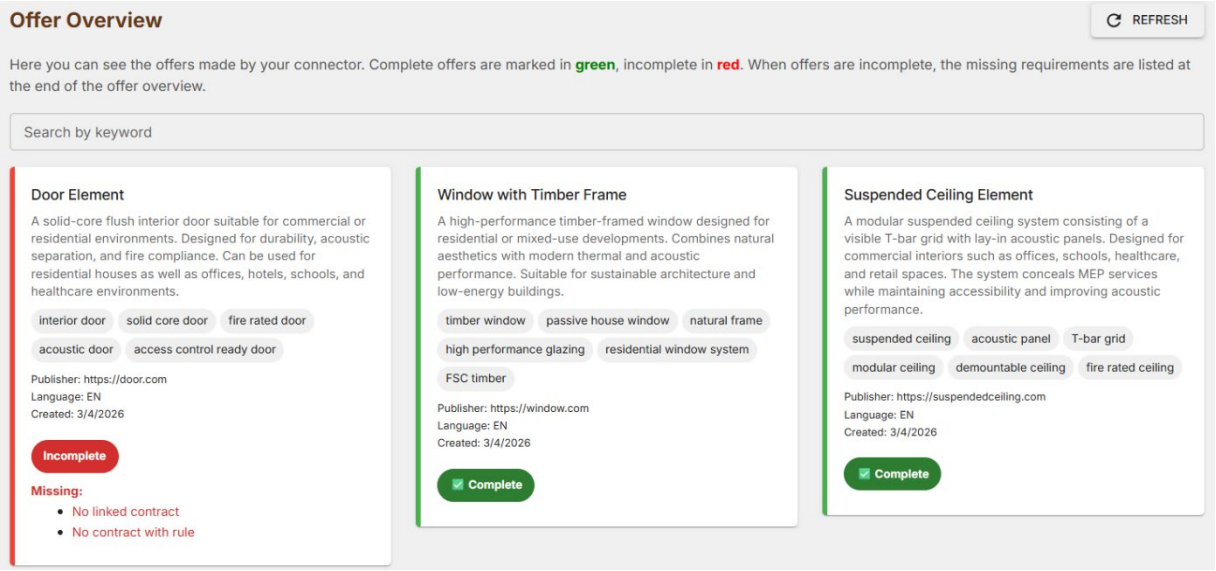


Figure 4. User-interface showing the complete and incomplete data offers of the data provider.

[7] https://www.postman.com/

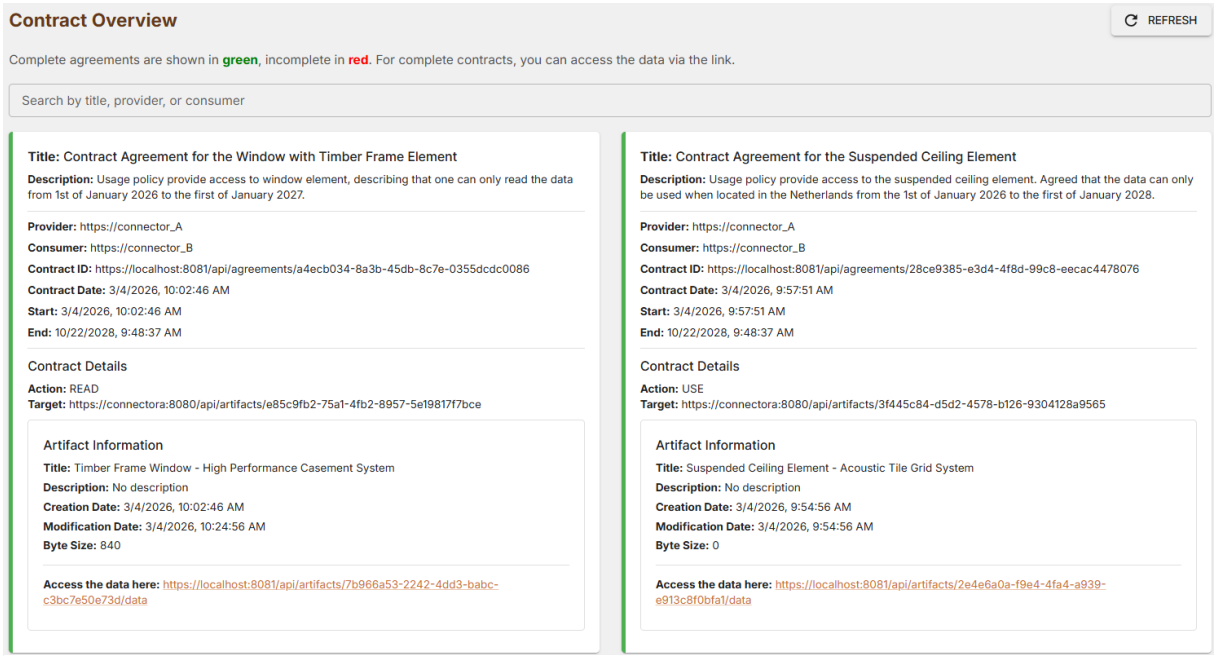


Figure 5. User-interface showing the data agreements of the data consumer.

complete when it includes at least one access and usage policy. This improved visibility allows providers to easily monitor and manage their contributions to the data space. Data consumers, can explore available catalogs and and the associated resource offers. They can negotiate access to data by submitting contract requests, and once these are accepted, the relevant offers are added to their personal overview, as shown in Figure 5. From this interface, consumers can easily access the data via the provided access URLs, making the entire process of discovering, negotiating, and retrieving data more transparent and user-friendly.

5. Conclusion

This research aims to conceptualize the Eclipse MVDS, making its code more understandable and transparent for non-technical AECO stakeholders. It identifies the requirements for a data offer and maps the workflow for providers and consumers to share and retrieve data. By adding a user-friendly interface, the study shows how the backend-only MVDS can become more transparent and accessible for non-technical users. This is important to illustrate the practical and added value of data spaces and to encourage adoption among industry actors. For the AECO industry, decentralized systems like the MVDS are particularly interesting because they have the potential to improve life-cycle data management and access while enhancing data sovereignty for data owners. By giving stakeholders control over who can access and use their data, these systems build trust and encourage data sharing, which Çetin et al. (2023) identify as crucial for advancing a circular and digitally integrated AECO industry.

The research resulted in several insights that are worth exploring in future research. First, future research should explore the range of open-source data space and connector implementations available online, analysing how they function and assessing their strengths and weaknesses in the context of the AECO industry. Steinbuss et al. (2025) identify 38 connectors of which 16 are open source. In addition, the International Data Space Association (2024b) maps nearly 150 global data space initiatives. Building on this, future work should investigate which open-source components are most suitable for the specific needs and

characteristics of the AECO industry, with particular attention to identifying which connector solutions are easy and user-friendly to implement and adopt for non-technical AECO stakeholders. Examples of open-source components for further exploration include the Ecplise Connector[8], the FIWARE Connector[9] and the TNO security Gateway Connector[10]. Although not included in this paper, an initial exploration of the IDSA MVDS has already been conducted within the present research and is available in the associated GitHub repository.

Next, the findings show the importance of several technical components that need to be explored in more detail. First, data usage policies play a critical role. In the current prototype, only a basic usage policy template is applied, which states that the data provider allows the data consumer to use the data without any additional constraints. Nevertheless, Steinbuss et al. (2021) define 21 different policy templates that distinguish data access and usage based on context, obligations, and modifications or filtering. For example, data usage could be restricted to specific locations, purposes, or time intervals. At present, it remains unclear which usage policies are most appropriate for data retrieval within the AECO industry and how compliance with these policies can be effectively enforced within a data space. Therefore, future research should focus on defining AECO-specific data sharing and usage policy templates that align with industry workflows and building lifecycle data management requirements.

In addition, the MVDS relies on identity providers and verifiable credentials to establish trust among participants. To participate in the data space, an individual or organization must first obtain a verified digital identity issued by a trusted authority. This identity can then be used to request and store verifiable credentials within an identity hub, enabling authenticated and policy-compliant interactions. The generation and governance of digital identities, however, are outside the scope of the MVDS and are therefore not includes in the demo code. Nevertheless, it remains unclear how fully decentralized, self-sovereign identities can be effectively integrated into data space identity hubs. Future research should therefore explore decentralization possibilities to move towards self-sovereign digital identities as explained in Yildiz et al. (2023).

While the Eclipse MVDS enables secure and standardized data retrieval between providers and consumers in accordance with IDSA specifications, the content of the exchanged data remains largely domain-specific. Although providers are required to document their data structures, this documentation alone does not guarantee semantic interoperability, which is a persistent challenge in the AECO industry and the data space domain. Ramachandruni et al. (2025) have already explored how a vocabulary hub can address interoperability, standardization, and legacy system integration challenges in the AECO industry, proposing the adoption of a domain-specific vocabulary hub. Building on this approach, future research should focus on achieving semantic and domain-level interoperability within data spaces.

Acknowledgements

This work is supported by the UPSCALE project, funded by the Dutch Organization for Scientific Research (NWO).

[8] https://github.com/eclipse-edc/Connector
[9] https://github.com/FIWARE/data-space-connector
[10] https://gitlab.com/tno-tsg/dataspace-protocol/tno-security-gateway

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Building Identifiers for Open Building Data and Long-Term Archival in the Netherlands

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Keywords: Persistent identification, Lifecycle information management, Open building data, Governance.

Introduction

Across the lifecycle of a building, spanning design, construction, operational, and end of life, substantial amounts of data are generated. This includes design documentation, building information models, regulatory submissions, and quality assurance information. Despite the importance, building data is frequently fragmented across stakeholders, stored in inconsistent formats, lost or inaccessible over time (Gómez-Gil et al., 2023). An underlying issue is the absence of a stable way to identify buildings throughout their lifecycle and link all relevant data to them. At the same time, the Netherlands is coping with several societal challenges, such as the housing shortage, climate change, and the energy transition. Consequently, the built environment increasingly depends on reliable, long-term building data to enable informed decision-making (Minnecré et al., 2023).

In the Netherlands, the exchange of building-related data with public authorities is governed by a range of regulatory frameworks, such as environmental permit applications[1], deed of division[2], and documentation required under the Quality Assurance for Building Act (Wkb) (Noordegraaf & van Haaften, 2024). This data is already collected by public authorities, yet there is no established specification detailing the methods or location for storing the information, nor the conditions governing its use (Noordegraaf & van Haaften, 2024). A central question in the development of a long-term building data archive concerns who should initiate, govern, and maintain such a system, and whether this responsibility should rest with public authorities (European Commission, 2020). Several Dutch initiatives already address the aspects of building data exchange and long-term information preservation, such as the Data System for Sustainable Utilities[3], My Government[4], Digital System for the Built Environment[5], and the Dutch National Archives[6] all addressing a part of the problem, but there is no integrated solution. Existing studies, such as Gómez-Gil et al. (2025); Hwang et al. (2025), primarily focus on use-case-specific challenges and opportunities, with a strong emphasis on building-level technical implementation, use-case-specific implementation, and policy analysis. Additionally, tools like ProjectWise and Planon provide mechanisms for structuring and managing building data, but they predominantly operate within project or organizational

[1] https://business.gov.nl/regulations/permit-for-building/
[2] https://www.kvk.nl/en/rules-and-laws/the-owners-association-a-deed-of-division-and-a-manager/
[3] https://www.datastelselverduurzamingutiliteit.nl/
[4] https://mijn.overheid.nl/
[5] https://www.digigo.nu/wat-is-dsgo/
[6] https://www.nationaalarchief.nl/

boundaries. Open standards like Industry Foundation Classes (IFC) support data interoperability across systems; however, they do not provide a mechanism to identify buildings across their lifecycle and ensure that data remains consistently linked to a building across stakeholders and over time. Creating a coherent, interoperable framework for multiple applications requires a central coordinating body, as diverging objectives, complex ownership structures, and overlapping responsibilities prevent it from emerging organically (Minnecré et al., 2023). Without such coordination, separate initiatives risk remaining fragmented, integration opportunities are missed, and individual solutions may lack robustness and long-term implementation (PBLQ, 2021). A hybrid system, in which the government defines standards, sets interoperability rules, and hosts core infrastructure, while private actors develop applications, value-added services, and innovate on top of the system, is therefore essential to ensure alignment and scalability (Tao et al., 2023).

Therefore, this research develops a prototype for long-term building data archival in the Netherlands using persistent building identifiers, defined as unique identifiers assigned to a building that remain consistent throughout its lifecycle and enable linking of data across time and stakeholders. The identifiers form the backbone for open yet controlled access to building data, while ensuring governance, access control, and traceability, and clarifying the role of a neutral public actor as coordinator. The remainder of the paper discusses the system engineering methodology, results, evaluations, and future research recommendations.

Method

The research applies a systems engineering approach to develop and evaluate a prototype for long-term building data archival, defining key requirements and functionalities, including authentication and authorization, access, viewing, and uploading building data. The prototype implements persistent building identifiers as the backbone for lifecycle-based data management. As shown in Figure 1, the prototype is developed using a Django Model-View-Template architecture, which separates data, application logic, and user interfaces while supporting role-based access for administrators, building managers, and general users (e.g., public authorities, researchers, and third parties). Users can explore buildings via an interactive 3D map, view and upload documents, and request access, while only the administrators control ID generation and data governance. All building data is versioned and automatically archived, ensuring a traceable and auditable record throughout the building lifecycle. Finally, the prototype was validated through scenario-based testing, focusing on the creation, linkage, authorization, and retrieval of documents across the lifecycle.

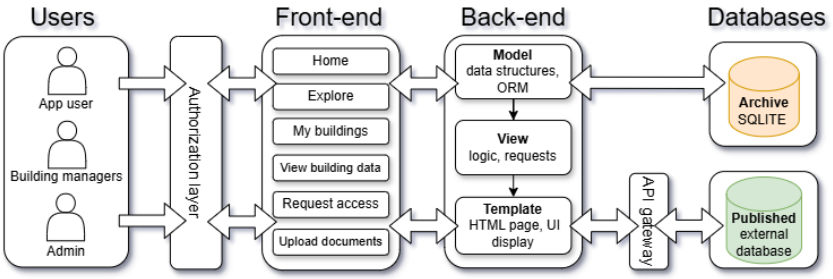


Figure 1. System architecture for building data archival

Results

Each building in the system is automatically assigned a unique and persistent identifier, which can only be accessed by the administrator to prevent duplication and ensure consistent lifecycle

referencing. These identifiers link all related building data, which can be accessed, viewed, and uploaded by authorized users according to their roles. All documents are systematically versioned and archived, maintaining a historical record of each building. The prototype addresses the fragmentation and loss of building data across stakeholders and lifecycles through structured archival. The system demonstrates a technical and organizational approach that bridges fragmented efforts and clarifies the role of a neutral regulatory coordinator. However, several challenges remain; the current role structure is limited, highlighting the need for finer-grained roles that clearly define who can access documents and who approves access to data. Additionally, regulations around data sharing, use of secondary data sources, and linking separate datasets must be altered to enable benchmarking and interoperability. Long-term archival requires standards for data formats, storage, and traceability, while questions remain about who validates the correct classification of documents and who can access data, and under which terms one can reuse it. Addressing these issues requires clear governance structures, further technical development, and additional research into regulations, responsibilities, and practical implementation on a national scale.

Conclusion

The findings show that implementing persistent building identifiers enables structured, lifecycle-based archival of building data across stakeholders. By assigning unique identifiers and linking versioned documents to clearly defined moments, the prototype illustrates how fragmented building information can be organized within a traceable and interoperable framework, while clarifying the coordinating role of a neutral public actor. While governance design, role differentiation and access control, and regulatory alignment for data sharing and reuse remain critical challenges, the findings confirm that the prototype provides a viable conceptual and technical starting point for lifecycle-oriented data management in the AECO sector. Future research should explore how such an archival system can be implemented at a national scale and integrated with existing data infrastructures. In parallel, governance questions regarding data ownership, stewardship, access rights, and long-term responsibility must be addressed to operationalize lifecycle-consistent building data for decision-making.

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A Two-Layer Framework for Digital Building Logbook Implementation as a Gateway in Federated Data Environments

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Abstract

The Energy Performance of Buildings Directive (EPBD) 2024 introduced the Digital Building Logbook (DBL) as a common repository of all relevant building information to improve building lifecycle data management and support informed decision-making. The DBL is intended to link with other information tools, promoting interoperability and efficient resource management. However, implementation complexity due to data heterogeneity and inconsistencies in conceptualizing the general DBL information model leads to lower adoption rates in industry practice despite having significant business value. To address this gap, this paper proposes a two-layered DBL framework distinguishing a metadata layer, which stores structured references to building systems and resources, from a content layer that retains system-specific datasets such as BIM models, sensor data, or documents. This approach provides a unified view of building changes, filtered by resource or user access, and supports integration via standardized APIs. A proof-of-concept implementation demonstrates the feasibility of tracking Industry Foundation Classes (IFC) changes within this framework, a metadata-driven DBL approach which is aligned with European Commission technical guidelines for DBL implementation and architectural best practices.

Keywords: Lifecycle Data, Building Information Systems (BIM), Digital Asset Management, Change Logs, Data Modelling, Digital Product Passports (DPP).

Introduction

In building lifecycle data management, lack of a common data repository has resulted in increased costs and process inefficiencies (European Commission, 2020). Hence, DBL is conceived as an important digital tool to store, update and access building-related information across lifecycle phases. While DBL initiatives are primarily envisioned to improve energy performance, implementing a DBL for a building project can also generate benefits throughout the construction value chain by improving information accessibility and lifecycle data management. However, a simple DBL implementation remains a challenge because of data heterogeneity (Çetin et al., 2026), inconsistency around the scope and functionality of a DBL (Mêda et al., 2024) and implementation complexity (Gonçalves et al., 2024).
Clarifying the scope and definition of a DBL is essential before attempting its implementation. The European Commission (2020) defines DBL as *"a common repository for all relevant building data…a dynamic tool that allows a variety of data to be recorded, accessed, enriched*

and organised under specific categories" and *"represents a record of major events and changes over a building's lifecycle"*. Several existing studies often relate DBL with other data-driven concepts such as Digital Product Passports (DPPs) (Çetin et al., 2026; Gonçalves et al., 2024), Digital Twins (DTs), and Material Passports (MPs) (Gonçalves et al., 2024) to explore the similarity in underlying conceptual models and implement them for different use cases. Most DBL implementation studies (Gómez-Gil et al., 2024; Signorini et al., 2023; Mêda et al., 2025) focus on defining hierarchical data structures and storing building information directly within the logbook, often using Level of Information Need (LOIN)-style levels. It is also important to note that each of these DBL implementations follow a unique data structure (aspects and data fields) based on their interpretation of DBL and use case and are largely non-standardised. Thus, treating DBL as a federated gateway, for example in the EUB SuperHub Project, or as a metadata-driven service that links heterogeneous building information systems is conceptually different (Puček et al., 2023) and less prominently addressed in implementation-focused studies. Hence, establishing clear conceptual boundaries for a DBL is essential to develop an implementable information model that distinguishes it from related concepts. Accordingly, this study defines and structures a DBL to enable a simple and practical implementation across heterogeneous building information systems.

Hence, this paper first clarifies the conceptual scope of the DBL and distinguishes it from related concepts such as DPPs and MPs using a two-layered information model framework as shown in Figure 1. This forms the primary contribution of the paper. The proposed framework is then validated by implementing the DBL application interfaces (APIs) with a data model built on PostgreSQL, an open-source RDBMS application. This paper does not aim to introduce a fundamentally new DBL paradigm. Instead, it operationalizes these existing concepts into a simplified and implementable two-layer framework that distinguishes between metadata management and content-level data sources. The contribution of this paper lies in translating abstract DBL principles into a minimal, API-driven architecture that can be readily adopted in practice, particularly by industry stakeholders not yet prepared for fully semantic or ontology-based implementations.

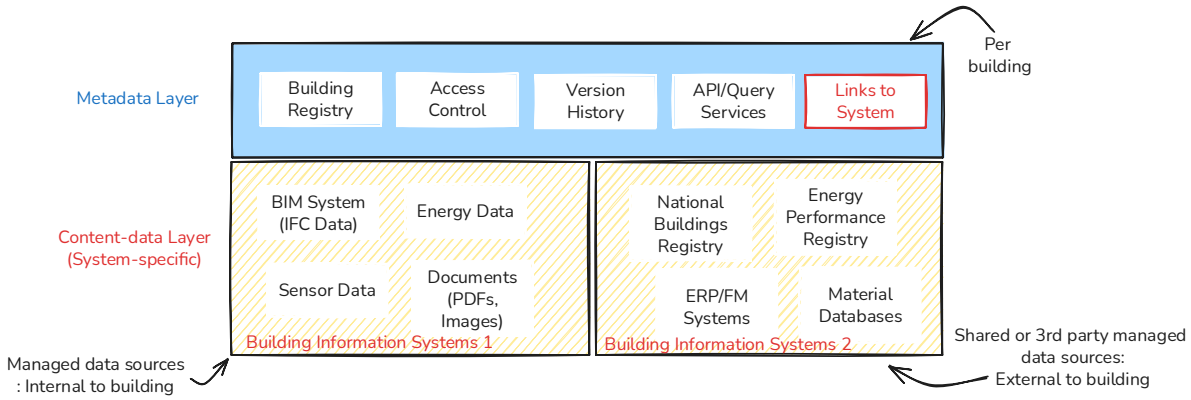


Figure 1. Proposed two-layered DBL framework. Content level data can be from single source or from a federation of sources within a decentralised environment.

The structure of the paper is as follows. The next section, **Background** covers the state-of-the-art with respect to DBL and related concepts, and DBL implementation studies. Section **Methodology** introduces the proposed two-layered information model and framework implementation. Section **Results and Discussions** elaborates on architectural alignment with

DBL studies, role in BIM-based building management, and the rationale for choosing an RDBMS over other database management solutions for the current study. The final Section **Conclusions** summarises the contributions and limitations of the study.

Background

Lifecycle Data Challenges and DBL vs other concepts:
Information loss is one of the biggest challenges in lifecycle data management that leads to increased costs and decision errors (Raitviir & Lill, 2024). DBL as a digital tool is perceived to address this challenge because DBLs are capable of aggregating lower-level passports, thereby inheriting information from DPPs and MPs to present a comprehensive view of a building (Çetin et al., 2026). This broader perspective allows DBLs to support informed decision-making, maintenance planning, energy management, and circularity objectives in ways that individual passports alone cannot achieve. However, DBLs differ from DPPs and MPs in terms of scope and level of detail as shown in Figure 2. DBLs function at the building or system level and act as "living" repositories that record ongoing changes throughout the lifecycle whereas DPPs and MPs typically provide static, component- or material-specific information respectively (Gonçalves et al., 2024).

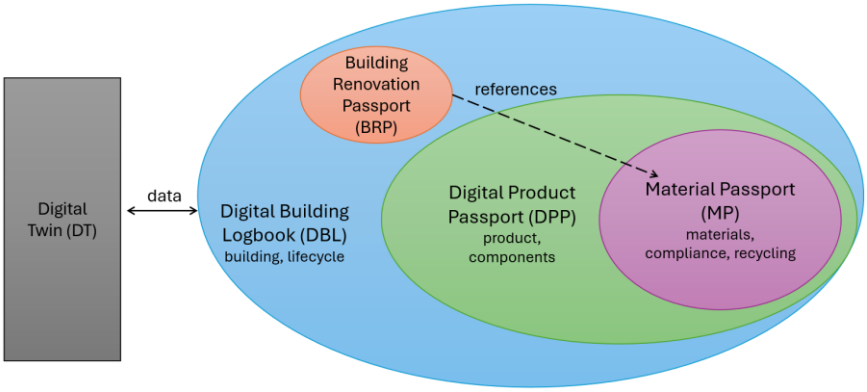


Figure 2. Conceptual hierarchy of data-driven concepts in the built environment, showing how MPs and DPPs can be nested within a DBL.

Implementation of DBLs:
Recent studies have explored the implementation of DBL through structured data models and prototype applications. For example, Gómez-Gil et al. (2024) propose a European Digital Building Renovation Logbook (DBrL) data model with a specific focus on renovation processes as shown in Figure 3. Puček et al. (2023) propose a data structure consisting of six levels of information, ranging from high-level building information categories to detailed data fields, while Signorini et al. (2023) develop a DBL architecture with four levels of information and additionally explore implementation using semantic web technologies along with development of Digital Building Logbook ontology (Signorini et al., 2024). Similarly, Redmond (2024) demonstrates the application of a renovation decision-support tool integrated within a DBL environment. Although these studies differ in their technical approaches and application focus, they generally follow a LOIN-based hierarchical structuring of building information, where DBL data are organised from broad categories to detailed attributes.

Moreover, these approaches largely conceptualise DBL as a direct data repository, where building information is stored within the DBL system itself.

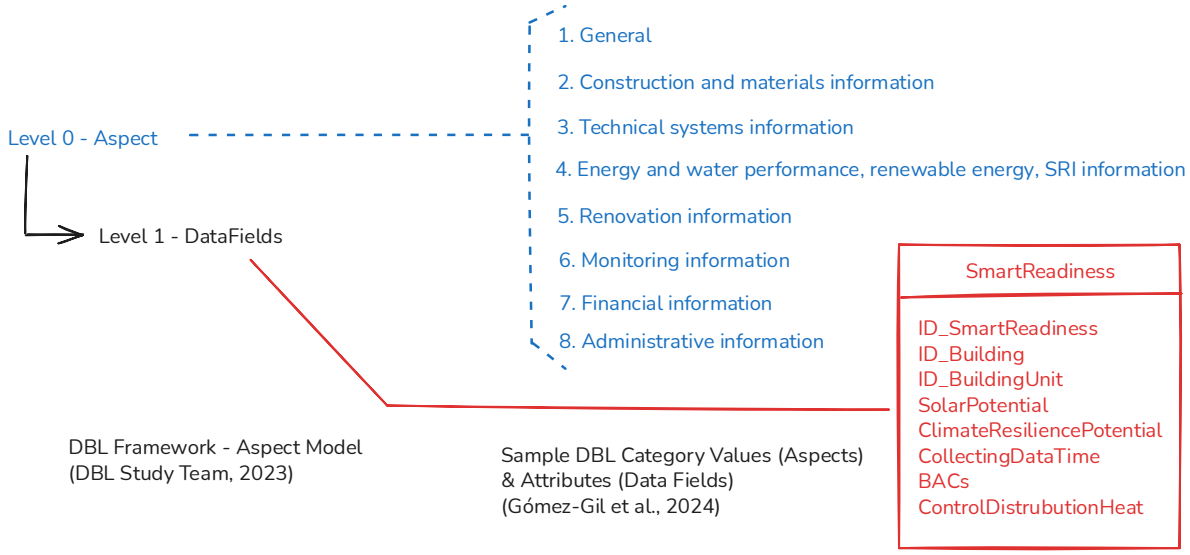


Figure 3. Example data model as proposed in Technical Guidelines for DBL (DBL Study Team, 2023). Varying number of aspects and data fields per aspect show that DBL implementation is not standardised and is dependent on use case.

An alternative approach conceptualises the DBL as a digital gateway or federated data access layer, as proposed in the DBL study (European Commission, 2021). In this approach, information remains distributed across heterogeneous building information systems and is accessed through references rather than centralised storage. DBL implementations may combine content-level data (e.g., building parameters such as footprint area) with meta-level references to external systems such as BIM models or document repositories (van der Ende et al., 2023). This enables data sharing in distributed or federated architectures, where data remain at their source while being accessible through the DBL interface.

As shown in Table 1, existing DBL studies can be broadly categorized into centralised repository-based and federated approaches. Despite these differences, a common abstraction can be identified: the separation between metadata describing systems and relationships, and content-level data residing in heterogeneous sources. The proposed two-layer framework formalizes this separation into an implementable architectural pattern.

Table 1. Comparison of DBL approaches in existing literature

Category of approach	**Key references**	**How DBL is mainly treated**	**Main modelling emphasis**	**Main limitation highlighted in this paper**
Structured repository-oriented implementations	Gómez-Gil et al. (2024); Puček et al. (2023); Redmond (2024)	DBL as a structured environment for organizing building information	Hierarchical categories, levels of information, or application-specific data structures	Approaches differ by use case and do not provide a common standardized DBL structure

Semantic or ontology-oriented implementations	Signorini et al. (2023); van der Ende et al. (2023)	DBL as a semantically linked information environment	Ontologies, semantic web technologies, linked data	Stronger semantic interoperability, but higher implementation complexity
Conceptual Studies	Mêda et al. (2024, 2025)	DBL as an evolving concept with unresolved scope and implementation issues	Analysis of challenges, sectoral needs, and implementation barriers	Confirms lack of standardization and inconsistency in DBL interpretation
Federated or gateway vision	European Commission (2020); European Commission (2021)	DBL as a gateway or common access point to distributed building information	Access through references and links to heterogeneous systems	Vision is clear, but implementation patterns remain under-specified
This study	-	DBL as a gateway implemented through a two-layer framework	Separation of metadata layer and content layer	Simpler implementation path, but no validation on automated synchronization

Methodology

This study develops a framework to conceptualize and implement a DBL. Existing DBL studies often define hierarchical data structures or centralised repositories, but provide limited clarity on how DBLs should interact with heterogeneous building information systems and distributed data sources. To address this gap, the methodology consists of two stages. First, a two-layered information model is proposed to structure the DBL as a gateway service connecting distributed building information systems. The model is derived from an analysis of existing DBL definitions and implementation studies. Second, the framework is demonstrated through a proof-of-concept implementation, illustrating how a metadata-driven DBL can link heterogeneous systems without centralising data.

Building on the defined two-layer structure, the metadata layer is responsible for storing building information in a structured manner. This layer holds only high-level details of systems and can be organized using a schema based on a predefined set of data fields. By querying the metadata layer, users can retrieve the list of IFC models associated with a building and their corresponding links to original files stored in system-specific databases such as graph databases or document repositories. It includes services supporting DBL functionalities such as logging, user access management, and links to content-level data sources.

The next layer, Building Information Systems (BIS), contains the actual data sources. To demonstrate feasibility in federated ecosystems, two systems, BIS 1 and BIS 2, are introduced. BIS 1 represents internal data sources, while BIS 2 represents third-party sources managed by

private companies or government agencies. The framework remains independent of the original source technology or implementation. However, it assumes a synchronization or matching mechanism between content-level DBL data sources and the metadata-level DBL with an active connection. This paper demonstrates the feasibility of the proposed framework by retrieving lifecycle changes made to a building wall. The content-level (BIM-specific) data are accessed via an API endpoint querying a graph database loaded with RDF from IFC files.
The next step is to create the database schema for a few standard classes, as shown in Listing 1. For this metadata layer, we use PostgreSQL as the implementation approach. Listing 2 presents the SQL CREATE script for the IFC element transactions logging table. Column values are populated based on two possible transaction event types: component change and property change. Component change refers to the replacement of a child component, for example replacing an old window of an IFC wall with a new window. Property change refers to modification in attribute values for one of the data fields, for example changing the wall colour.

Listing 1. SQL script for creating the standard tables to store DBL metadata implementation. Components table is created for illustrating that storage of windows information to be used during the framework validation

```
CREATE TABLE buildings (
    building_id INT PRIMARY KEY,
    name VARCHAR(255),
    address TEXT,
    construction_year INT,
    owner VARCHAR(255)
);

CREATE TABLE components ( //to store windows information. Alternatively, we can use IFC data
    component_id INT PRIMARY KEY,
    building_id INT,
    component_type VARCHAR(100),
    installation_date DATE,
    status VARCHAR(50),
    FOREIGN KEY (building_id) REFERENCES buildings(building_id)
);

```

A database connection is created and used to generate various service endpoints as shown in Figure 4. Using these endpoints, RDF data are queried for the IFCWall object GUID and the components table for two windows. A PUT request is then made to update the existing IFC entity, followed by a POST request to the RDBMS to log the update transaction with all required information in the request body. To enable automated synchronization, the proposed framework can be extended using an event-driven architecture. In such an approach, changes occurring in content-level systems (e.g., BIM updates, sensor data modifications) would trigger events published through a message broker (e.g., MQTT or Apache Kafka). The DBL metadata layer would subscribe to these events and automatically update transaction logs and references accordingly. This mechanism would enable near real-time synchronization between distributed systems while maintaining the decoupled nature of the architecture. Although not implemented in this study, this extension represents a critical step toward operational DBL deployment in federated environments. This is considered as one of the core functionalities identified in the study on DBL by the European Commission (2020). The proposed separation between

metadata and content layers is intended as a pragmatic trade-off, enabling integration across heterogeneous systems without requiring centralised storage or full semantic modelling.

Listing 2. SQL script for storing the version history of the IFC component is to validate the feasibility of the proposed framework. APIs are implemented

```
CREATE TABLE ifc_element_transactions (
    id BIGSERIAL PRIMARY KEY,

    -- Core IFC linkage
    parent_guid CHAR(22) NOT NULL,  -- e.g. IfcWall GUID
    event_type VARCHAR(64) NOT NULL,-- 'component_change', 'property_change',
'geometry_change',
                                    -- 'element_created', 'element_removed', 'renovation',
                                       -- 'responsibility_change', 'temporary_modification'

    -- Component change fields (used only when event_type = component_change)
    child_type VARCHAR(64),                    -- e.g. 'IfcWindow' (NULL for wall painting)
    old_child_guid CHAR(22),                   -- previous child GUID
    new_child_guid CHAR(22),                   -- new child GUID

    -- Property or responsibility changes
    property_name VARCHAR(128),                -- e.g. 'FinishMaterial', 'FireRating',
'Maintainer'
    old_value TEXT,                             -- old property value (nullable)
    new_value TEXT,                             -- new property value (nullable)

    -- Metadata
    change_reason TEXT,
    changed_by VARCHAR(128),
    change_timestamp TIMESTAMP NOT NULL DEFAULT NOW()
);

```

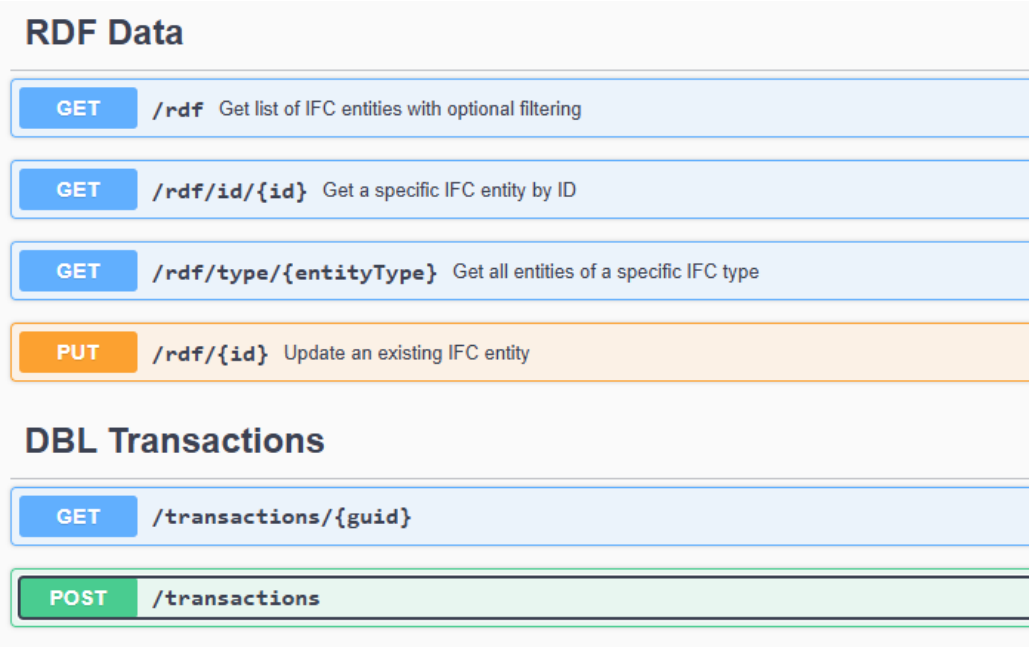


Figure 4. Swagger documentation showing the API endpoints that query both metadata and content-data. RDF Data – Graph DB & DBL Transactions – PostgreSQL.

Results and Discussions

The proposed framework demonstrates a gateway-based DBL, linking heterogeneous building information systems without centralising data - an approach less clearly operationalized in existing implementation studies. On this foundation, the framework can be extended to support federated or distributed DBL architectures, enhancing scalability and integration across multiple systems. Next, Figure 5 presents the response obtained from the implemented API endpoint. The response contains the information retrieved from the underlying systems together with the corresponding DBL records. In this example, the request queries the lifecycle changes associated with a building wall element identified through its IFC GUID. The API response confirms that the DBL service is able to access the underlying content-level data source and update the metadata layer with the corresponding transaction record.

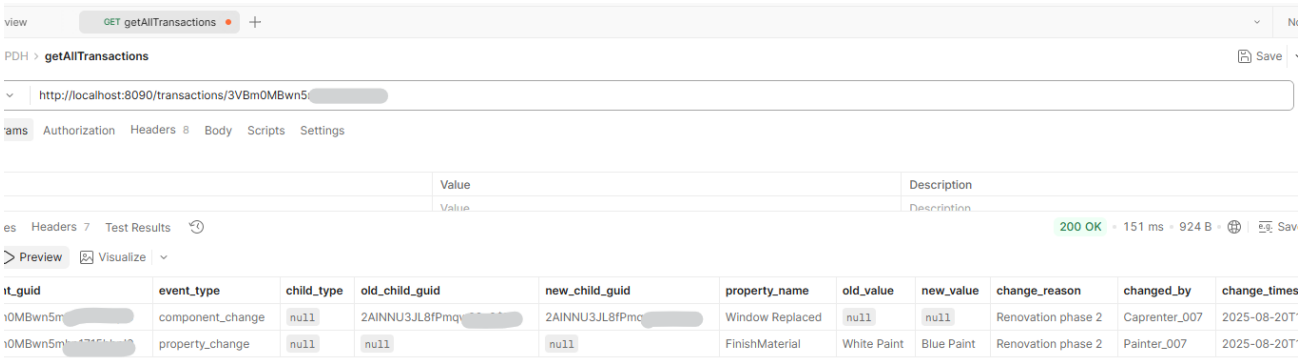


Figure 5. Response of getAllTransactions Endpoint showing two historical changes made to the queried IFC Wall.

The proposed two-layer DBL framework aligns with the recommendations made by the European Commission (2020) and DBL Study Team (2023) Technical Guidelines. The metadata layer (implemented using PostgreSQL) provides strong data integrity, schema consistency, and support for complex queries compared to document-oriented NoSQL databases. The content layer remains flexible, allowing semantic building data to be stored in RDF triple stores or graph databases (GraphDB, Neo4j) when semantic interoperability is a primary requirement. This graph approach also supports the technical guidelines' recommendation that DBLs progressively move toward fully semantic data representations.

The demonstration of the proposed DBL framework, which captures lifecycle changes of BIM elements and logs them in the metadata layer, illustrates how a DBL can support BIM-enabled smart building management. By linking updates from content-level BIM models such as component replacements or property changes to the DBL, building managers can track dynamic data, monitor smart readiness indicators (SRI), and evaluate energy or cost-saving potentials in near real time. This approach promotes key DBL functionalities identified as gaps in current implementations (European Commission, 2021).

Existing studies such as Signorini et al. (2023) and Gómez-Gil et al. (2024) have also highlighted interoperability challenges in DBL implementations, particularly when integrating third-party-managed sources or publicly inaccessible databases. The proposed two-layer framework addresses some of the interoperability issues by standardizing metadata references and transaction logs, promoting syntactic and structural interoperability while aligning with guiding principles of fairness, standard protocols, exchange formats and data accessibility.

In real-world deployment scenarios, additional considerations such as data governance, security, and multi-stakeholder coordination become critical. The DBL, when acting as a gateway, must address questions related to data ownership, access rights, and trust across participating systems. Role-based access control mechanisms and standardized authentication protocols would be required to ensure secure interaction with third-party data sources. Furthermore, conflicts arising from asynchronous updates or inconsistent data across systems must be managed through clear governance policies and synchronization strategies. While these aspects are beyond the scope of the current implementation, they represent essential components for operational DBL ecosystems.
However, as the current RDBMS-based metadata layer cannot fully capture machine-readable relationships across heterogeneous systems, semantic interoperability remains limited. Using graph databases or RDF-based triple stores could enhance semantic linking and reasoning across distributed sources, improving integration with smart building management workflows. Yet, such an approach would increase system complexity, require ontology alignment, and may complicate standardization, highlighting practical simplicity in DBL deployment.

Conclusions

This study proposed a two-layered DBL framework that separates data into a metadata layer and a content layer, thereby providing clarity on the definition and scope of DBL as well as its distinction from related concepts such as DPPs and MPs. The metadata layer is implemented using PostgreSQL to prioritize structural consistency, transactional integrity, and ease of integration, offering a lower-complexity alternative to semantic or ontology-based approaches, which is recognized as a key technical barrier to DBL adoption in the construction sector (European Commission, 2020). The framework was further validated through a proof-of-concept using a BIM system, with meta information stored in PostgreSQL and content data stored in a graph database, demonstrating how changes to building elements can be traced and logged efficiently. Architectural decisions, including the use of a RDBMS for the metadata layer, were guided by practical considerations such as mature query support, ease of implementation, and compatibility with existing data management practices. While the proposed framework adopts a relational approach, the metadata layer could also be implemented using graph-based databases depending on the required level of semantic linking and system complexity. Future research should focus on architectural aspects of DBL deployment in more distributed environments, particularly investigating decentralised DBL infrastructures and mechanisms for secure data exchange across heterogeneous systems. In this context, the role of Common Data Environments (CDEs) and similar collaborative data-sharing platforms could be further explored to support controlled access, interoperability, and integration of third-party or restricted data sources.

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Thematic session:

Parametric and Data Driven Design

Automated Compliance Checking with SHACL-based Digital Building Regulations using GraphRAG

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Abstract

Checking whether a building design complies with building regulations is a complex task. Especially in early design phases, it is difficult to create a structured overview of relevant building regulations, let alone check a design for compliance against those regulations. Regulatory compliance checking is therefore often moved to later design phases, leading to costly redesigns and mistakes. We previously presented a method for querying building regulations using natural language queries based on a GraphRAG (Retrieval Augmented Generation) method (Donkers & Petrova, 2025). This method provides the user with text-based regulations, which are not yet machine-readable. This paper introduces a novel approach to bridge the gap between text-based regulation retrieval and automated compliance checking. The paper shows how regulatory documents can be converted to RDF (Resource Description Framework) graphs, enabling querying. It then converts the text-based regulations to SHACL (Shapes Constraint Language) shapes, enabling validation of Linked Building Data graphs. A GraphRAG method enables querying regulations using natural language. The method presents the user with a text-based regulation and simultaneously sends the corresponding SHACL shape to a SHACL validator, enabling validation of the building information. After validation, the SHACL validator presents the user with a validation report. This method enables flexible generation of digital rulesets based on textual input from an end-user and lowers the barrier for regulatory compliance checking in early design phases.

Keywords: GraphRAG, SHACL, Automated Compliance Checking, Neuro-Symbolic AI.

Introduction

The interpretation and application of building codes remain a significant challenge in the Architecture, Engineering, and Construction (AEC) industry, as regulations are primarily authored as ambiguous and complex natural language documents that require manual expert interpretation (Zhang et al., 2023). This manual process is time-consuming and prone to human error, and the semantic gap between legal text and Building Information Models (BIM) makes interpretation of these codes difficult, especially in early design stages. The delay of applying those building codes to later stages often leads to costly changes (Donkers & Petrova, 2026).

Recent developments in BIM and neurosymbolic AI (Artificial Intelligence) are promising to mitigate some of these challenges (Amor and Dimyadi, 2021).
To bridge the gap between natural language regulations and machine-executable code, various researchers applied neural and symbolic AI techniques, and more recently, neurosymbolic AI techniques (Garcez & Lamb, 2023). Developments can be found in symbolic methods to describe regulatory building information using formal logic and structured knowledge representations such as ontologies (Werbrouck et al., 2026), neural AI methods to digitize regulations (Fuchs et al., 2024), and retrieval of natural language building regulations and building information (Donkers & Petrova, 2025; Iranmanesh et al., 2025). An end-to-end pipeline that enables a full interaction, meaning retrieval, execution, and the generation of validation reports, has not yet been developed.
This paper aims to fill this research gap and extend earlier work to not only retrieve building regulations using natural language but also enable the execution of these codes. It does so by applying a neurosymbolic AI pipeline that leverages GraphRAG to retrieve both textual regulations and their corresponding machine-executable SHACL shapes, after which the system validates a Linked Building Data (LBD) model against those shapes and returns a stakeholder-specific validation report. The following subsections describe the state-of-the-art in this domain, the applied methodology, some results achieved through this method, and a discussion and conclusion.

State of the art

Automated compliance checking (ACC) requires two main data sources: building information (typically in the form of BIM models) and normative knowledge (typically digital representations of regulatory statements) (Amor and Dimyadi, 2021). Research in the past decade led to a variety of ontologies that were developed to structure normative knowledge digitally, including AEC3PO[1], the DigiChecks ontology[2], OntoBPR (Hagedorn et al., 2025), and the FireBIM Regulation Ontology (FRO) (Donkers & Petrova, 2025). These developments enable the application of neurosymbolic AI methods, where these symbolic representations are used to generate more accurate neural AI predictions (Garcez & Lamb, 2023). Examples are the use of human-in-the-loop Large Language Model (LLM) methods to predict RASE (Requirement, Applicability, Selection, Exception) tags for natural language regulations (Al-Turki et al. 2025), a neurosymbolic AI pipeline to generate SHACL shapes from natural language regulations (Donkers & Petrova, 2026), and the prediction of structural elements in regulatory documents using an ontology-enhanced BERT-LLM method (Jorge et al., 2025).
ACC has naturally been a deterministic process, amongst others, for trust reasons. Rules are traditionally hard-coded into rule (markup) languages, such as RASE and RuleML. A variety of symbolic (linked data) approaches has been developed and tested for the AEC industry, including SWRL, N3Logic, SPARQL, SHACL, and OWL (Nuyts et al., 2024). The application of Neural AI for ACC has long been controversial, given its black box nature, but research in this domain is recently gaining attention (Bloch et al., 2023).
While much work can be found on the generation and execution of digital building regulations, less research exists on the retrieval of such regulations. Especially in early design phases, the exact set of regulations that are applicable is often unknown, and retrieving them requires

[1] https://w3id.org/lbd/aec3po/
[2] https://github.com/semmtech/digichecks-ontology

expert knowledge (that often enters a project in later stages in the form of expert consultancy). Standard information retrieval methods have not been able to solve this challenge. The development of neurosymbolic AI technologies is promising, and examples enable end-users to query building information (Iranmanesh et al., 2025) or regulations (Donkers and Petrova, 2025) using natural language. These technologies also found their way into practice, such as the DAISY assistant (Masella and Rebkowski, 2025). The work underscores the importance of symbolic logic to improve the reasoning of their AI assistants.

Methodology

The methodology builds upon existing developments related to the generation and retrieval of digital building regulations. Figure 1 shows an overview of the method developed in this work, which shows parts that are taken from existing work in grey, parts related to the creation of the shapes graph in blue, parts related to the creation of the data graph in green, and parts related to compliance checking in purple.

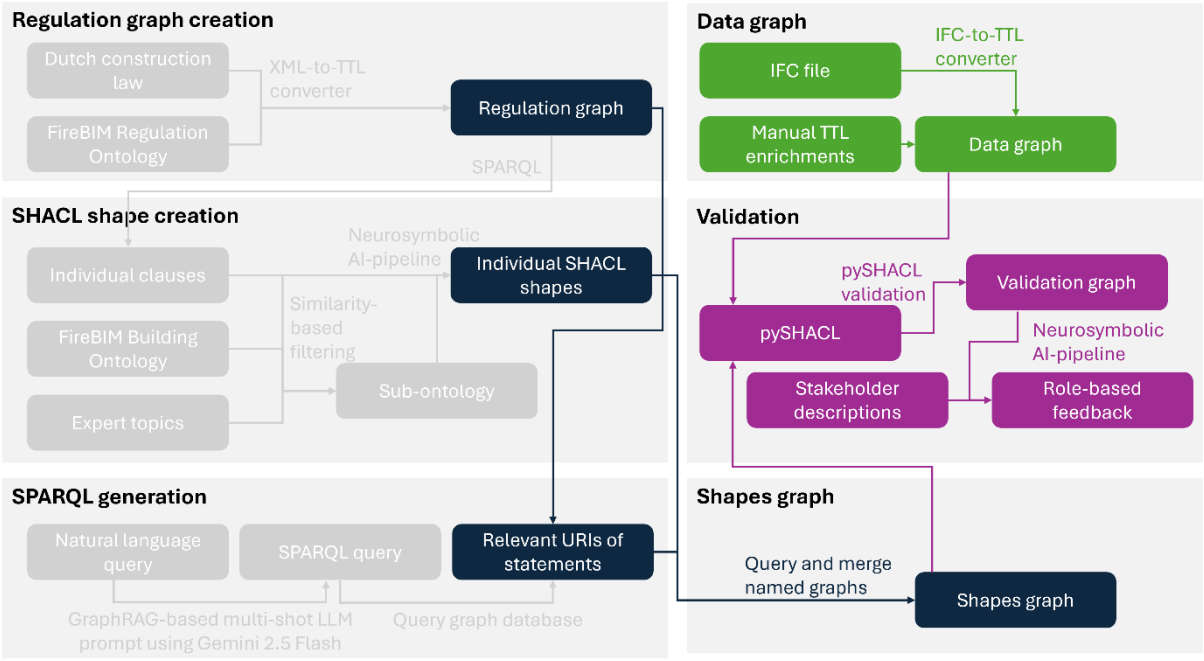


Figure 1. Graphical overview of the methodology

Regulation graph

The fire safety section of the Dutch Construction Law ("Besluit Bouwwerken Leefomgeving")[3] is exported as XML, and converted to an RDF TTL serialization using a custom rule-based XML-to-TTL converter that is developed in Python using rdflib[4]. Structural components, including concepts such as *Chapter*, *Paragraph*, and *Article*, are modelled using the FireBIM Regulation Ontology. Similar concepts already exist in the Dutch Construction Law, enabling a rule-based conversion. The result is a hierarchical graph that contains the document node in

[3] https://wetten.overheid.nl/BWBR0041297/
[4] https://pypi.org/project/rdflib/

```
FBR:NL-RO-OmW a fro:Document ;
    rdfs:label "Omgevingswet"@nl ;
    fro:hasID "NL-RO-OmW" ;
    fro:hasSubdivision FBR:NL-RO-OmW-BBL .

FBR:NL-RO-OmW-BBL a fro:Document ;
    rdfs:label "Besluit bouwwerken leefomgeving"@nl ;
    fro:hasChapter FBR:NL-RO-OmW-BBL-4,
        FBR:NL-RO-OmW-BBL-6 ;
    fro:hasID "NL-RO-OmW-BBL" .

FBR:NL-RO-OmW-BBL-4 a fro:Chapter ;
    rdfs:label "Nieuwbouw"@nl ;
    fro:hasID "NL-RO-OmW-BBL-4" ;
    fro:hasReference              <https://wetten.overheid.nl/BWBR0041297/2024-01-
01#Hoofdstuk4> ;
    fro:hasSection FBR:NL-RO-OmW-BBL-4-4.2,
        FBR:NL-RO-OmW-BBL-4-4.7 .

FBR:NL-RO-OmW-BBL-4-4.2 a fro:Section ;
    rdfs:label "Veiligheid"@nl ;
    fro:hasID "NL-RO-OmW-BBL-4-4.2" ;
    fro:hasParagraph FBR:NL-RO-OmW-BBL-4-4.2-4.2.10,
        ... ;
    fro:hasReference              <https://wetten.overheid.nl/BWBR0041297/2024-01-
01#Hoofdstuk4_Afdeling4.2> .

FBR:NL-RO-OmW-BBL-4-4.2-4.2.8 a fro:Paragraph ;
    rdfs:label "Beperking van uitbreiding van brand"@nl ;
    fro:hasArticle FBR:NL-RO-OmW-BBL-4-4.2-4.2.8-4.49,
        FBR:NL-RO-OmW-BBL-4-4.2-4.2.8-4.50,
        ... ;
    fro:hasID "NL-RO-OmW-BBL-4-4.2-4.2.8" ;
    fro:hasReference              <https://wetten.overheid.nl/BWBR0041297/2024-01-
01#Hoofdstuk4_Afdeling4.2_Paragraaf4.2.8> .
FBR:NL-RO-OmW-BBL-4-4.2-4.2.8-4.50 a fro:Article ;
    rdfs:label "brandcompartiment: ligging"@nl ;
    fro:hasID "NL-RO-OmW-BBL-4-4.2-4.2.8-4.50" ;
    fro:hasStatement FBR:NL-RO-OmW-BBL-4-4.2-4.2.8-4.50-1.0,
        ... ;
    fro:hasReference              <https://wetten.overheid.nl/BWBR0041297/2024-01-
01#Hoofdstuk4_Afdeling4.2_Paragraaf4.2.8_Artikel4.50> .

FBR:NL-RO-OmW-BBL-4-4.2-4.2.8-4.50-1.0 a fro:Statement ;
    fro:hasSHACLShape FBR:NL-RO-OmW-BBL-4-4.2-4.2.8-4.50-1.0_SHACL ;
    rdfs:label "1.0" ;
    fro:hasID "NL-RO-OmW-BBL-4-4.2-4.2.8-4.50-1.0" ;
    fro:hasText "A confined space is located in a fire compartment."@en,
        "Een besloten ruimte ligt in een brandcompartiment."@nl .
    fro:isAbout fbo:FireCompartment , fbo:ResidentialFunction.
```

Listing 1. An excerpt of the RDF TTL representation of the Dutch Construction Law

the center, and gradually lists more detailed parts the further one moves from the center. The individual *Statements* or *Items*, which are the individual rules that collectively form the

regulatory document, are presented at the outer boundary of the graph in natural language (as *rdf:Literals*). Listing 1 shows an excerpt of the regulation graph. Using a method developed by Donkers and Petrova (2025), these individual *Statements* and *Items* are extended with topical metadata tags, e.g., stating that a *fro:Statement fro:isAbout fbo:FireCompartment*. These metadata tags can relate to any kind of topic, e.g., specific building elements, function types, building types, and building heights, and should reflect the terms that experts want to use to filter specific regulations when querying. This tagging procedure follows a human expert-controlled neurosymbolic AI method.

SHACL generation

While the regulation graph enables querying parts of regulatory documents via a structured ontology, the rules themselves are still presented in natural language. Using a neurosymbolic AI pipeline developed in earlier work (Donkers and Petrova, 2026), those regulatory statements are converted to individual SHACL shapes. Listing 2 shows such a SHACL shape, representing one statement in the regulation graph. The shape clearly distinguishes the antecedent (using *sh:target*) and the consequent (using *sh:PropertyShapes*), to follow First Order Logic representations. It is simultaneously mappable to other rule markup languages, such as RASE (Applicability/Selection and Requirement/Exception), IDS (Applicability and Requirements), SWRL (Rule body and Rule head), and N3 (LHS and RHS). The specific *sh:SPARQLTarget* is used to enable selecting antecedents that are not directly represented by a dedicated class, but by a more complex combination of classes and properties (such as the enclosed space in Listing 2). Listing 1 shows how the instantiation of a statement (article 4.50, member 1) is linked to this SHACL shape using *:Statement_01 fro:hasSHACLShape :Statement_01_SHACL*.

```
FBR:NL-RO-OmW-BBL-4-4.2-4.2.8-4.50-1.0_SHACL a sh:NodeShape ;
    sh:target [
        a sh:SPARQLTarget ;
        sh:select """
            SELECT ?enclosedSpace WHERE {
                ?enclosedSpace a bot:Space .
                ?enclosedSpace fbo-nl:isEnclosedSpace true .
            }
        """ ;
    ] ;
    sh:property [
        sh:path [ sh:inversePath bot:containsZone ] ;
        sh:class fbo-nl:FireCompartment ;
        sh:qualifiedValueShape [
            a sh:NodeShape ;
            sh:targetClass fbo-nl:FireCompartment ;
        ] ;
        sh:message "An enclosed space must be contained within a fire compartment."
;
    ] .
```

Listing 2. A SHACL shape representing article 4.50 member 1 from the Dutch Construction Law

SPARQL generation

A GraphRAG method developed by Donkers and Petrova (2025) is used to convert natural language queries to SPARQL, to enable querying the regulation graph. The method combines ontologies that cover the structure of regulatory documents (in this case, the FireBIM Regulation Ontology), ontologies that cover the content of the documents (in this case, the FireBIM Building Ontology and a set of W3C Linked Building Data ontologies), and example Q&A sets that explain how a natural language question should be converted to SPARQL. Those are loaded in Gemini 2.5 Flash, which returns a SPARQL query. However, that method only returned the regulations in natural language. Therefore, this work extends the capabilities of this method to automatically generate a SPARQL query from natural language that returns the URI of the *Statement*, after which we apply a fixed query that returns the SHACL shape that is related to that *Statement*. To do this, first the *fro:hasSHACLShape* is used to return the SHACL shape, after which a *DESCRIBE* query returns the entire shape. When the SPARQL query returns multiple *Statements*, this latter functionality will return the SHACL shape of each *Statement*.

Linked building data

A simple BIM model is converted to LBD[5] using a Python-based IFC-to-LBD converter[6]. The result is a relatively generic LBD graph following the W3C LBD ontologies. The returned TTL file is manually extended to represent fire safety information, e.g., by adding concepts such as fire compartments, fire ratings, evacuation paths, and so forth. These concepts are based on the FireBIM Building Ontology, which is an ontology that captures fire safety logic in buildings.

SHACL validation

The compliance checking is executed using a SHACL validation, where a Data graph (containing instance data, in this case Linked Building Data) is validated against a Shapes graph (containing one or more SHACL shapes). A SHACL validator is then able to say whether a Data graph fails to comply or not. The latter does – unintuitively – not necessarily mean that the Data graph complies; 'not failing' can also mean that compliance is unknown, even though SHACL operates under a closed world assumption. Unknown compliance could, for example, happen when the Data graph is incorrectly modelled. In some cases, e.g., when the SHACL shape offers multiple pathways to comply with a rule (by nesting multiple *sh:PropertyShapes* in an *sh:or*-statement), a rule violation can also be caused by missing data. Applying SHACL for compliance checking, therefore, requires performing an information requirements check first, to test whether the Data graph contains the expected terms. This can also be executed by SHACL, but is outside the scope of this work.
The SHACL validation is performed using the *validate* function from the pySHACL[7] Python library, which returns a Boolean (indicating whether the Data graph fails to comply), a results graph (following SHACL's validation report semantics), and a result text (which is a textual

[5] https://github.com/AlexDonkers/OpenSmartHome
[6] https://github.com/SSoLDAC2024/handson-querying-and-interaction/blob/main/3_3-Transforming-IFC-to-LBD.ipynb
[7] https://pypi.org/project/pyshacl/0.9.5/

representation of the validation report). The validation report indicates which node in the Data graph failed to comply, and can therefore be used to guide the user into finding design errors (and potential solutions). As pySHACL does not enable features from the SHACL Advanced Specification (which *sh:SPARQLTarget* belongs to), the *advanced=True* variable is set inside the *validate* function.

Stakeholder-specific feedback

Next to generating the validation report, a functionality was built to generate stakeholder-specific feedback. First, example stakeholder profiles (representing stakeholders in Dutch design projects) are generated and serialized as RDF graphs. For each stakeholder, a name, role, responsibility, legal responsibility, communication interactions, and handover interactions are defined. These profiles are loaded in Gemini 2.5 Flash to generate specific textual advice for a stakeholder in a specific project phase, based on the compliance report generated by pySHACL.

User interface

For this work, the modules defined in Figure 1 are all built in Python using Google Colab. This enables easier communication and training, as the goal of this work is to migrate these developments to industrial products. A JavaScript-based user interface is developed using the same principles (Donkers and Petrova, 2025), enabling users to interact with the regulation graph. Figure 2 shows how the interface is able to interpret a question in natural language and how it returns related regulations.

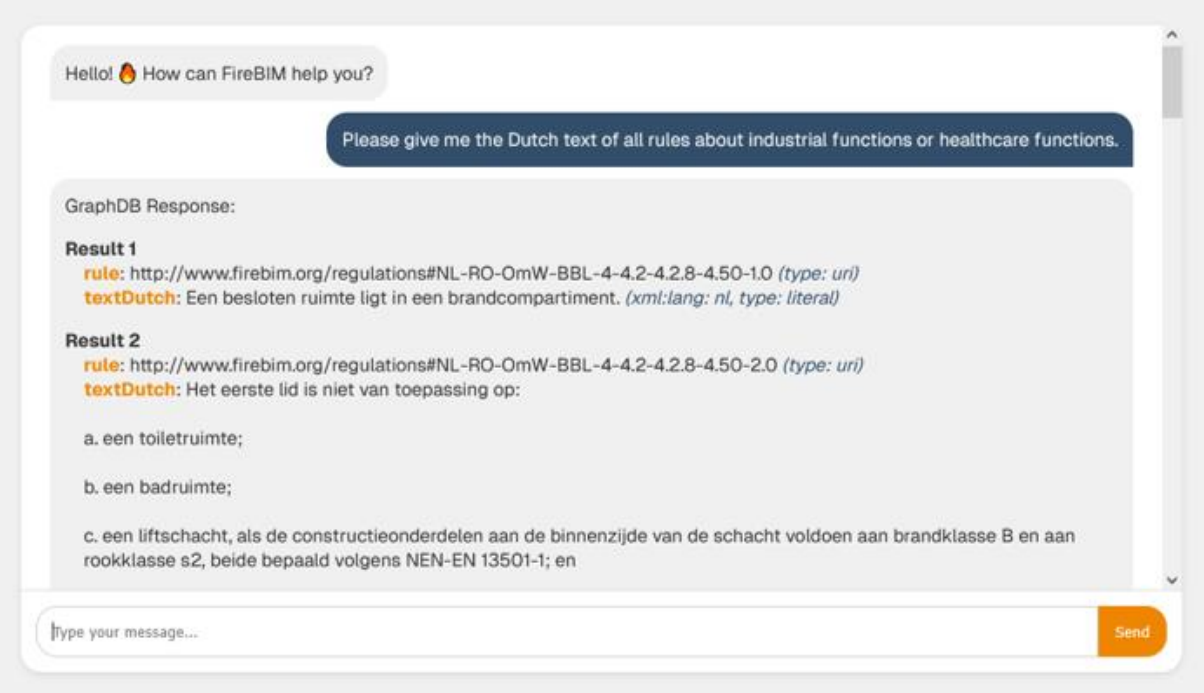


Figure 2. A Chatbot-like user interface that converts natural language questions into SPARQL

Results

To test the method, the SHACL shapes generated in Donkers and Petrova (2026) are added to the regulation graph. The OpenSmartHome was manually extended with triples related to fire safety, to reflect the rules that are tested in this study. 2 SHACL shapes are added to the regulation graph, representing article 4.50 member 1 and article 4.51 member 2. The first shape checks whether all enclosed spaces are located in a fire compartment. The second shape checks whether a fire compartment contains a maximum of four caravans and secondary uses thereof with a total usable area of no more than 1,000 m2. Both SHACL shapes are tagged with *fro:isAbout fbo:FireCompartment , fbo:ResidentialFunction*.
The system starts with the user asking a question, being: "Give me all regulations about Fire Compartments and Residential Functions". The neurosymbolic AI pipeline converts this question into the SPARQL query in Listing 3, which returns the URIs of the regulations with these tags. For those regulations that have a SHACL shape, the shapes are then queried, returning the two shapes. A pySHACL validation then loops over each SHACL shape individually, after which a validation report is printed for each shape.

```
SELECT DISTINCT ?regulation WHERE {
      ?regulation fro:isAbout ?class1 , ?class2 .
      ?class1 rdfs:subClassOf* fbo:FireCompartment .
      ?class2 rdfs:subClassOf* fbo:ResidentialFunction .
}
```

Listing 3. Generated SPARQL query returning all regulations about fire compartments and residential functions

The OpenSmartHome is deliberately extended so that one of the *bot:Spaces* is not contained in an *fbo:FireCompartment*. It is therefore expected that the Data graph would fail compliance with article 4.50 member 1, and comply with article 4.51 member 2 (as the fire compartment does not contain any caravans). Listing 4 and 5 show the respective validation reports.

```
SHACL Validation Report for http://www.firebim.org/regulations#NL-RO-OmW-BBL-4-
4.2-4.2.8-4.50-1.0_SHACL
Validation Report
Conforms: False
Results (1):
Constraint Violation in MinCountConstraintComponent
(http://www.w3.org/ns/shacl#MinCountConstraintComponent):
      Severity: sh:Violation
      Source Shape: [ sh:class fbo-nl:FireCompartment ; sh:message Literal("An
      enclosed space must be contained within a fire compartment.") ; sh:minCount
      Literal("1", datatype=xsd:integer) ; sh:path [ sh:inversePath
      bot:containsZone ] ]
      Focus Node: :Room
      Result Path: [ sh:inversePath bot:containsZone ]
      Message: An enclosed space must be contained within a fire compartment.
```

Listing 4. Validation report of article 4.50 member 1

```
All nodes targeted by http://www.firebim.org/regulations#NL-RO-OmW-BBL-4-4.2-4.2.8-
4.51-2.0_SHACL are valid.
```

Listing 5. Validation report of article 4.51 member 2

Finally, the validation report of article 4.50 member 1 is passed to the LLM agent that generates stakeholder-specific feedback. Listing 6 shows the generated solution based on a specific stakeholder profile (architect) and project phase (early design).

```
As the Architect in the early design phase, your primary duty is to resolve the
SHACL violation by ensuring every room is assigned to a FireCompartment to comply
with Bbl performance requirements. You must immediately coordinate with the Fire
Engineer and Structural Engineer to integrate fire-resistant boundaries into your
architectural layout, as these will dictate both the building's spatial safety and
its cost profile. Ensure all fire safety principles are documented for municipal
review under the Omgevingswet, as your design serves as the legal foundation for
the building permit. By resolving these data gaps now, you protect the project
from non-compliance during the eventual handover to the Contractor and Building
Control.
```

Listing 6. Generated stakeholder-specific solution to the validation report (stakeholder: architect, project phase: early design)

Discussion and Conclusion

Checking a design for compliance with building regulations is a complex and time-consuming task, especially during the early design phase of a project. This paper proposed an end-to-end method that allows end-users to simultaneously retrieve and execute applicable building regulations for a project, without needing much technical (programming) knowledge.

The developed solution enables stakeholders in design projects to query relevant regulations using natural language, execute them on a BIM/LBD model, and generate stakeholder-specific feedback. To the best of our knowledge, this is the first work to execute SHACL-based compliance checking using natural language input. However, certain limitations remain; the generation of SPARQL queries is dependent on the quality of the Q&A dataset, and it is yet uncertain how large these datasets must be to ensure practical robustness across diverse regulatory domains. Additionally, while the current chatbot interface effectively returns text-based regulations and validation reports, it lacks the multi-turn conversational depth found in modern LLMs. Future research should investigate whether these methods are best suited for standalone chatbots or if they should be integrated directly into BIM viewers to provide contextual, real-time feedback. Finally, this work applies pySHACL as the SHACL validation engine. In an ideal scenario, other validation engines would be able to build on top of the same regulation graph. As different SHACL engines interpret shapes slightly differently, differences in validation reports can occur. Establishing an accepted configuration for those engines and subsequently the SHACL shapes themselves is essential for reliability.

Despite these challenges, the method successfully bridges the gap between unstructured text and machine-executable logic. By allowing end-users to retrieve and execute complex building codes using natural language, this neurosymbolic AI approach significantly lowers the barrier for automated compliance checking in early design phases, ultimately reducing the risk of costly redesigns and regulatory non-compliance.

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Thematic session:

Data Modelling

A comparative analysis of data requirements for Digital Building Logbooks and Building Renovation Passports in Europe

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Keywords: Digital Building Logbook, Building Renovation Passport, Data interoperability, Data harmonisation.

1 Introduction

The European Union aims to transform its building sector into a highly efficient, decarbonised stock by 2050, a critical step toward climate neutrality, since the sector currently accounts for 40% of primary fossil fuel energy use and 36% of greenhouse gas emissions [1, 2]. To achieve this 2050 goal, the EU has determined that the current rate of building renovation (approximately 1% per year) is insufficient [2, 3]. Consequently, the 'Renovation Wave' strategy was launched in 2020 to accelerate this rate [2, 4]. This strategy serves as a catalyst to reach EU climate targets faster, leading to the introduction of more concrete policy instruments within the revised Energy Performance of Buildings Directive (EU/2024/1275, EPBD) [3].

To manage the necessary building data, the EU introduced the Digital Building Logbook (DBL). While national data repository concepts have historical precedents dating back to the 1980s and 1990s [5], the DBL was formally conceptualized at the European scale in the 2020 'Renovation Wave' strategy and legally defined in the 2021 EPBD recast proposal [6]. The DBL acts as the foundational 'information component' as a "common digital repository for all relevant building data."

Building upon this data infrastructure is an action-oriented instrument: the Building Renovation Passport (BRP). The BRP was officially introduced into EU legislation in 2018 through the amended EPBD (2018/844/EU) as an evolution of the static Energy Performance Certificate (EPC) [7, 8]. Most recently, the 2024 EPBD recast (Directive (EU) 2024/1275) made it mandatory for all EU Member States to establish a BRP framework by May 2026 [3]. The BRP acts as the 'evaluation component', providing a tailored, step-by-step roadmap for the deep renovation of a specific building.

Together, these instruments serve distinct but interdependent roles: the DBL provides the necessary data infrastructure, while the BRP translates that data into a long-term strategy to significantly improve energy performance.

Parallel to this evolving regulatory framework, various initiatives have emerged, both prior to and after the formalisation of EPBD recast IV, to pilot these concepts in real-world scenarios. These initiatives cover both residential, such as iBRoad [9], and non-residential sectors, such as ALDREN [10], with varying scopes and leadership structures. They range from government-led schemes, such as the Flemish Woningpas [11], to private-sector-driven tools, such as the

French Cléa (Carnet Numérique) [12]. The target scope also differs, from platforms designed to accommodate the entire building stock (e.g., Woningpas) [11] to highly individualised instruments like the German iSFP (Individueller Sanierungsfahrplan) [1]. Technical architectures also range from open data models, as exemplified by the EUB SuperHub DBL project, to proprietary/closed-source systems. Furthermore, functional depth varies significantly: while some projects focus primarily on designing the building repository (the logbook), others extend to actionable renovation roadmaps or integrate multiple advanced applications, such as the BUILDCHAIN project [13].

Although diverse initiatives have proposed and/or implemented their own definitions and interpretations, the EPBD recast IV serves as the foundational legislative framework definition adopted by the EU. However, despite this overarching regulatory framework, there remains no consensus on a unique and standardised set of attributes or a standard data model for what actually constitutes these 'relevant' building data [14]. Similarly, the role of geospatial data, despite the advances of Building and City Information Models (BIM and CIM), is still not thoroughly addressed. Although the European Commission's framework study (2020) has established a foundational taxonomy of eight data categories [4], it functions primarily as a strategic guide rather than a technical specification, lacking the explicit metadata, data formats, and semantic granularity required for immediate software interoperability [15]. Another obstacle is that many initiatives fail to provide clear metadata or documentation of their data structures, making the adoption by others, as well as systematic, well-informed comparisons, difficult.

As a result, the primary aim of this research is to address this fragmentation by identifying what we define as a 'Minimum Set of Required Data' (MSRD). Specifically, this study focuses on the Building Renovation Passport (BRP) as the principal use case guiding the goal of the data collection requirements. To achieve this, we lay out a methodological path that begins by reviewing the actual regional implementations currently in use. While our ultimate focus is oriented toward the BRP, our comparative analysis evaluates a broad spectrum of prominent EU initiatives. Crucially, even initiatives formally defined as Digital Building Logbooks (DBLs) are included in this comparison, as they frequently contain an underlying renovation layer. Therefore, our inclusion criteria encompass all initiatives that feature both the systematic collection of building information and an actionable plan for renovation. By systematically comparing, analysing, and harmonising these diverse data models, this study extracts an empirical baseline of current industry practices, providing the necessary foundation to subsequently review and evaluate these requirements.

2 Methodology

Our research adopts a methodology that bridges empirical industry practices with formal information management standards. It proceeds in three sequential phases, each building on the output of the previous. In Phase 1, we conduct a comprehensive bottom-up review of existing DBL/BRP initiatives, their project deliverables, and the broader academic literature on DBLs, BRPs, Energy Performance Certificates (EPCs), and related tools. In Phase 2, we systematically compare the data models collected in Phase 1 by extracting and semantically mapping their features and properties across thematic layers. In Phase 3, we synthesise these comparisons into an empirical baseline, which we define as the 'Minimum Set of Required Data' (MSRD).

2.1 Phase 1: Semantic review and mapping of past initiatives

We begin with a systematic review of prominent EU initiatives, policy documents, and research articles, such as the revised EPBD and the European Commission's 2020 framework. The pri-

mary objectives of this phase are twofold: first, we want to establish precise definitions for EPCs, DBLs, and BRPs, as the Commission provides a foundational framework, but interpretations vary significantly across different pilot projects; and second, to systematically collect and document data models from existing DBL and BRP proposals and implementations. To ensure a comprehensive overview, this inventory includes tools with diverse scopes, ranging from district-scale platforms to specific energy performance instruments. Consequently, this stage identifies how various initiatives conceptualise data categories, ensuring our model captures as much of the regulatory and technical spectrum as possible.

2.2 Phase 2: Comparative analysis of data models

For each initiative with a documented data structure, we perform a crosswalk analysis. The data models are first decomposed into their constituent features and properties, which are then characterised, if the documentation permits, by their data type, unit of measure, and description. To enable a structured comparison across initiatives, we organise these features into three semantic layers derived from the recurring functional patterns observed across the reviewed initiatives: (i) a repository layer, containing raw building information such as identification details, physical characteristics, and technical systems; (ii) an assessment layer, aggregating derived performance indicators such as energy ratings and indoor environmental quality scores; and (iii) a functional layer, capturing renovation-related outputs and actionable recommendations. Within each layer, features are further grouped into thematic modules (e.g., 'Identification and administrative details', 'Technical systems') to allow fine-grained comparison at the attribute level. A key challenge in this process is terminological heterogeneity: different initiatives often describe semantically equivalent concepts using different labels, structures, or levels of granularity. To address this, we perform a manual semantic alignment in which attributes are matched based on their documented meaning and context rather than their label alone. Where ambiguity persists, we consult the original project deliverables and, when possible, the initiative developers directly to verify interpretation. Not all initiatives provide equally detailed or accessible data models. Several offer only high-level data category descriptions without attribute-level specifications, while others operate as closed-source platforms with limited public documentation. In such cases, we document what is available and include these initiatives in the layer-level comparison (Table 2) but exclude them from the finer-grained attribute-level crosswalk (Table 3) where precise semantic matching is required.

2.3 Phase 3: MSRD definition

Because the current definitions and implementations of BRPs are highly variable and fragmented, we propose a bottom-up methodology to establish a foundational baseline language. Therefore, we opt to first extract a Minimum Set of Required Data (MSRD) by systematically analyzing what existing regional implementations currently require. To achieve this, we apply a frequency-based selection logic: attributes that appear in a high percentage of existing initiatives (e.g., 50%) are prioritized for the core model. Although this approach is relatively simple, it provides a highly useful, practical indication of which attributes currently play a major role in the industry, and which may be deferred to a later point. Once this empirical baseline is established, we will subsequently apply Level of Information Need (LOIN) principles to evaluate the extracted attributes, keeping only those that fulfill a specific, justified purpose and discarding the rest.

This bottom-up strategy is a deliberate departure from pre-established industry standards that guide how information requirements should be defined and collected based on their intended aim. The two principal standards are ISO 19650 and the Level of Information Need

(LOIN) standard (ISO 7817-1). ISO 19650 is primarily known as the standard that establishes the overarching information management framework and processes throughout the entire life cycle of a building, from planning and construction through to operation and management. Meanwhile, the LOIN framework dictates how to define the exact extent, quality, and granularity of the information that should be included based on a specific goal or purpose [16, 17].

While the ISO 19650 series provides a comprehensive framework for information management, its strict hierarchy is inherently optimized for BIM-enabled projects. Specifically, ISO 19650-2 governs the delivery phase (design and construction) [18, 19], while ISO 19650-3 governs the operational phase, wherein Asset Information Requirements (AIR) must be rigidly defined to systematically build an Asset Information Model (AIM)[16]. We argue that this top-down methodology is not an ideal starting point for harmonizing the EU's vastly diverse and largely unmodeled existing building stock.

Despite this limitation, a highly valuable concept to adopt from the ISO 19650 standard is the Common Data Environment (CDE). The CDE provides a managed workflow and shared source of truth that allows multiple stakeholders to collaboratively collect, access, review, and modify information containers [18]. While the operationalisation of this concept falls outside the scope of the present paper, it will inform the subsequent development of the MSRD, which is intended not as a closed specification but as a shared, interoperable baseline that can serve as a common reference across diverse national implementations.

Another highly relevant framework is the Level of Information Need (LOIN) standard (ISO 7817-1). LOIN is based on the principle that to accurately determine what information is required, one must first establish specific prerequisites: the purpose (why it is needed), the information delivery milestone (when it is needed), the actor (who provides or receives it), and the object to which it relates. Furthermore, the framework dictates that the required information must be categorized into Geometrical information, Alphanumerical information, and Documentation [17], specifying the exact quality, quantity, and granularity of the deliverables[16]. We find this to be an extremely valuable approach for the creation of a Building Renovation Passport (BRP). Once the empirical MSRD baseline is established, we therefore intend to apply LOIN principles to critically evaluate the extracted attributes, retaining only those that serve a specific, justified function within the BRP context.

3 Preliminary results

The comparative analysis reveals a rather heterogeneous landscape of DBL and BRP initiatives in national and European contexts, differing in scope, maturity, and technical ambition. These initiatives range from formal DBL/BRP data model proposals and implementations to related tools that, while not explicitly defining a data model, still rely on structured building information to be operationally effective. Table 3 summarises the assessed initiatives and their key characteristics, distinguishing between DBL/BRP proposals or implementations (above the thin line) and related tools with complementary perspectives (below the thin line).

Table 1: Overview of Digital Building Logbook and Building Renovation Initiatives

Initiative	Aim	Type	Building Types	Year(s)	Geographic Scope
EUB SuperHub DBL	Development of DBL structure for all types of buildings	Data model proposal	Entire stock	June 2021 to Dec. 2024	Transnational (7 countries)
ALDREN	DBL/BRP development for deep renovation of non-residential buildings	Data model proposal	Non-residential	Nov. 2017 to Sep. 2020	Transnational (8 countries)
Gómez-Gil et al.	Academic proposal for DBL data structure	Data model proposal	Entire stock	Oct. 2024	European (comparative analysis)
iBRoad Logbook	DBL development for individual residential buildings	Data model proposal	Residential	June 2017 to June 2020	Transnational (4 countries)
iBRoad-Plan	BRP development for individual residential buildings	Renovation roadmap	Residential	June 2017 to June 2020	Transnational (4 countries)
Woningpas	Digital building passport and renovation decision-making support tool	Implementation	Entire stock	Dec. 2018 to ongoing	Regional (Flanders, Belgium)
X-tendo	Next-generation EPC schemes toolbox	Data model proposal	Entire stock	Sep. 2019 to Aug. 2022	Transnational (10 regions)
EU DBL (Led by Ecorys)	EU Framework for Digital Building Logbooks	Framework study	Entire stock	November 2023	European
BUILDCHAIN	Blockchain-based DBL for trustworthy building lifecycle knowledge	Data model proposal	Entire stock	Jan. 2023 to June 2026	Transnational (11 partners)
OneClickRENO	Automatically generated, customisable BRPs via web tools	Data model + tool	Entire stock	Nov. 2023 to Oct. 2026	Transnational (5 countries)
EPA (by VABI)	Software for energy auditors to calculate energy usage and generate EPC scores	EPC software	Entire stock	Since 2008	National (Netherlands)
BuurtWarmteWijzer	Digital tool for residents to explore district heating options and assess collective heat network feasibility	Decision-support tool	Residential	Since 2020	National (Netherlands)
CAPSA	Efficient building data gathering and management for asset management and renovation	Implementation platform	Entire stock	Since 2020	International (focus on Europe)
iSFP	Individual Building Renovation Roadmap (Germany's national BRP)	Implementation	Residential	Since July 2017	National (Germany)

The analysis reveals a conceptual inconsistency in how DBLs and BRPs are defined and discussed in the literature, as synthesised in Figure 1. We have identified six distinct categories of DBL–BRP relationships. These include initiatives that focus exclusively on DBLs with only implicit references to BRPs (Category A), approaches that treat DBLs and BRPs as interchangeable concepts (Category B), and models that explicitly distinguish DBLs as data repositories from BRPs as standalone renovation roadmaps aligned with the EPBD (Category C). Other initiatives position DBLs and renovation roadmaps as complementary components within a broader BRP framework (Category D), define the DBL as an overarching system encompassing multiple modules, including a BRP (Category E), or address BRPs exclusively without reference to DBLs (Category F).

Based on this synthesis, our research adopts the Category E interpretation, in which the DBL provides the foundational, interoperable data infrastructure, while the BRP operationalises these data through customised, long-term renovation roadmaps supporting informed decision-making and deep energy renovation.

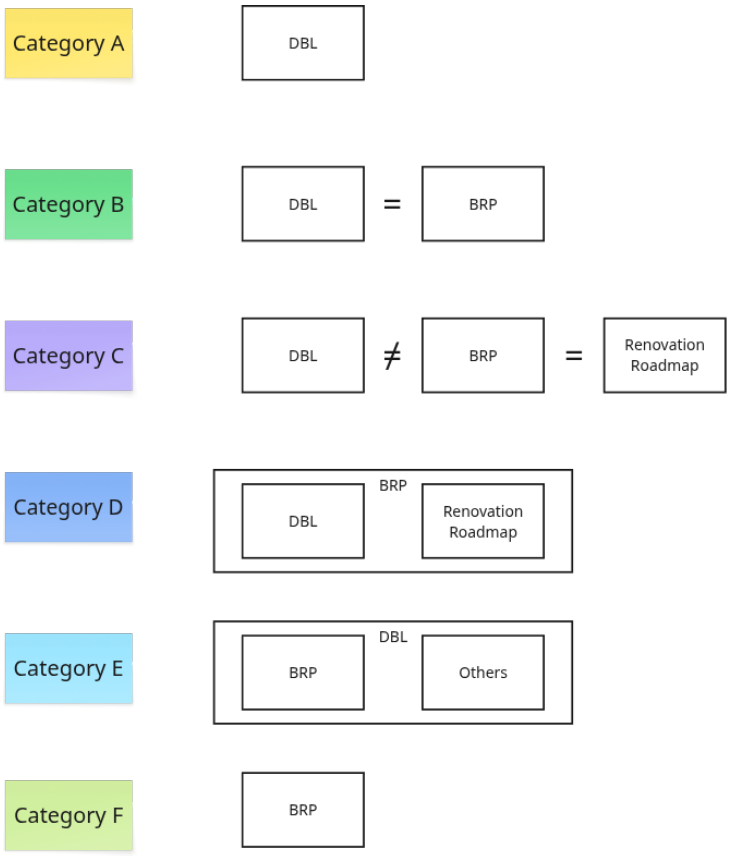


Figure 1: Conceptual Taxonomy of DBL–BRP Relationships Identified in the Literature

The comparative analysis reveals that existing DBL and BRP initiatives can be consistently characterised across three semantic layers: (i) a repository layer containing raw building information, (ii) an assessment layer aggregating performance indicators, and (iii) a functional layer supporting renovation-related outputs. Each initiative has been evaluated against these layers, revealing substantial variation in the depth and consistency of data coverage, as summarised in Table 2.

Table 2: Comparative data model analysis across DBL/BRP initiatives: I1 EUB SuperHub DBL, I2 ALDREN, I3 Goméz-Gil et al., I4 IBRoad, I5 Woningpas, I6 X-tendo, I7 DBL semantic data model, I8 BUILDCHAIN, I9 Clea France, I10 Vabi, I11 The Early Birds.

Layer	Data category & description	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11
Layer 1 Repository	1. Identification & admin details (IDs, cadastral info, ownership)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	2. General building characteristics (year, renovation history, type)	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
	3. Construction & materials (inventory, circularity, BoM)			✓	✓		✓	✓	✓			✓
	4. Technical systems (HVAC, lighting, equipment catalogue)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	5. Documentation (plans, deeds, IFC repository)	✓	✓	✓	✓	✓				✓		
	6. BIM / IFC files	✓	✓	✓			✓	✓	✓			
	7. Dimensions (areas, volume, height, envelope)	✓	✓	✓	✓	✓	✓	✓			✓	✓
	8. Operation & use (occupancy, consumption, generation)	✓	✓	✓	✓	✓	✓		✓	✓		✓
	9. Legal & finance (tax, LCC, rent, transactions)	✓	✓	✓	✓		✓	✓	✓			
Layer 2 Assessment	10. Energy performance (EPC rating, consumption, production)	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
	11. Indoor environmental quality (comfort, health, TAIL index)		✓	✓	✓	✓			✓			
	12. Smart readiness (automation, grid adaptation, fault detection)	✓		✓	✓		✓	✓	✓			
Layer 3 Functional	13. BRP output (renovation roadmap)		✓	✓	✓	✓	✓		✓			✓
	14. Ancillary data & environmental context					✓			✓	✓		✓

Following an initial broad-scale comparison, the analysis progresses to a finer level of detail by examining the second-level modules, such as ”Module 1: Identification and administrative details” defined in the Repository Layer, as shown in Table 3. These details were compared across the different initiatives; the same approach will be applied to the remaining modules.

Table 3: Comparison of building logbook implementations. Projects: I1 = EUB SuperHub DBL, I2 = ALDREN, I3 = Goméz-Gil et al., I4 = iBRoad Logbook, I5 = iBRoad-Plan, I6 = Woningpas, I7 = X-tendo, I8 = EU DBL (Ecorys), I9 = BUILDCHAIN, I10 = OneClickReno, I11 = Vabi, I12 = TheEarlyBirds, I13 = CAPSA, I14 = ISFP.

Data item	**I1**	**I2**	**I3**	**I4**	**I5**	**I6**	**I7**	**I8**	**I9**	**I10**	**I11**	**I12**	**I13**	**I14**	**T**	**%**	**M/O**
Building address details	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	13	93%	M
Building identification (local cadastral ID / INSPIRE ID)	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			11	79%	M
Ownership and occupancy details	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓		✓	11	79%	M
Geospatial coordinates (latitude, longitude, altitude)	✓	✓	✓	✓		✓	✓	✓							8	57%	M
DBL author / assessor credentials	✓	✓			✓		✓		✓	✓	✓			✓	8	57%	M
Timestamps (collection, provision, modification)			✓	✓	✓		✓		✓	✓	✓			✓	8	57%	M
Building–building unit relationship			✓	✓		✓		✓		✓	✓	✓			7	50%	M
Building owner address details			✓								✓			✓	3	21%	O
Associated cadastral parcel details	✓					✓		✓							3	21%	O
Regulations in force at time of construction										✓					1	7%	O

4 Conclusions and future work

With this research, we aim to address the fragmented landscape of DBL/BRP initiatives by establishing a systematic framework for semantic comparison. Our preliminary analysis of fourteen major initiatives reveals significant conceptual inconsistencies in how DBLs and BRPs are defined and implemented. By decomposing the initiatives data models into three distinct layers (repository, assessment, and functional), we provide a structured approach for cross-initiative comparison. The frequency-based attribute selection method enables the derivation of the MSRD that captures the most consistently represented data elements across existing proposals. As such, the first result is a technically grounded foundation for future DBL/BRP efforts that aims to remove current semantic gaps and improve interoperability.

In the near future, we plan first and foremost to finish the systematic comparison between the initiatives, resulting in the aforementioned ’Minimum Set of Required Data’ (MSRD). Building on the Common Data Environment (CDE) principles outlined in our methodology, the MSRD will be benchmarked against established international geospatial standards, specifically CityGML and its Energy ADE extension. The purpose is to develop a robust database schema capable of storing, linking, and simulating energy-related data for existing buildings. The purpose is to verify whether CityGML + Energy ADE could be a meaningful starting point as a data model underpinning the DBL/BRP, or not, and to find and define gaps that need to be addressed if one would actually want to build upon these standards.

The proposed MSRD will also be practically tested by implementing representative case studies that range from the building unit to the building and neighbourhood level. We will use a combination of publicly available datasets, private building records, and, where possible, building audit data to populate the resulting database schema and support renovation scenario energy simulations.

5 Acknowledgements

This work is being carried out within the project ”RenoDAT” (Accelerating building RENOvation and Decarbonization through DATa integration), funded by the Dutch Research Council (NWO) in the framework of the Research programme on Digitalisation of Energy Renovations in the Built Environment.

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Thematic session:

Scenarios and Simulation

Development and verification of a method to evaluate energy grid effects of retrofit strategies at neighbourhood level

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Abstract

The decarbonization of the Dutch housing stock requires the large-scale adoption of retrofitting measures to reduce heating demand, alongside the introduction of sustainable heating systems such as heat pumps. However, the widespread introduction of heat pumps may increase electricity demand beyond the current capacity of local grids, making grid reinforcements a necessity. Given the long lead times faced by grid operators and infrastructure contractors, early insight into how retrofit strategies will affect local electrical demand, and consequently local energy infrastructure, is essential. This study proposes a methodological framework to provide early phase assessments and demonstrates it through a case study of a residential neighbourhood. Open-source spatial and energy datasets were used to simulate baseline heating demand, which was validated against publicly available consumption data. A retrofit scenario was then modelled to quantify reductions in thermal energy demand. Electricity demand profiles were generated by combining household electricity consumption with simulated heat pump loads. To capture realistic peak load behaviour, a heuristic was applied to construct stochastic, normally distributed load profiles at dwelling and neighbourhood level. Additional scenarios incorporated varying levels of photovoltaic electricity generation. The results show that the modelled load profiles correspond well with empirical observations from comparable retrofit projects. Notably, the findings suggest that the large-scale deployment of all-electric heat pumps may not impose the level of stress on local distribution grids that is commonly anticipated. The proposed methodology offers a practical decision-support tool for early-phase retrofit planning, enabling rapid assessment of energy, emissions, and grid impacts to help accelerate energy renovations.

Keywords: energy transition, retrofit strategies, electricity load modelling, decision-support methodology

Introduction

To reach the aim of a carbon neutral built environment in 2050 (Directive 2024/1275), a large share of the housing stock will have to be energetically retrofitted (Ballarini et al., 2014). Retrofitting strategies typically comprise of a set of measures to reduce the heating load and heating energy demand, i.e. thermal insulation, airtightness measures and the installation of mechanical ventilation with heat recovery (Rovers et al., 2025), after which the remaining heat demand can be provided by sustainable, low-temperature heating systems, such as heat pumps.

Given the large scale of required energy renovations, it has been noted that neighbourhood-oriented renovation approaches will be necessary for the feasibility, affordability and timeliness of the aforementioned aim (Klimaatberaad, 2019; Rovers et al., 2022).

Though heat pumps offer benefits in terms of the decarbonisation of the heating demand, their widespread adoption, particularly in existing neighbourhoods, introduces new challenges: the electrification of residential heating is expected to substantially increase the instantaneous electricity demand at the local level. Most residential electricity grids in the Netherlands were originally designed on the assumption that the total coincident power draw of all the dwellings connected to a common neighbourhood transformer would not exceed 1.5 kW (van Melle, Ramaekers, & Terlouw, 2014). The expected increase of the coincident power draw as a result of widespread heat pump adoption has led to raising concerns regarding grid congestion, which triggers the need for costly and time-consuming grid upgrades.

Given the large number of neighbourhoods that need to be decarbonised, and the relatively lengthy planning, permitting, and construction processes associated with infrastructure reinforcement, there is growing interest in tools that can provide early insights into how retrofitting strategies will affect future electrical demand and, by extension, the local energy infrastructure.

Whilst many authors have focused on either building-level retrofit performance (Ascione et al, 2021; Wüllhorst et al, 2025; Kleinebrahm et al, 2025) or heat pump electricity demand profiles specifically (Earle et al, 2023; Anderson et al, 2020; Conrad et al, 2019), studies that combine both within a single, accessible framework are scarce (Johari et al, 2024; Protopapadaki et al, 2017; Deb et al, 2021). Existing load profile methodologies often depend on proprietary simulation tools that require a large number of inputs, extensive smart metering datasets or field measurements (Earle et al, 2023; Ascione et al, 2021; Anderson et al, 2020; Conrad et al, 2019; Agrawal et al, 2026), which are generally unavailable during early-phase planning. In addition, most approaches employ an hourly resolution (Conrad et al, 2019; Deb et al, 2021; Anderson et al, 2020), which is insufficient for accurate local grid assessments (Protopapadaki et al, 2017; Wüllhorst et al, 2025; Anderson et al, 2025).

For the Dutch context specifically, no lightweight, open-source methodology exists yet that connects neighbourhood-scale retrofit scenarios to sub-hourly electricity load profiles without requiring specialised expertise or private data access (Kleinebrahm et al, 2023; Mascherbauer et al, 2025).

Methodology

The method presented below consists of three main parts and is based on a framework that relies on open-source spatial and energy datasets in combination with established modelling tools to: (i) quantification of pre- and post-retrofit heating energy demand, (ii) generation of electricity demand profiles for a full-electric post-retrofit scenario, and (iii) exploration of the system-level implications of full electrification, including photovoltaic electricity generation. The approach is demonstrated through application on a case study of a Dutch neighbourhood consisting of thirty terraced dwellings, constructed in 1969.

i. Simulation of pre- and post-retrofit heating demand

Firstly, the baseline heating demand of the dwellings is calculated using both UMGO (Hillenius et al., 2025) and SimStadt (Duminil et al., 2026) (see Figure 1). These tools integrate building thermal characteristics with archetype-based data of dwellings to estimate annual heating demand. UMGO applies key parameters and usage assumptions from the NTA 8800 standard (NTA 8800:2024, 2025), whilst SimStadt employs 3D geometric building data, alongside physics and occupancy libraries, to compute monthly and annual heat demand. The simulated heating demand at neighbourhood scale is then verified against publicly available energy consumption data, made available by local grid operators, aggregated at postal code 6 level (Enexis, 2026). Following baseline verification, a retrofit strategy is introduced to assess the impact of improved building performance. The thermal characteristics of the strategy are implemented in the tools, and the resulting heating demand is recalculated.

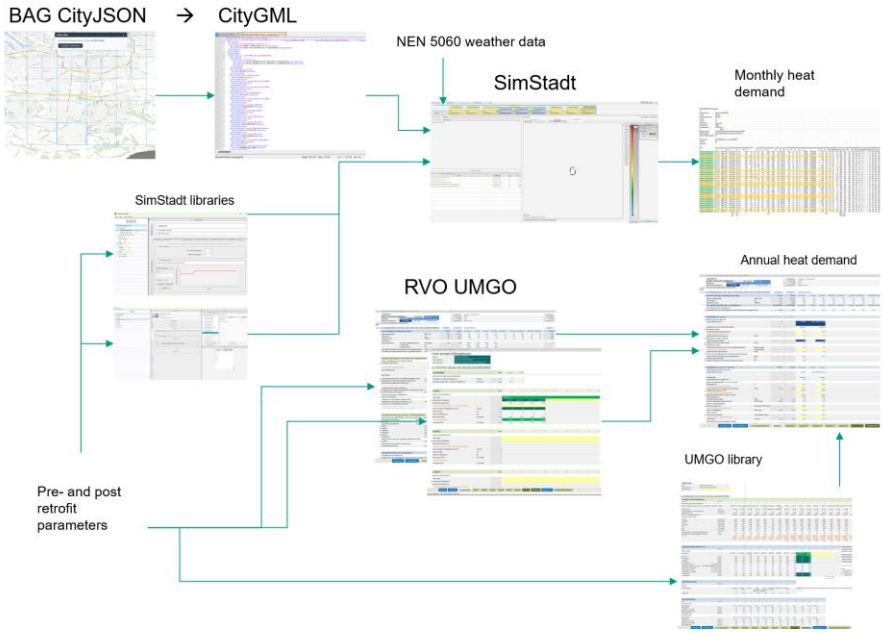


Figure 1. Procedure for heat demand calculations using UMGO and SimStadt

ii. Generation of electricity demand profiles

For the purpose of translating the calculated annual heating demand into realistic profiles with a high (one-minute) temporal resolution, the When2Heat (Ruhnau et al., 2019) dataset is applied. When2Heat provides hourly heat demand profiles for space heating, COP and domestic hot water use, derived from national statistics for various European countries. For the Netherlands, datasets are available for the years 2008 to 2013. For the selected year, the demand profiles are first converted into unit sum normalized profiles and subsequently scaled by the calculated annual heat demand of the retrofit scenario. The profiles are then combined with their related temporal COP-profile to generate a representative heat pump electricity load profile representing both space heating and domestic hot water demand.

With the aim of capturing realistic peak load behaviour as well as introducing differences between individual household profiles, a heuristic based on observed coincidence factors is introduced. Assuming heat demand exhibits mean centred fluctuations influenced by human

behaviour and societal rhythms, the interhousehold variation is taken to be approximated by a normal distribution (Hansen et al., 2022; Van den Brom et al., 2019). This collective effect is also commonly referred to as simultaneity. The simultaneity or coincidence factor quantifies the extent to which individual, otherwise independent systems experience their peak loads at the same time. In other words: because households use space heating and domestic hot water at different moments, the aggregated demand at neighbourhood or district level is lower than the sum of the individual peak loads. In practice, a coincidence factor of 0.55 is typically applied for space heating demand in the Netherlands (ISSO, 2025).

For domestic hot water demand, it is assumed that all heat pumps are equipped with a buffer tank. Buffer tanks reduce peak heat demand by spreading hot water production over the course of the day. Both the filling time of the buffer and the degree of simultaneity are affected by this storage. When a domestic hot water buffer is charged over multiple hours, simultaneity at neighbourhood level is expected to approach unity (van Meerkerk, Pothof, & van Vossen, 2022). This assumption means that the representative demand profile for hot water demand can be used for all the dwellings.

The considered normal distribution is taken to be truncated at ±3 standard deviations (σ) from the mean, this captures approximately 99.7% of observations. In practice, however, values are further constrained by physical limits, most notably the maximum capacity of individual heat pumps.

Taking the coincidence factor to be defined as the ratio of average power and maximum power, it can be written as:

$$f_c = \frac{P_{average}}{P_{max}} \tag{1}$$

Because the normal distribution is bounded by ±3 standard deviations, σ can be expressed as:

$$\sigma = \frac{P_{max} - P_{average}}{3} \tag{2}$$

Since P_{max} is unknown, equation 2 can be rewritten by substituting in equation 1:

$$\sigma = \frac{\frac{P_{average}}{f_c} - P_{average}}{3} \tag{3}$$

Rearranging and combining terms, equation 3 simplifies to:

$$\sigma = P_{average} * k \tag{4}$$

Where $P_{average}$ is the representative heat demand load profile of space heating and k is:

$$k = \frac{1}{3} * \frac{1 - f_c}{f_c} \tag{5}$$

Equations 4 and 5 are used to generate normally distributed heat pump electricity load profiles for all thirty dwellings.

Household electricity demand unrelated to heating is modelled using the ALPG (Artificial Load Profile Generator) (Hoogsteen, Molderink, Hurink, & Smit, 2016). The ALPG generates stochastic household electricity profiles that reflect realistic daily and seasonal consumption patterns, based on device scheduling and predefined household types. The profiles assume fully electric households. The generated household electricity demand and heat pump electricity demand are then combined to form a total electricity load profile for each dwelling.

(iii) System-level implications of full electrification, including photovoltaic electricity generation

As a final step, the influence of rooftop photovoltaic (PV) deployment is explored. Three different PV electricity generation levels are applied at neighbourhood scale to examine their interaction with increased electricity demand due to electrification, as well as related side-effects. The analysis focuses on changes in net electricity demand, self-consumption, and residual load profiles. Carbon dioxide emissions are then calculated for all scenarios using national electricity emission factors.

Results and analyses

Simulation of pre- and post-retrofit heating demand

Following the methodology presented above, the pre- and-post retrofit heating demand for the case neighbourhood were calculated. Table 1 includes the modified parameters of the retrofit strategy. The simulation results (SimStadt and UMGO), as well as the measured (PC6 and In-situ monitoring post- retrofit) annual heating demand of the thirty dwellings are included in Table 2.

Table 1. Input parameters used in heat demand calculations

Thermal characteristics		
Input parameters	**Pre retrofit**	**Post retrofit**
$U_{ground\ floor}$ (W m^{-2} K^{-1})	0.34	0.19
$U_{ext.\ walls}$ (W m^{-2} K^{-1})	0.56	0.12
U_{roof} (W m^{-2} K^{-1})	0.49	0.14
$U_{windows}$ (W m^{-2} K^{-1})	1.8	0.9
U_{doors} (W m^{-2} K^{-1})	3.5	1.1
η heat recovery (%)	0	90%

Table 2. Results of the heat demand simulations and verification figures (average)

Annual heating demand (kWh th.)		
Source	Pre retrofit	Post retrofit
SimStadt	13,786	5,534
UMGO	12,998	4,729
PC6	12,878	-
In-situ monitoring, average	-	5,225

Generation of electricity demand profiles

With the annual heat demand having been determined, the When2Heat (Ruhnau, Hirth, & Praktiknjo, 2019) dataset was referenced, and the year 2012 was selected as an archetypal reference year. This particular year includes a period of extreme cold (-10 °C) that corresponds to standardized design conditions used for Dutch residential buildings. By normalizing the heat demand profiles to a unit-sum distribution and subsequently scaling them by the calculated annual heat demand of the retrofit scenario, the corresponding representative heat pump electricity load profiles are obtained. In this case, an air-source heat pump and radiators are considered for all dwellings.

Figure 2 shows the maximum heat pump electricity load at every one-minute time interval in 2012, averaged over the thirty dwellings. It shows both the underlying daily space heating patterns, as well as the peak heat pump load across all days.

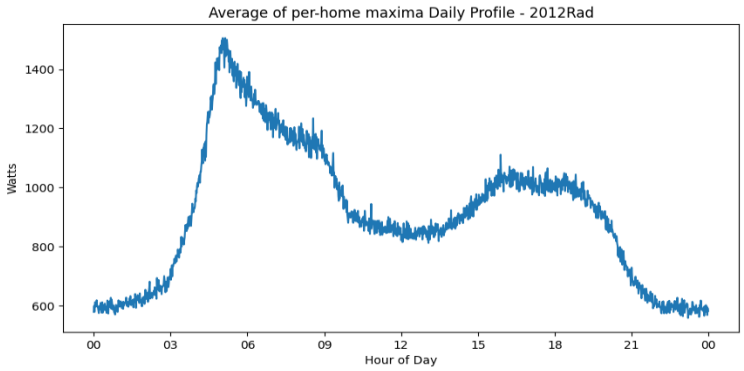


Figure 2. Maximum heat pump electricity load in 2012, averaged over thirty dwellings

Secondly, the ALPG was employed to generate profiles for the electricity demand other than that of the heat pump. Figure 3 shows two household electricity load profiles (without heat pump loads): with electric cooking (left) and without (right).

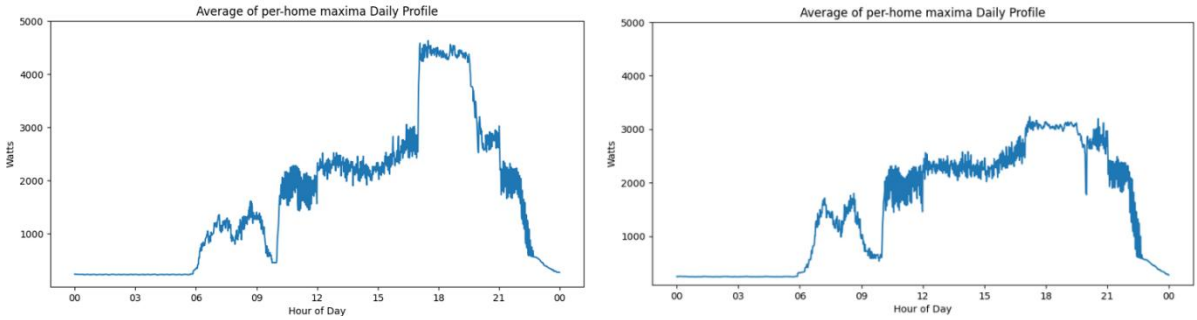


Figure 3. Maximum household electricity load in a year, averaged over thirty dwellings, with (left) and without (right) electric cooking.

Combining the heat pump and household electricity load profiles (with electric cooking), a composite profile is generated representing the aggregated electricity demand for the thirty dwellings. It is observed in the data that at certain times of the year, grid congestion occurs in the post-retrofit scenario: the aggregate coincident power demand at the neighbourhood level exceeds 1.5 kW per dwelling, in the case of thirty dwellings, 45 kW.

Analysis of the week in which the maximum electricity load occurs (Figure 4), shows that the peak cannot be attributed to electric cooking or the heat pump alone. While electric cooking introduces a notable additional peak, the introduction of electric space heating demand shifts the demand higher, leading to a total demand higher than the designed capacity. In addition, a new morning peak appears that was not present in the original situation. In total, using the profile of the year 2012, 473 minutes of exceedance (i.e. >45 kW, dotted black line) was registered, where coincident demand reached as high as 1.8 kW. This amounts to 0.09 % of the year.

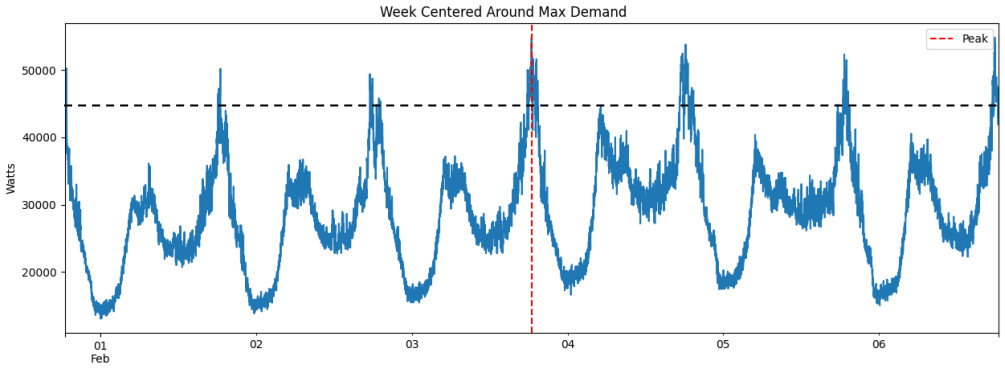


Figure 4. Maximum observed electricity load at neighbourhood level (first week of February)

Verification of electricity demand profiles

To verify the obtained results, a publicly available dataset consisting of six monitoring projects (amounting to 256 homes) of comparable all-electric terraced houses, similar in floor area and annual heat demand, was consulted (Verduijn & Witkamp, 2024). See Table 3.

Table 2. Summary of consulted monitoring project and the case study

Group	**No. of homes**	**Floor area**	**Heat demand**	**Heat generation**	**Annual heat pump electricity use**	**Annual non-heat related electricity use**
#	**#**	**m^2**	**$kWh_{th}\ m^{-2}\ a^{-1}$**	**Type**	**$kWh_{el}\ a^{-1}$**	**$kWh_{el}\ a^{-1}$**
1	100	115	30	Air-source	2105	2790
2	28	87	54	Air-source	1782	2590
3	29	91	35	Ground-source	1222	2139
4	26	85	18	Ground-source	1381	1964
5	25	78	33	Air-source	1424	1654
6	48	99	126	Air-source	2449	2454
Average					**1894**	**2437**
Case study	**30**	**116**	**23**	**Air-source**	**1635**	**2483**

For comparison, three relevant facets were identified from the dataset: (i) Similar to the selected archetypal year (2012), the observation period in which the monitoring occurred recorded a cold period, reaching as low as -8 °C. (ii) The frequency with which the sum of a group's coincident electricity load surpassed 1.5 kW was relatively similar to the case study, i.e. 0.01 - 0.06% (excluding group 2: 0.9 % and group 6: 2.2%) of the observation period. Group 4 recorded no exceedance. (iii) Proportionally adjusted for population, the group averages show similar annual heat pump and non-heat related electricity use.

As illustrated in Figure 5, the monitored aggregate load profile, of all the projects, exhibits a relative shape and amplitude that aligns closely with the generated profile shown in Figure 4. Similarly to the profile generated for the case study, the monitored dwellings show a morning peak, followed by a dip in the afternoon hours, and finally a peak power demand around dinner time. As Dutch terraced houses are constructed in largely the same way, this similarity indicates that the method can at least approximate profiles comparable to a real-world situation.

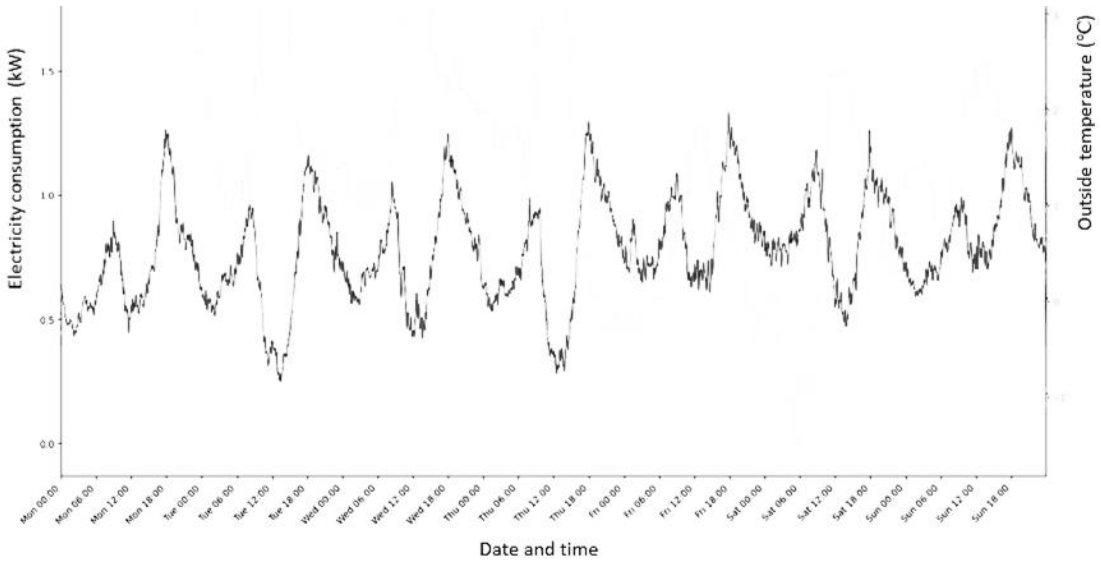


Figure 5. Aggregate electricity load profile of the consulted monitoring project (adapted from: Witkamp, Verduijn, & Opstelten, 2024).

System-level implications of full electrification, including photovoltaic electricity generation

As a final step, using the ALPG, load profiles were generated where each of the thirty dwellings in the case study is fitted with six, ten or fourteen mono-crystalline photovoltaic panels (400 Wp). A summary of the relevant results from the generated profiles is presented in Table 4.

Table 4. Summary of annual production and consumption of installed PV panels

Configuration	Annual overproduction, where P > -45 kW	Curtailed overproduction, where P < -45 kW	Total consumption	Portion of production that had to be curtailed
Name	kWh_{el}	kWh_{el}	kWh_{el}	%
No PV	0	0	123520	0
6 PV	-35876	-10	94620	0.015
10 PV	-61473	-12009	89820	11
14 PV	-76933	-40471	86360	26

When PV panels overproduce electricity and export it back to the grid, allowable maximum power capacity also applies. For PV panels this is not an issue as overproduction can be curtailed. With six PV panels, losses due to curtailment remains negligible (<0.02%). The highest impact appears with fourteen PV panels, where 26% of generated electricity must be curtailed. However, total electricity consumption decreases only slightly as more panels are added, since less of the produced energy can be used locally during the afternoon hours. The

results summarized in Table 4 indicate that in this situation, five or six panels is the optimal number, and in general adding more panels beyond a certain point is not beneficial given the high curtailment.

For the analysis of the CO_2 impact of employing the PV panels, the embodied carbon emissions of the panels (497.2 kg, (Millieudatabase, 2025)) over their lifetime (25 years) are considered. For the case study, this means that installing 6, 10, or 14 PV panels per dwelling amounts to a total embodied carbon emission of 89.5, 149.2, and 208.8 tons, respectively. To determine CO_2-emissions due to electricity generation and consumption, a dataset (ElectricityMaps, 2025) containing dynamic CO_2-intensity values, expressed in gCO_2-eq kWh^{-1}, was used. The dataset covers a four-year period (2021 - 2024). Using a Python script, the CO_2-intensity profiles were multiplied with the electricity consumption profiles adjusted with the PV electricity production. The results are summarized in Table 5.

Table 5. Summary of CO_2 emissions due to electricity generation and consumption

Configuration	CO_2 intensity profile	Import emissions kg-CO_2	Export emissions kg-CO_2	Total emissions kg-CO_2	Avoided emissions kg-CO_2
No PV	2021	46,631	0	46,631	0
6PV	2021	38,263	-10,001	28,262	18.369
10PV	2021	36,724	-17,434	19,289	27.342
14PV	2021	35,686	-22,117	13,569	33.062
No PV	2022	43,085	0	43,085	0
6PV	2022	36,097	-7,671	28,426	14.659
10PV	2022	34,703	-13,662	21,041	22.044
14PV	2022	33,753	-17,727	16,026	27.059
No PV	2023	37,304	0	37,304	0
6PV	2023	31,518	-6,472	25,046	12.258
10PV	2023	30,360	-11,320	19,041	18.263
14PV	2023	29,568	-14,468	15,100	22.204
No PV	2024	35,040	0	35,040	0
6PV	2024	29,957	-5,241	24,717	10.324
10PV	2024	28,883	-9,404	19,479	15.561
14PV	2024	28,146	-12,192	15,954	19.087

Using this data, a trend analysis was performed to determine the CO_2-footprint over the lifetime of the installations. Firstly, analysis of the grid CO_2-intensity shows that it is trending downwards to 19 gCO_2-eq kWh^{-1} in 2050, starting from 405 gCO_2-eq kWh^{-1} in 2020, almost fully in line with the aim of carbon neutrality in 2050. Using the four years of data presented in Table 5, a trend analysis is performed for each configuration, and the CO_2-balance over the lifetime of the panels is predicted. The results are presented in Figure 6.

Figure 6 shows that, except for the scenario with 14 PV panels, the avoided CO_2 emissions as a result of the electricity generation by the PV panels offset the embodied carbon emissions of the panels during their lifetime. It also shows a clear decline in cumulative avoided CO_2 emissions over time. This is because the CO_2 intensity of the grid electricity mix has and will continue to decline with increasing deployment of renewable electricity generation. This trend indicates that if the embodied CO_2 emissions of PV panels do not continue to decline towards CO_2 neutrality, there will come a point at which newly deployed PV panels no longer fully offset the emissions produced over their own lifetimes.

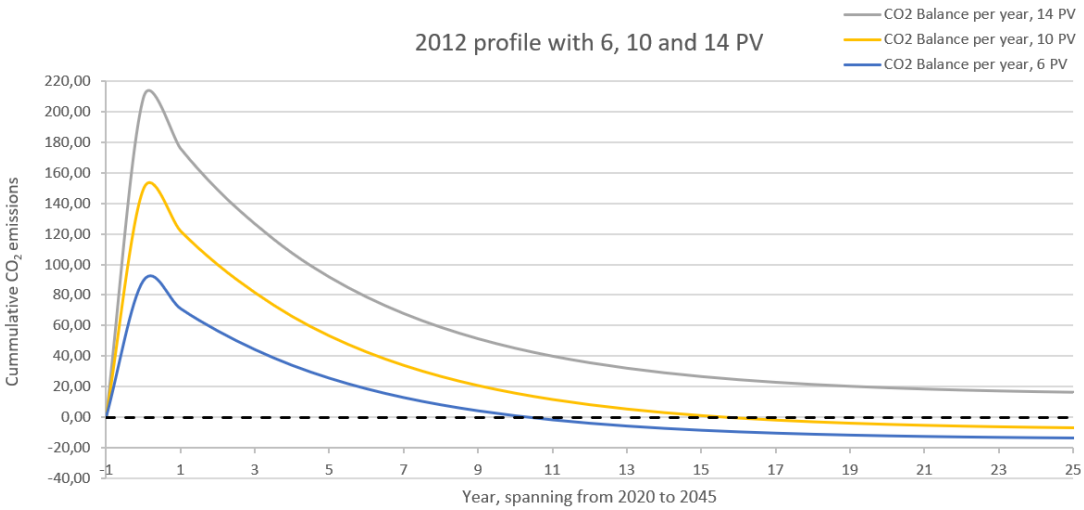


Figure 6. CO_2 emissions over the lifetime of the installed PV panels

Discussion and conclusions

Overall, the results presented in this paper indicate that it is possible to use open-source tools and data for the creation of simulated load profiles that are, to a certain extent, consistent with measured data from comparable retrofit projects. However, a number of limitations of the present study must be taken into consideration. Firstly, each of the used tools carries several assumptions. The ALPG, for instance, treats electric vehicles as flexible loads and excludes them from simulation by default. In practice, EV charging can exert substantial influence on electricity profiles and grid loading. It must also be noted that the method was only applied to a single case neighbourhood and verified against a limited set of six monitoring projects.

Contrary to widespread expectations, the findings of this study indicate that large-scale adoption of all-electric heat pumps may not place as severe of a strain on local distribution grids as commonly anticipated. This challenges prevailing concerns and points toward a potentially smoother pathway for residential electrification. It is noted, however, that the modelled retrofit scenario for the case neighbourhood comprises a high level of thermal insulation (as shown by the heat demand in Table 2), which exceeds common retrofit approaches.

Besides its technical contributions, the presented method offers a practical decision-support tool for municipalities, housing associations, and other stakeholders involved in retrofit planning. By enabling rapid, data-driven assessment of energy use, emissions, and grid impacts at the district level, the approach can help streamline early planning stages and support more informed, scalable strategies for sustainable renovation. The open-source and simple nature of the method allows for a wide range of customizability, including for example the addition of electric vehicle charging loads or battery storage, and other potential future permutations to the existing building stock.

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Extended Abstracts

Thematic session:

Data Management

Automating IFC version control through geometry-aware comparison on building element level

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Keywords: Industry Foundation Classes (IFC), Building Information Modeling (BIM), IFC version comparison, Geometric change detection, Semantic representation.

Extended abstract

Building Information Models (BIM) evolve as design revisions, construction updates, and renovations occur (Esser *et al.*, 2023; Oraskari & Törmä, 2015). With every set of changes to the project or BIM model, a new Industry Foundation Classes (IFC)-based model is exported. The IFC data schema ensures that the model is reusable and shareable across platforms and stakeholders simultaneously or in the future. However, a persisting issue is that as multiple versions of an IFC model accumulate, it becomes difficult to determine what changes have between them. In practice, such differences are often identified through manual inspection or visual comparison, which is time-consuming and difficult to apply consistently. File-oriented comparison approaches are limited because plain text comparison ignores the semantic structure of IFC data and may produce misleading results (Shi *et al.*, 2018). This study proposes an automated workflow to identify and report changes between successive IFC versions of the same building model, producing structured and interpretable change (a.k.a delta) reports.

Previous research has explored both IFC-native and graph-based approaches for model comparison. IFC-native methods analyse entities and attributes directly within the IFC schema, but their results may be unreliable in cases where identifiers such as Global IDs (GUID) change during model exchange, causing identical elements to be interpreted as different ones (Shi *et al.*, 2018). To address these limitations several studies have proposed converting IFC models into semantic graph representations using the Resource Description Framework (RDF) and the ifcOWL ontology, enabling graph-based processing of model changes (Oraskari & Törmä, 2015; Zhu *et al.*, 2023). Graph-based approaches have also been investigated for version comparison and change detection in BIM models (Esser *et al.*, 2023; Oraskari & Törmä, 2015). However, meaningful comparison of geometric information remains challenging because small numerical differences or alternative geometric representations may be detected as changes even when the building element itself has not been modified (Shi *et al.*, 2018).

This study proposes a workflow to compare two IFC files representing different versions of the same building model. Figure 1 illustrates the overall system architecture. The Python-based workflow consists of five layers: input, transformation, comparison and enrichment, interpretation, and reporting. First, two IFC versions (V0 and V1) are converted into RDF graphs (Turtle serialization) using the IFC2RDF converter based on the ifcOWL ontology (Ramonell, 2024). The resulting RDF graphs are compared using RDFLib (RDFLib

Developers, 2025) to detect added and removed triples between model versions. To enable element-level analysis, building elements are matched using their IFC GlobalId. Although GUID stability has been identified as a limitation in previous studies (Shi et al., 2018), it provides a practical basis for element correspondence in the controlled test cases used in this study. In addition, geometric and relational attributes such as element length, height, position, and the number of openings or doors are extracted from the IFC geometry using IfcOpenShell and integrated into the RDF representation. In the interpretation layer, numerical rounding and threshold-based evaluation are applied to distinguish meaningful geometric modifications from minor export-related variations. Detected changes are classified into four categories: (A) entity, (B) property, (C) relationship, and (D) geometry changes. In this study, the analysis focuses on wall-related geometric and relational modifications (C and D), including dimensional changes, positional movement, and variations in openings or doors. The workflow produces a structured delta report, consisting of an Excel-based management report for interpretation and a technical report containing detailed comparison results.

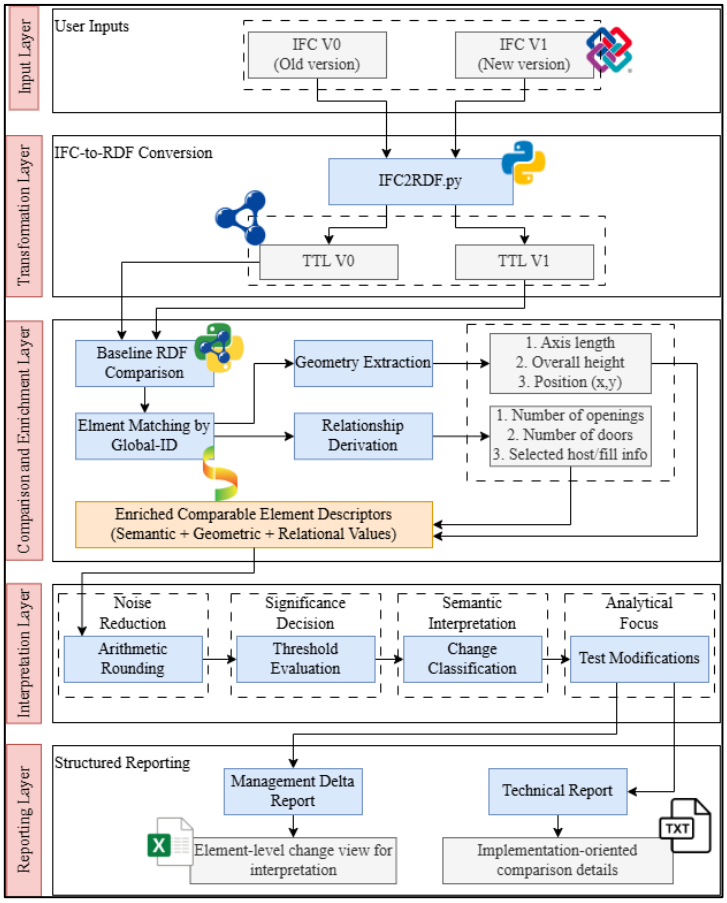


Figure 1. System architecture of the comparison workflow

The workflow was evaluated using controlled test cases derived from successive versions of an IFC model containing a single wall element. The initial model (Model_V0) contains a single wall. In Model_V1, the wall was moved, its height reduced, and a door was added. The generated delta reports demonstrate that the workflow can successfully detects geometric and relational changes, including dimensional modifications, positional movement, and variations in openings and doors. Table 1 presents the structured delta report produced for the comparison between Model_V0 and Model_V1. The report lists detected changes per element using the

IFC GlobalId and includes the modification category, old and new values, tolerance evaluation, and a short textual explanation. In this example, the system detects the reduction of the wall height (4.000 m to 3.600 m), a positional shift of the wall, and the increase in openings and doors due to the added door element. The small difference in axis length (6.000 to 6.005 m) is identified but classified as within tolerance.

Table 1. Element-level delta report between Model_V0 and Model_V1

Element GUID	**0pluSL1nF1faawuHn7Njp**				
IFC Type	**IfcWall**				
Modification	Axis Length Within Tolerance	Overall Height Changed	Moved2D	Openings Count Changed	Doors Count Changed
Tolerance Check	Δ=0.005 <=TOL	Δ=-0.400 >TOL	|Δp|=2.789 >MOVE_TOL	-	-
Change Classification	D	D	D	C	C
Old Value (Model_V0)	6.000	4.000	(x=3.000, y=0.000)	0	0
New Value (Model_V1)	6.005	3.600	(x=5.700, y=-0.700)	1	1
IFC Location	Derived Geometry	IfcWall. OverallHeight	Derived Geometry	IfcRelVoids Element	IfcRelFills Element
Comment	axis length within tolerance	overall height changed by -0.400 m	element moved +2.700 m in X, -0.700 m in Y	number of openings changed	number of doors changed

Overall, this study presented a workflow for semantic and geometry-aware comparison of successive IFC models using an RDF-based representation and element-level delta reporting. The results demonstrate that the approach can identify and organize geometric and relational modifications in a structured and interpretable way, distinguishing meaningful model modifications from minor numerical variations introduced during model export. Although the current implementation focuses on a limited set of wall-related changes, the workflow provides a foundation for automated comparison of IFC model revisions. Future work will extend the evaluation to additional IFC element classes and more complex building models.

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Thematic session:

Parametric and Data Driven Design

Spatial Optimization of Subsurface Utilities: Case Study Amsterdam

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Keywords: Subsurface Infrastructure, Urban Underground, Utilities, Generative Design

Extended Abstract

Currently over half the world's population lives in urban areas, and these spaces are only expected to get more crowded [1]. As more people move into cities, the infrastructure will continue to see increased pressure when trying to support these new residents. They will need sufficient access to the basic needs of water, heat, electricity, waste removal, and internet. At the same time, city planners are trying to create cities that are more environmentally sustainable and enjoyable to live in. All of these needs and aspirations demand more space from the urban underground space (UUS)[2]. A space that for many decades has been ignored by planners and thus is already suffering from disorganization, leading to challenges in planning and costly upgrades [3].

The city of Amsterdam has ambitions of building a more forward-looking urban development. With plans for an Energy Transition, and initiatives like the Greener Infrastructure Vision a significant portion of the buried utilities in Amsterdam will need to be redone. Looking at just the Energy Transition, Gemeente Amsterdam aims to be natural gas free by 2040[4]. With 85% of the homes in Amsterdam using natural gas for heat major change to the subsurface infrastructure [5]. This to say 100's of new design for the subsurface will need to be drafted as each change will require one if not many versions, demanding a lot of time following the conventional process.

The proposed study would aim to understand the possibilities of integrating generative design as a way to explore the use of subsurface space. Error checking and conflict awareness tools already exist or are under development; this research explores ways to improve the iterative design process for laying subsurface utilities. Generative design is an iterative design method that uses computational algorithms to autonomously generate a multitude of design alternatives based on defined goals and constraints. Algorithms used to generate new designs can include topological optimization, artificial intelligence and machine learning techniques [6]. Generative design (GD) has been used widely in the manufacturing industry, and now there has been a growing interest in

the architecture, and structural engineering space. Most relevant to this project, is the capacity for GD to address feasibility during the initial phase of a project [7]. The goal of this research is to see if the GD method can be used to address the question of, is there enough space in the UUS to fit all the desired assets?

Gemeente Amsterdam is in the process of developing an parametric modelling tool for the subsurface using Rhino Grasshopper. This will be used as the input for the generative design process. The initial constraints for the design will be derived from the uitleschema, the official guideline for burying assets. Given that exceptions are frequently made to the uitleschema interviews and working sessions will be required to uncover the unofficial norms that impact how pipes and cables are buried. In addition to the design norms, stakeholders will also be asked to rank the priority of different assets

The project is at its early stages. Appropriate stakeholder are being identified, but working sessions to understand unofficial norms and asset rankings are being planned but not been conduct yet. The outcome of this study is twofold. First, exploring and documenting the unofficial norms that guide the placement of utilities and other assets in the subsurface. Second, to present a proof of concept where GD would produce a 2D designs of the subsurface appropriately integrating stakeholders preference.

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Developing an Inventory-Responsive Matchmaking Framework for Reclaimed Component Integration in Architectural Design

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Keywords: Urban Mining; Reclaimed materials; Structural reuse; Circular construction; Digital tools, Matchmaking tool.

Extended abstract

Introduction

The digitalisation of circularity within the construction sector has substantially improved the documentation and traceability of reclaimed building materials. Material passports, online marketplaces, and inventory platforms now offer structured data regarding component dimensions, provenance, environmental impact, and availability (Byers et al., 2024; European Union, 2024). Despite these developments, reclaimed materials are rarely integrated into architectural practice and remain marginal (Rakhshan et al., 2020; Rose and Stegemann, 2019). The reason is not data scarcity. Most existing circular tools function as repositories or transaction platforms, passive in nature and structurally disconnected from the environments where design decisions are actually made such as BIM, Rhino environments. Conventional architectural design unfolds within iterative, geometry-driven workflows where building components are parametrically defined, adjusted, and evaluated against spatial and performance constraints. In contrast, Reclaimed elements do not conform to this baseline: their dimensions vary, their performance data may be incomplete, and their availability is time-bound. The result is that designers motivated to use reclaimed stock must manually locate external inventories, interpret heterogeneous data, and re-enter selected components through ad hoc workarounds, a process that is slow, error-prone, and produces only a binary outcome (Kröll et al., 2026). Either the component meets the design requirement as specified, or it does not. This all-or-nothing logic conceals near-matches, suppresses adaptation potential, and is incompatible with how architectural decisions are iteratively negotiated. The combined gap between inventory systems and design decision-making is termed here the design-inventory disconnect.

Methodology

This research adopts a Design Science Research (DSR) methodology (Peffers et al., 2007) to develop a solution artefact that directly addresses the design-inventory disconnect. The study proceeds through problem identification, design objective definition, framework development, and prototype implementation, currently in progress. Problem identification draws on a targeted literature review, a digital tool landscape analysis mapping commercial and academic tools against building-layer coverage and design integration, and preliminary observations

within reuse-oriented architectural practices and a demolition contractor in the Netherlands. These inputs established that the missing mechanism is not better data exchange alone, but a compatibility logic capable of operating within the iterative, parameter-driven character of early-stage design environments.

Design and Development

The research artefact under development is the Inventory-Responsive Matchmaking (IRM) framework and its associated standalone computational tool. Unlike earlier conceptualisations focused on a single BIM platform, the IRM tool is implemented as a platform-independent, Python-based application that accepts IFC-formatted inventory data as input. This decision is grounded in the finding that platform-specific implementations create adoption barriers that a design-integrated tool must avoid. The framework introduces a tolerance-based scoring logic in which compatibility between a reclaimed component and a design requirement is treated as a matter of degree rather than a binary pass-or-fail. For each design position, the designer defines target values and acceptable tolerance ranges per parameter. Components are then evaluated parameter by parameter against those tolerances. Where a component falls outside tolerance but within its established adaptability limit, the range within which a component can be modified without losing its reuse value, the system registers a conditional near-match rather than an exclusion. Per-parameter scores are aggregated into a weighted composite compatibility score, producing a ranked, revisable candidate list. The IRM scoring logic is summarised in Figure 1.

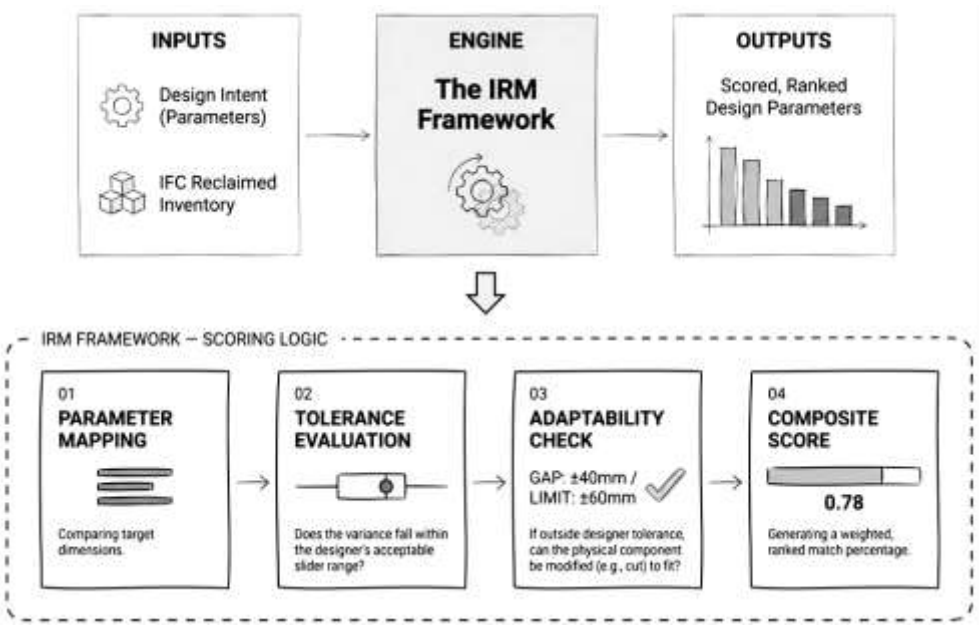


Figure 1. Inventory-Responsive Matchmaking (IRM) logic

A critical feature of the framework is its component typology structure. Rather than treating all reclaimed stock as a generic material pool, components are classified by type, each associated with a defined parameter set and an adaptability profile that distinguishes fixed attributes from those open to acceptable intervention. This distinction determines whether a dimensional mismatch constitutes a hard incompatibility or a workable near-match, and keeps the scoring grounded in what inventory platforms and demolition contractors can realistically document.

The system is structured around three coordinated modules. The Input Module parses IFC component data and extracts relevant parameter fields per typology. The Processing Module executes the scoring and matching logic, applying tolerance inputs, checking adaptability limits, and computing composite scores. The Output Module returns a ranked, scored candidate list per design position with near-match indicators and adaptation guidance through a three-panel graphical interface: a tolerance input panel, a ranked results panel with colour-coded compatibility scores, and a component detail panel.

Based on the tool landscape analysis and initial practice engagement, the building skin layer, encompassing facade cladding panels and window units, is the potential primary demonstration scope. This layer combines high renovation volume in the Dutch context with a near-total absence of dedicated computational tool support among the higher-impact building layers (Kröll et al., 2026). Demonstration and evaluation are planned through a retrospective case study in collaboration with Cityförster, an architectural practice active in circular renovation in the Netherlands. The evaluation will assess whether the IRM tool reduces manual translation effort, supports early-stage decision iteration, and enables more systematic integration of reclaimed components into design workflows..

Conclusion

This research contributes to closing the interoperability gap between reclaimed material inventories and BIM-based design workflows by shifting the framing from a data problem to a logic problem. Scaling up component reuse requires not only improved documentation of available stock but computational intermediaries that translate variable, uncertain material inventories into actionable, graduated design inputs. The IRM framework addresses this through a tolerance-based matching logic that makes compatibility negotiable, positioning reclaimed-material information as active design intelligence rather than passive documentation. The broader implication is that circularity in the built environment depends as much on how reclaimed data enters the design process as on whether it exists at all.

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Thematic session:

Process and Monitoring

AI for Value-Driven Bridge Renewal

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Keywords: Bridge Asset Management, Public Values, Artificial Intelligence, Early Planning and Design, Barrier Mitigation.

Extended abstract

Bridge asset management in the Netherlands has historically emphasised technical performance, safety, and cost efficiency (Van der Velde *et al.*, 2013). Renewal decisions are triggered by ageing infrastructure and expert tend in their assessments to put less focus on broader societal considerations. However, as societal values —such as social inclusion, sustainability, heritage, and spatial quality— get more attention, operational choices in asset management are increasingly expected to align with these values.
This study examines how Artificial Intelligence (AI) can enhance value driven decision-making during the early planning and design (EPD) stages of the Dutch bridge Replacement and Renovation (V+R) programme. While this phase offers the greatest potential to embed long term public value, it remains constrained by fragmented governance structures, technical path-dependencies, and limited operationalisation of public values (Wijnia & Herder, 2010). These conditions contribute to early lock in, limiting the capacity of renewal projects to assess alternatives that reflect societal values and ambitions (Rasker *et al.*, 2023).
Although AI is widely discussed in infrastructure management, its practical use remains narrow and largely confined to technical tasks such as defect detection or predictive maintenance (Shahrivar *et al.*, 2025). Little is known about how AI can contribute to broader societal objectives during EPD stages. The objective of this study is to understand how AI can effectively support the integration of public values in the EPD phase of Dutch bridge renewal projects. The study identifies the fundamental barriers to value integration in the EPD phase and explores how distinct families of AI applications can address these barriers.

Public values and the Early Planning and Design Stage

Public value is defined as the societal benefits generated by infrastructure across time and space, beyond its immediate functional performance. This encompasses contributions to long term well-being, environmental quality, social inclusion, sustainability and heritage preservation. Public values are multidimensional and context specific. They are not reducible to a single performance metric or economic indicator, but reflects shared societal ambitions that evolve over time. As a result, public values often remain implicit or inconsistently applied, particularly in the early stages where project objectives and evaluation frameworks are defined.
The Early Planning and Design (EPD) phase is decisive for determining whether and how public values become embedded in infrastructure. It is during this front end stage—before detailed designs are finalised or budgets committed—that societal ambitions can be defined

and stakeholder perspectives show up. In this study, the EPD phase refers to the pre design and strategic decision-making period in which problem framing, goal setting, and option development occur. This applies equally to the renewal of existing bridges and the development of new structures.

Methodology: Three Step Approach

This study adopts a structured three step methodology. Identifying and validating barriers in the first step consisted of two interconnected phases: literature review and desk research and an empirical validation through three case studies (a municipal movable bridge, a corridor railway lift bridge and highway bridge renewal project) and semi structured interviews.

The second step focused on identifying application families—coherent clusters of AI enabled decision-support environments that align with EPD workflows. AI applications were included only when they met two criteria: applications needed to support at least one of the EPD steps and could plausibly mitigate at least one validated barrier (e.g., improving transparency, broadening evidence, supporting participation, reducing uncertainty).

The third step determines how the identified AI application families can be systematically aligned with the barriers identified. Each barrier was assessed to determine which AI application families directly or indirectly address its core cause. For each barrier, AI families were classified as dominant (directly targeting the root of the barrier) or supporting (contributing indirectly or supplementing dominant families).

Barriers and AI-powered application families

Most barriers identified (step 1) that inhibit public value integration in early-phase bridge renewal projects found in the literature were confirmed empirically in the three case studies. However, based on the interviews and project documentation (e.g., ambition documents, variant studies, workshop notes, and MCDA matrices) several additional barriers emerged. These relate primarily to fragmented ownership and decision-making, communication frictions, interpretive ambiguity around public value, path-dependent lock-in, methodological constraints in the Multi-Criteria Decision Analysis (MCDA), gaps in cross-project learning, and documentation shortcomings.

To analyse how AI can support public-value integration in the EPD phase (step 2), the following nine AI-powered application families were identified (Siddiqui, 2024): Knowledge Graphs & Semantic Search, AI-Supported Engagement Tools, Versioned Dashboards, Digital Twins, BIM + AI , MCDA + AI, Scenario Exploration Tools and Sensitivity Tools. Each family represents a type of integrated digital application aligned with specific EPD activities. This classification therefore reflects how AI is implemented in the EPD phase, where multiple techniques are combined within decision-support tools for tasks such as evidence synthesis, condition assessment, stakeholder engagement, and trade-off analysis.

Mitigating Barriers to Strengthen Public Value Integration

Findings from literature (e.g. Prakash et al., 2025: Srivastava & Narkhede, 2025) and case study interviews show that AI contributes to public value integration in four principal areas.

1. Limited generation of alternatives.

Narrow KPI focus, early technical framing, and path dependency often restrict the option space in early planning. AI-enabled scenario exploration, forecasting, and knowledge-integration

tools keep alternatives open for longer and counteract premature lock-in, enabling more balanced consideration of multifunctional and future-oriented solutions.
2. Insufficient operationalisation of public values.
Public values frequently remain implicit or poorly translated into decision criteria. AI-enhanced MCDA, semantic analysis, and knowledge-structuring tools help convert qualitative values into explicit, evaluable criteria. These tools support a more systematic and transparent inclusion of societal objectives.
3. Weak integration of stakeholder input.
Fragmented, late, or weakly documented engagement reduces legitimacy, limits understanding of local needs, and weakens alignment. AI-supported engagement tools help collect, interpret, and document stakeholder input more systematically. Together, these applications strengthen timely inclusion and reinforce decisions grounded in shared values.
4. Lack of transparency and legitimacy.
Versioned dashboards, sensitivity analysis, and structured decision-support environments increase traceability by clarifying how assumptions evolve and how trade-offs are made. Making uncertainties explicit strengthens confidence in decision processes.

Conclusion

Addressing the four shortcomings mentioned improves the conditions under which societal aims and public values—such as sustainability, inclusiveness, resilience, and accessibility—can be integrated in the EPD phase. Specifically, AI-supported barrier mitigation:

- integrates qualitative, contextual, and technical information;
- enhances the quality and traceability of stakeholder involvement;
- reduces premature lock-in by keeping alternatives and assumptions visible;
- and makes uncertainty and value trade-offs more explicit and auditable.

AI thus enhances the governance quality of early-phase decision-making in bridge renewal projects by integration of public values as early as possible.

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Retrieval-Augmented LLM Framework for Robust Automated Generation of HVAC Diagnostic Models

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Keywords: Fault Detection and Diagnosis, HVAC System, Diagnostic Bayesian Network, Large Language Model, Retrieval-Augmented Generation.

Extended abstract

Fault detection and diagnosis (FDD) are essential for reducing energy waste and maintenance costs in heating, ventilation, and air conditioning (HVAC) systems. While data-driven FDD methods are popular, they are slowly adopted by the building industry due to the lack of the high-quality labelled dataset, the challenge of generalization, and the nature of "black box". Diagnostic Bayesian networks (DBNs), as a probabilistic graphical model, offer effective, robust and interpretable FDD solutions. However, constructing and deploying DBNs in practice is a labor-intensive and knowledge-demanding process. Engineers must simultaneously understand HVAC system behavior, probabilistic reasoning, and modeling or programming skills. This multi-disciplinary expertise requirement creates substantial barriers for practitioners, particularly in Western Europe, where skilled labor shortages further exacerbate the challenge of implementing DBNs at scale.

This work presents an end-to-end large language model (LLM)-driven automated generation framework of DBNs for HVAC systems. This framework mainly consisting of four step: ontology-based prompting engineering, LLM-driven code generation, output validation, and DBN implementation and evaluation. Machine-readable, ontology-based representations of HVAC process and instrumentation diagrams (P&IDs) are used to construct structured and reproducible prompts. To mitigate hallucinations common in LLM-only approaches, we integrate retrieval-augmented generation (RAG) over a library of DBN modules and expert-elicited priors. This knowledge library provides standardized, modular templates of possible symptoms for common faults of components, sensors, and controls in HVAC systems, enabling the LLM to reliably retrieve, adapt, and assemble causal DBN structures tailored to specific HVAC configurations. The framework is currently being evaluated on the task of generating DBNs for four representative air-handling-unit (AHU) faults (heating coil valve stuck, heat recovery wheel stuck, supply air temperature sensor bias, and supply fan stuck) in an office building located in Breda, the Netherlands. Initial experiments using GPT-5.2 show that RAG-enhanced LLMs substantially improve generated symptom correctness compared with non-retrieval LLM baseline. When evaluated on real faulty data, the generated DBNs correctly diagnosed all four fault cases, whereas the non-retrieval LLM baseline succeeded on

only two cases. These results highlight the potential of combining LLMs with structured domain knowledge to accelerate reliable and scalable DBN development for real-world HVAC fault diagnosis. Detailed structure and parameter analysis of the generated DBNs, as well as benchmarking with open-source LLMs, are ongoing.

Acknowledgements

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A Modular Digital Twin Architecture for Urban Flood Resilience

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Keywords: Digital Twin, Flood Resilience, Simulation Integration, Decision Support

Extended abstract

Urban areas are increasingly exposed to flood risks driven by climate change, urban densification, and aging infrastructure. Conventional flood risk assessment workflows rely on fragmented tools and static simulations, limiting their ability to support dynamic, multi-stakeholder decision making. In response, Digital Twins have emerged as a promising approach to integrate data, models, and interactive tools within a unified environment (Batty, 2018). In the context of urban systems, such approaches rely on the integration of geospatial datasets and simulation tools (Agugiaro et al., 2020). However, current implementations still face challenges related to interoperability, scalability, and transparency in model integration (Biljecki et al., 2021).

This paper presents the Resilient Hydro Twin (RHT), a modular Digital Twin architecture designed to integrate flood simulation models, urban data, and user interfaces within a unified and extensible platform. The main contribution of this work is the design and implementation of a modular, stakeholder oriented architecture that enables integration of simulation models and supports reproducible, scalable deployment in cloud environments. In contrast to tightly coupled Digital Twin systems, the proposed approach emphasizes modularity, enabling incremental system evolution and easier integration of new components.

The architecture is organized into three primary layers: (1) a data and model layer, (2) an integration layer, and (3) an application layer. The data and model layer integrates domain-specific simulation tools, including hydrodynamic flood models and impact assessment frameworks, alongside urban geospatial datasets such as 3D building data and other crucial geographical data. These components are created as independent services, allowing them to be deployed and maintained separately.

The integration layer acts as the backbone of the system, managing scenario configuration, data exchange, and coordination between system components. In the current implementation, users can define simulation scenarios through a structured interface, selecting from a library of intervention strategies (e.g., green, grey, and blue infrastructure measures) in combination with predefined climate scenarios. These scenario configurations are stored and managed within the system database.

At present, the execution of simulation workflows involves a human-in-the-loop process, where defined scenarios are processed externally to generate simulation results. These results are subsequently integrated back into the system and made available for visualization and

analysis through the application layer. This approach ensures flexibility and allows iterative refinement of scenarios while the system architecture is still evolving.
The architecture is designed to support future automation of this workflow, where scenario execution, and result generation can be generated directly within the system. This transition would enable a more seamless and fully integrated Digital Twin environment.
In addition, while the current implementation focuses on functional integration, the architecture is designed to accommodate a future semantic layer, which will support improved interoperability and traceability through explicit representation of relationships between data, models, and interventions.

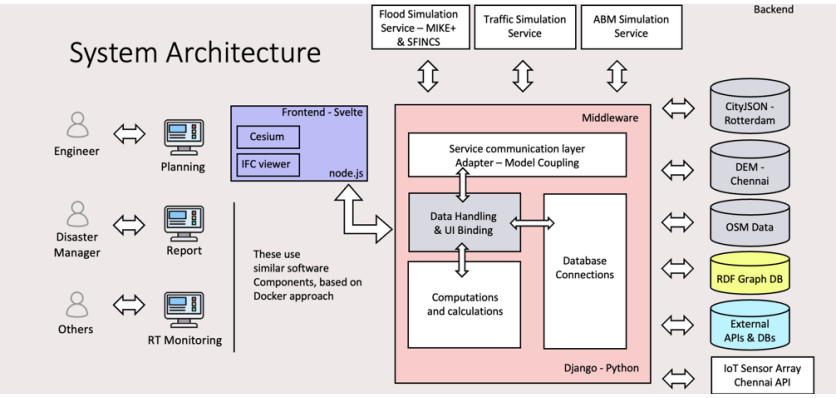


Figure 1. Overview of the Resilient Hydro Twin architecture, illustrating modular components and the central knowledge graph integration.

The application layer provides multiple user interfaces tailored to different stakeholders. A planning interface enables users to define and explore intervention scenarios, while a reporting interface supports analysis and communication of simulation results. A monitoring interface is designed to support integration with real-time data sources. These interfaces share a common backend infrastructure but provide role-specific interaction modes.
The system is implemented using containerization technologies (e.g., Docker) to ensure portability and reproducibility, and is deployed in cloud environments to support scalability. Containerization also allows for setting up modified implementations for different cities. Workflows are designed to support scenario creation, model execution, and result visualization in a coherent pipeline.

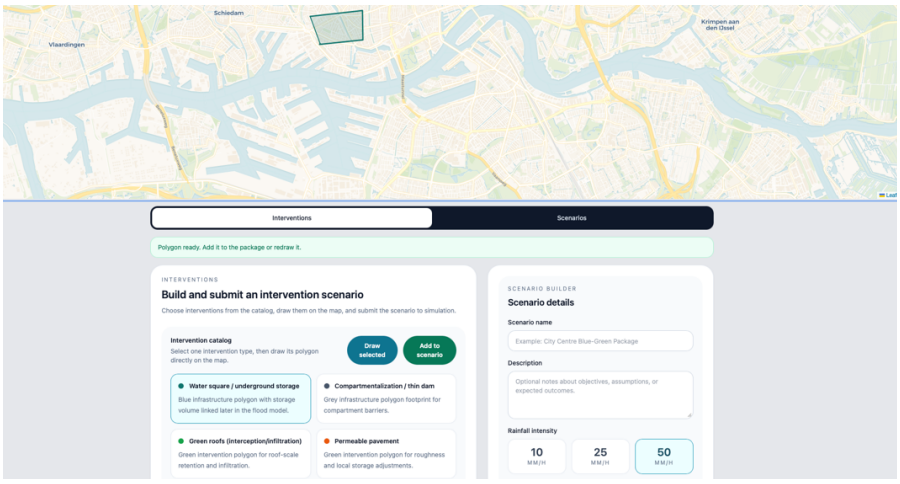


Figure 2. Conceptual workflow of the RHT system, illustrating intervention selection

The RHT is currently being developed and tested using urban datasets from Rotterdam and Chennai, demonstrating its ability to integrate different data sources and simulate flood scenarios under varying conditions. The modular design allows the system to adapt to different urban contexts and incorporate additional models or datasets as needed.
The proposed approach addresses several limitations in existing Digital Twin implementations. Interoperability is partially achieved through modular integration, with further improvements expected through the planned semantic layer. Scalability is enabled by the containerized system design, while transparency is improved through structured workflows. The system also supports multi-stakeholder decision-making processes by providing tailored interfaces for different user roles (Zeiler et al., 2010).
In conclusion, the Resilient Hydro Twin provides a flexible and extensible framework for urban flood resilience, combining modular system design, reproducible infrastructure, and interactive interfaces. Future work will focus on implementing the semantic integration layer, enhancing real-time data capabilities, and evaluating the system in participatory planning contexts. These developments will contribute to more robust and adaptive Digital Twin systems for sustainable urban environments.

Acknowledgements

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Extracting Generalizable Robot World Models from BIM Models

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Keywords: Building Information Models (BIM), Robotics, Robot World Models, Localization.

Extended abstract

Robots are increasingly being deployed in indoor environments such as warehouses and hospitals and are also used in emergency and rescue operations. To operate effectively, a robot must possess knowledge of the environment, its own location within it, and feasible paths for navigation. In scenarios requiring immediate deployment, relying solely on online exploration to map the environment is often insufficient. Instead, prior environmental knowledge is required in the form of a readily available world model. Building Information Models (BIM) provide structured digital representations of indoor environments that can be used as prior world models for robotic deployment. BIM models contain geometric information about building elements such as walls, doors, and furniture, as well as spatial structures like rooms and corridors, together with semantic relationships between them.

Although BIM models contain rich and detailed information, robotic systems require only a subset of the data, specifically the geometric and semantic descriptions of the physical environment relevant to tasks such as planning and localization. However, BIM models are primarily designed for facility design, construction, and maintenance workflows, and are not optimized for the lightweight, real-time queries required during robot operation.. Existing literature focus on extracting task specific world modes, either focusing on extracting geometric information for tasks like robot (Hendrikx *et al.*, 2021) or utilize the semantic information available to create ontological models useful for robot navigation inside a building (Sijs *et al.*, 2021).

In complex environments involving multiple robots performing different tasks and equipped with diverse sensor modalities, it is beneficial for all robots to rely on a single world model that acts as a shared knowledge base. From this common representation, each robot can extract the specific information it requires for its own task, forming its skill-specific view. When changes in the environment are detected by any robot, these updates can be incorporated into the world model and made available to all other robots. This ensures that every robot operates with a consistent and up-to-date understanding of the environment, enabling reliable coordination and reducing the need for redundant mapping across platforms.

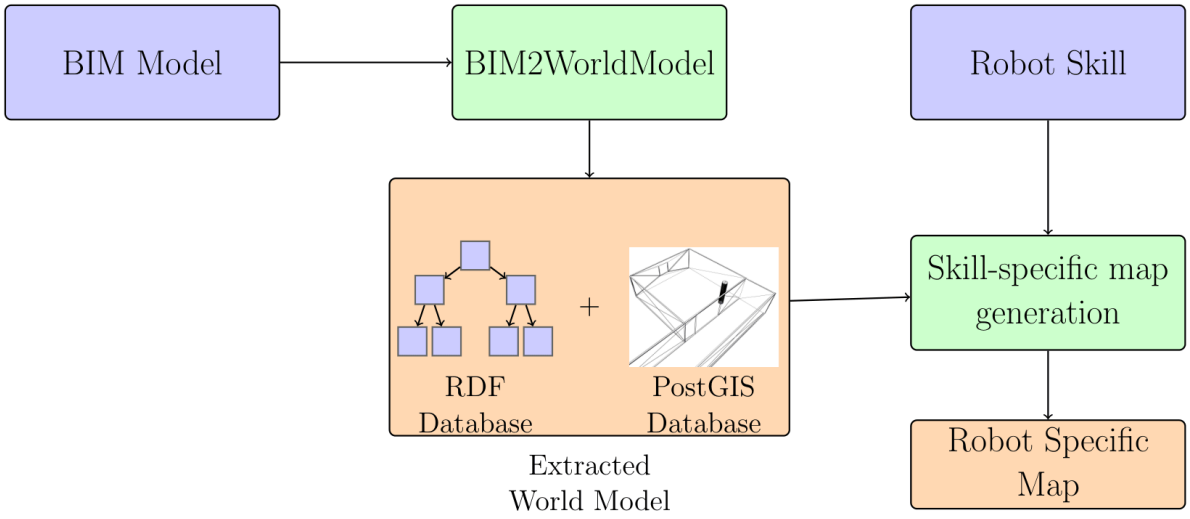


Figure 1. Pipeline from BIM Model to Robot World Model, and extraction of Skill-specific maps from the Robot World Model. Blue Boxes: Inputs. Green: Novel Algorithms. Orange: Outputs

We therefore propose an online-queryable world model that represents the environment in terms of its individual physical components rather than task-specific abstractions. . The model is initialized from an available BIM model, but operates independently as a live, queryable, and updatable world model. A persistent link to the source BIM model is maintained through the unique element identifiers (GUIDs) assigned to each building element, enabling updates to propagate in both directions. To structure the semantic content, we build on linked-building-data approaches using the Building Topology Ontology (BOT) (Rasmussen et al., 2021). BOT captures core topological concepts such as spaces, building elements, and their spatial relationships, represented here through RDF knowledge graphs (Pauwels et al., 2023) that are machine-readable and efficiently queryable. For geometric content, we store building-element surfaces as Triangulated Irregular Networks (TINs) in a PostgreSQL spatial database via PostGIS. TINs serve as lightweight yet accurate geometric representations, and PostGIS provides 2D and 3D spatial operations that allow task-specific geometric features to be computed directly from stored meshes.

The contributions of this work are as follows:

1. **A generalizable, element-centric world model** initialised from BIM data and maintained as an online, queryable, and updatable representation. The model is composed of a semantic graph database and a spatial geometry database. A persistent link to the source BIM through element GUIDs enables consistent updates in both directions, and initialization from BIM allows re-use of existing semantic-geometric facility models across a wide range of building types and levels of detail.
2. **A robot-specific view extraction pipeline** that dynamically generates task-oriented maps through the joint querying of the semantic graph and spatial databases based on a robot's sensor suite and task requirements, without modifying the underlying world model.
3. **A real-world validation** in a large-scale university building by generating the full world model and extracting robot-specific views for multiple robotic skills Using this world model, we construct three robot-specific views:

(i) a 2D LiDAR scan-matching map considering only the obstacles that are at the height of the Lidar's sensing zone, and filtering out elements not detectable to the sensor, such as transparent materials.

(ii) a 2D navigation costmap, containing only obstacles that can impede robot motion.

(iii) a semantic-localization map, geometric landmark features used in a factor-graph-based localization approach (Hendrikx et al., 2021).

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Thematic session:

Data Modelling

The Energy ADE 3.0: A CityGML Application Domain Extension for Urban Building Energy Modelling

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Keywords: Data Modelling, Standardisation, CityGML, Energy ADE, UBEM.

Extended abstract

Semantic 3D city models have established themselves as one of the relevant components of any Urban Digital Twin. The reason is that they can act as a source of harmonised spatial and non-spatial information, they can offer a series of interfaces to interact with such data, and allow for the development of domain-specific urban applications ranging from flood risk analysis to management of the built environment assets, to sustainability-related topics such as the assessment of the energy performance of the building stock, or the evaluation of the implementation of nature-based solutions.
The adoption of standards facilitates the adoption of semantic 3D city models and, as a result, the creation of Urban Digital Twins and the development of applications based on them. To this extent, when it comes to (geo)spatially enabled Urban Digital Twins, the most relevant international standard is CityGML by the Open Geospatial Consortium (OGC). CityGML offers an open data model and information exchange format, in that it defines classes and relations for 3D urban objects such as buildings, infrastructures, water bodies, vegetation, etc. Such objects are represented not only in terms of geometry but also topology, semantics, and appearance. For example, a building can be modelled through semantically distinct geometries (e.g. for roof, wall, and ground surfaces) as well as specific attributes such as the year of construction, the building function, the number of storeys, etc. CityGML 2.0 has been published in 2012 (OGC, 2012), while CityGML 3.0 has been published in 2021 (OGC, 2021). The latest version contains several enhancements to the conceptual data model, but is not yet widely adopted, although it is expected to eventually become the new reference data model in the near future.

In order to enrich the modelling capabilities of CityGML and to allow for to facilitate multi-scale Urban Energy Modelling applications, development of the Energy Application Domain Extension (ADE) started in 2014 and led to the release of version 1.0[1] in 2018 (Agugiaro *et al.*, 2018). A minor, updated release (version 2.0[2]) was then published in 2019. The Energy ADE has been conceived from the very beginning to offer an open and standardised data model to

[1] https://www.citygmlwiki.org/index.php/CityGML_Energy_ADE
[2] https://www.citygmlwiki.org/index.php?title=CityGML_Energy_ADE_V._2.0

deal with energy-relevant data at building and urban scale. Since its initial release, the Energy ADE has already been used several national and international projects (e.g.: Malhotra *et al.*, 2019; Rossknecht *et al.*, 2020). For example, it is possible to better exploit semantic 3D city models to perform simulation and computation of the energy performance of the building by means of a bottom-up approach that starts at the building (or building sub-part). Since 2018, the experiences collected, as well as the release of CityGML 3.0 in 2021, have led to forging new ideas to update the Energy ADE. For this reason, since 2024, a new and updated version of the Energy ADE (version 3.0) is being developed (still) as an extension of CityGML 2.0. A detailed discussion of all changes and improvements so far is beyond the scope of this extended abstract, therefore only a general overview and some specific details will be provided here. The interested reader is nevertheless invited to refer to the resources available in the GitHub repository[3], which contains, among the rest, extensive documentation on the data model and a detailed list of changes since the previous versions. In addition, further information can be found in (Agugiaro and Padsala, 2025).

The development of the Energy ADE 3.0, like the previous versions, has been driven by two main objectives: a) to store and manage energy-relevant data collected at urban scale, b) to provide data to assess the energy performance of buildings using a variety of different approaches and software tools, e.g. ranging from standard-based energy balance, to dynamic simulations by means of specific simulation software programs. The following goals have been additionally envisioned for version 3.0: c) to update the data model based on the experiences collected since the previous releases, and finally d) to design/improve the data model in order to avoid future conversion issues when porting it to CityGML 3.0.
The Energy ADE 3.0 builds upon and expands the previous versions of the Energy ADE. As briefly mentioned before, it is based on CityGML 2.0 modules (namely, the Core, the Buildings, and the CityObjectGroup ones) and extends some of their classes while adding its own classes, enumerations and codelists. As of beta 8, the latest version, still being in active development at the time of writing (March 2026), the Energy ADE is structured in a modular way, as depicted in Figure 1. The thematic modules are briefly described here:

- The **Core module** (represented in light pink in Figure 1) defines additional attributes for the CityGML core::*_CityObject* class. It also provides new abstract base classes for the other modules;
- The **Building module** (in yellow) defines additional attributes for the CityGML bldg::*_AbstractBuilding*, bldg::*_BoundarySurface* and bldg::*_Opening* classes. Additionally, it defines new classes to define *Zones* (e.g. thermal zones) and the thermal hull and thermal openings of a zone, as well as the building and/or zone occupancy characteristics;
- The **Devices module** (in orange) provides classes to model different types of energy-related devices that are responsible for transforming or storing energy (e.g. solar collectors, storage devices, etc.). Additional specific classes, e.g. for HVAC, may be added in future versions, depending on feedback collected from users;
- The **Urban function areas module** (in dark green) allows to define spatial entities that allow to aggregate values, e.g. at neighbourhood or district level;
- The **Weather station module** (in dark blue) contains a class to model weather stations;

[3] https://github.com/tudelft3d/Energy_ADE

- The **Material and Layered Construction module** (in blue) enables the modelling of the composition of construction surfaces through different layers and their physical properties;
- The **Resources module** (in light violet) allows to model resources (energy, water, food, etc.) that any urban object may demand, produce or store;
- The **Schedules module** (in dark pink) comprises classes for different types of schedules;
- The **Time series module** (in light yellow) comprises specific classes for different types of time series. They are used to add time-dependent values to the other module parameters;
- The **CodeLists** (in white), **Enumerations** (in dark grey) and **DataTypes** (in light orange) **modules** contain support classes that are needed by the other modules.

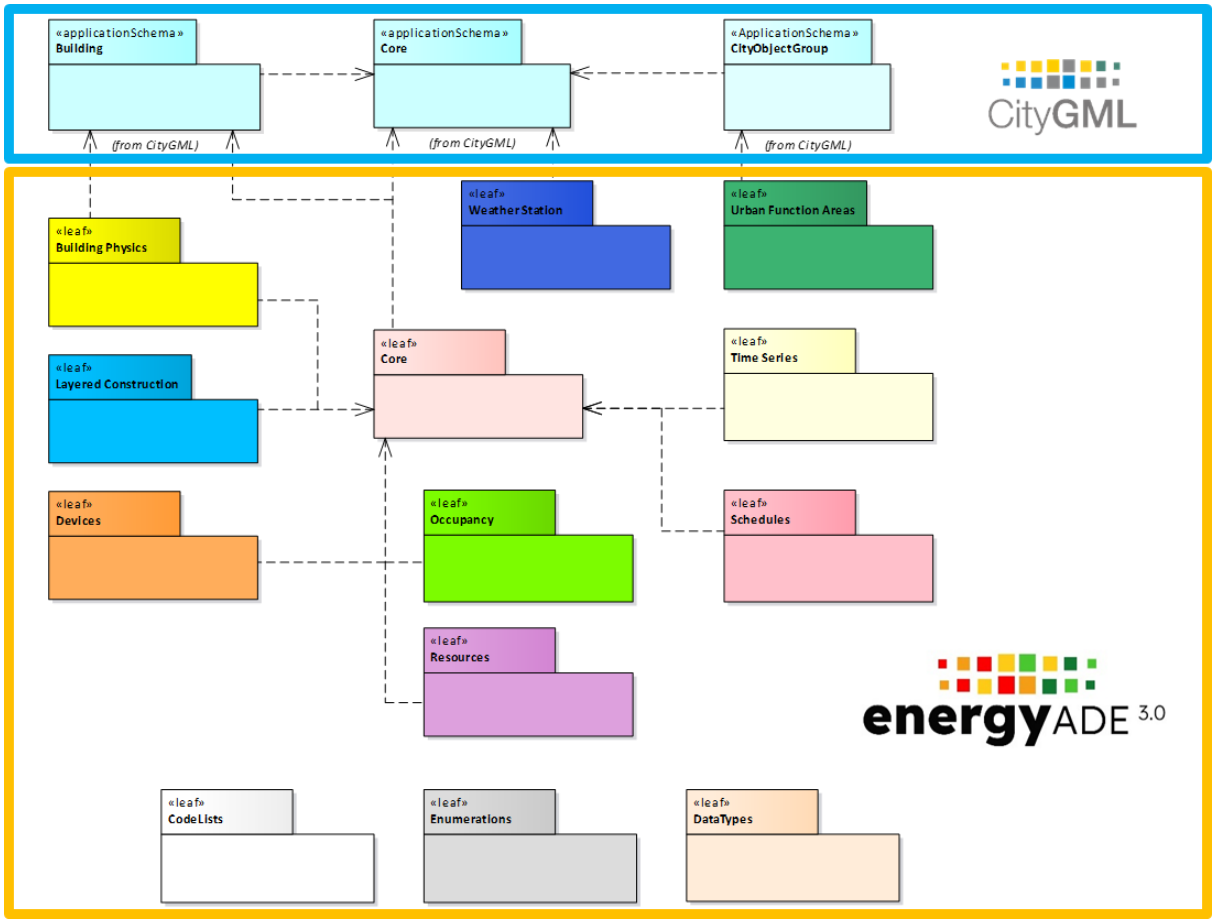


Figure 1. Overview of the Energy ADE 3.0 packages, indicating also the dependencies between the different modules and the relation to the CityGML modules.

Besides the conceptual model in UML (and the accompanying technical specifications), additional resources are either already available or planned.. While for the previous beta 7 all resources listed here are already available, the corresponding ones for beta 8 are currently being updated and prepared. They are:

- **DDL scripts** to set up the 3D City Database automatically using the Java-based ADE Manager, a plugin of the free and open-source CityGML 3D City Database Importer/Exporter[4]. This software allows to automatically generate the required new tables for the Energy ADE 3.0 that will be added to the default database schema of CityGML 2.0.

[4] https://github.com/3dcitydb/importer-exporter

- An **FME Workbench** that allows to import CityGML 2.0 + Energy ADE 3.0 data into the 3D City Database
- **Test datasets** that focus on different aspects/modules of the Energy ADE and can be used to testing or learning purposes
- A **set of modelling rules and suggestions** explaining how to use certain classes of the Energy ADE 3.0 (they are part of the documentation)
- Additionally, **Java-based libraries** are being developed by HFT Stuttgart to add support to the citygml4j[5] APIs and to the CityGML 3D City Database Importer/Exporter.

The Energy ADE 3.0 is being currently developed mainly within the framework of the European project DigiTwins4PEDs[6]. The project wants to use Urban Digital Twins based on semantic 3D city models to push the transformation towards positive energy districts. As a consequence, data from the case studies in the municipalities of Rotterdam, Stuttgart, Vienna and Wroclaw have already been collected and used to test (and further develop) the Energy ADE 3.0 date model, focusing for example on heating and cooling demand of the building stock, and how to reduce them. Further details on the case studies and the specific challenges tackled in each city can be found in (Gao *et al.*, 2025; Padsala *et al.*, 2025).
Nevertheless, since September 2025, the whole development resources have been made open in the dedicated GitHub repository and the development is now being carried thanks to a open consortium that brings together different stakeholders, experts, early adopters and technology enthusiasts. Despite still being in active development, the Energy ADE 3.0 has already proven to represent a valuable improvement compared to the previous versions. Its development will continue thanks to other research projects expected to begin in 2026, but the hope is that more interested people will join, test it, and provide constructive feedback to further enhance the current capabilities thanks to the open development approach.

Acknowledgements

The work presented in this paper has been mainly developed in the framework of the European project "DigiTwins4PEDs" (Utilisation of urban digital twins to co-create flexible positive energy systems for districts). The project is funded by the European Commission under the Horizon Europe Partnership scheme (Funding Indicator: 03EN3081A). The DUT Call 2022 also contributes to the Urban Transition Mission of Mission Innovation as part of the MICall 2022. In Germany, funding for "DigiTwins4PEDs" is granted by the Federal Ministry for Economic Affairs and Climate Protection (BMWK).
Since 2026, further development is being carried out in the European project "FlexPED" (Energy Data and Flexibility Management for Positive Energy Districts), funded by the European Commission under the Horizon Europe framework programme (DUT Call 2024, part of the MICall 2024).
Finally, the suitability of the Energy ADE 3.0 in the context of the Digital Renovation Passport for buildings is being investigated within the project "RenoDAT" (Accelerating building renovation and decarbonization through data integration), funded by the Dutch Research Counsil (NWO) in the framework of the Research programme on Digitalisation of Energy Renovations in the Built Environment, Mission-driven call (KIC 2020-2023).

[5] https://github.com/citygml4j/citygml4j
[6] https://digitwins4peds.eu

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A glimpse of the CityGML Scenario Application Domain Extension

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Keywords: CityGML, ADE, Urban Digital Twins, Scenarios management

Extended abstract

The increasing diffusion and adoption of CityGML-based semantic 3D city models in recent years has led to a growing number of applications being developed upon them. These models serve as convenient information hubs for computing several alternative scenarios to assess the qualitative and quantitative effects of interventions at multiple scales. However, the CityGML 2.0 data model (OGC, 2012) does not provide a standardised mechanism for representing scenarios. Nevertheless, this gap can be addressed through the extensibility mechanisms offered by CityGML's Application Domain Extension (ADE). Currently, when users want to store multiple simulation results that often refer to parameters defined by a projection scenario, they must either use the current specification and store relevant information in the current structure (e.g., the *name* or *description* of a *CityObject*) or add *GenericAttributes* to facilitate differentiation between scenarios. However, this approach does not follow a standardised approach and does not relay on clearly semantically and structurally defined classes or attributes.

The Scenario ADE presented in this document builds on a data model first proposed by Agugiaro (2018) and is therefore currently built and meant for CityGML 2.0. However, this work, while still being in active development, adopts a simplified version of that proposed data model for two main reasons. First, several modules from other established ADEs already cover parts of the earlier design – for instance, the Time Series module in the Energy ADE (Agugiaro & Padsala, 2025). Second, this data model aims at offering a generic approach, but starts with a small set of classes, tailored to specific use cases. The current design draws some inspiration also from the Versioning and Dynamizer modules in the latest CityGML 3.0 (OGC, 2021), but does not backport all capabilities and tries to focus on a formal definition and characterisation of scenarios. Nevertheless, additionally CityGML 3.0 functionalities might be backported in future if necessary.

Within this context, the Scenario ADE is designed to provide a structured mechanism for modelling "what-if" situations and their associated outputs. In a district-scale energy application, for example, a set of buildings may be evaluated through different energy-demand simulations under multiple hypothetical conditions. Besides a reference baseline or *status quo* situation, typical scenarios include changes in refurbishment rates, modifications to photovoltaic system deployment, or other urban-energy interventions. The Scenario ADE formalises how such scenarios and their results are represented, linked, and managed within a CityGML-based data model. Being able to store all this information has the additional

advantage of fostering simulation transparency and reproducibility, which is crucial, as simulation settings are often not explicitly documented or are lost after the simulation is run and the results are collected. Additionally, these simulations can also generate massive amounts of "what-if" data if run with parameters regarding refurbishment, PV adoption, and climate adaptation, to name a few. Managing these "*parallel futures"*, in which one building might have multiple renovation paths, is important for supporting decision-makers in allocating resources (Zvarikova et al., 2022). Additionally, further analyses can help identify vulnerable clusters, optimise grid stability, and prepare cities for the effects of climate change.

The default CityGML 2.0 data model represents cities at a single point in time. Although the data model includes a simplified mechanism to track temporally ordered versions of CityObjects, it lacks a standardised method for managing concurrent future alternatives to a single dataset. This absence leads to potential data redundancy, as users must duplicate city models for each scenario variant, complicating the data management and, finally, the evaluation of the impact of specific interventions across scenarios.

In the context of Urban Building Energy Modelling (UBEM), the term "scenario" is often used loosely to refer to any general future projection. However, to develop a robust and interoperable data model, a scenario must have a semantically and structurally clear definition, as it must eventually be decomposed into discrete, quantifiable, and storable components that can be programmatically retrieved, executed and compared. For this research, a scenario is defined as the intersection of three primary pillars: Membership (describing which elements (e.g. CityObjects) are part of a scenario), Intervention (describing the modifications applied to CityObjects), context (defining external environment conditions), and Configuration (ensuring the reproducibility of the scenario).

To avoid the excessive complexity of a generalised framework, the scope of the Scenario ADE is currently deliberately restricted to energy simulations, PV adoption, and building refurbishment. This focused scope allows for an iterative methodology. For example, by continuously testing and validating concepts with domain experts and with colleagues within the DUT 2022 DigiTwins4PEDS[1] project, the data model is being developed incrementally, ensuring that it remains also practically applicable.

The current version of the Scenario ADE (Figure 1) is built around four main classes: *Scenario, ScenarioMember, AbstractScenarioModification,* and *AbstractGenericParameters*. Further description of each of the classes is as follows:

- *Scenario* is a CityObject that:
    - Carries basic metadata (type/code, validity period, project name), and can be further characterised using standard CityGML's *generic attributes* (inherited via abstract class *_CityObject*).
    - Aggregates a list of *ScenarioMember* entries (each one targets a CityObject and marks the operation to apply).
    - Can hold scenario-level modifications (e.g., define a schedule or construction used by many members).
    - It can depend on other *Scenarios*.
- *ScenarioMember* is derived directly from GML AbstractFeature and:

[1] http://digitwins4peds.eu

    - Points to exactly one CityObject (of any thematic module, therefore also those defined by other ADEs).
    - States the operation on that object
    - Can carry member-level modifications (e.g., the schedule just for this object) that indicate the participation of the linked *CityObject* in the corresponding scenario.
- *AbstractModification* is derived directly from GML AbstractFeature. It represents modifications applied either to a whole scenario, or to specific scenario members. It is further specialised into:
    - *LayeredConstructionModification*, which links to a feature meant to contain information about layered constructions (e.g. see Energy ADE)
    - *ScheduleModification*, which links to a feature containing a schedule
    - *DescriptiveModification* is a meant to represent, simple, descriptive modifications.
    - *PropertyModification* targets a specific attribute of a feature via attributeRef (e.g. a string containing a XPath or a JSONPath query) and assigns it a new value.
- *AbstractGenericParameters*. This class (and its subclasses) is designed to be conceptually similar to CityGML *generic attributes*; however, it offer more data types and can be used also for features that are not derived from class *_CityObject*.

Once a Scenario object is created and acts as a container, if we need to represent "what happens to which object", a *ScenarioMember* shall be created for the affected *CityObject*, setting the corresponding operation and a reference to the targeted *CityObject* (e.g. via XLink). When recording the change to the corresponding *CityObject*, e.g., a new insulation build-up, a new *LayeredConstructionModification* shall be added, either at the Scenario level (shared by many members) or at the Member level (only for one object). The data model also supports temporal scoping definitions for each element using properties such as *validityFrom/validityTo*. Finally, it is possible to represent interdependencies between different scenarios using the *dependsOn* property (e.g., Scenario B assumes that Scenario A's measures are already in place).

The conceptualisation and validation of Scenario ADE follow a well-established methodological workflow specifically designed for CityGML ADEs by van den Brink *et al*. (2013) and used also for other ADEs, e.g. see Bachert *et al*. (2024). By adhering to this workflow, the UML model is structured to support both formal validation and automated schema derivation. Once the UML model is generated, the XML Schema Definition (XSD) file can be automatically derived using the free and open-source software tool ShapeChange (Echterhoff et al., 2016/2024). In the case of the Scenario ADE, resulting XSD file has been also carefully checked to ensure the correctness of the classes and properties. This process is fundamental for later DDL scripts that will generate the database schema for the open-source 3D City Database 4.x (Yao *et al.*, 2018) using the ADE Manager plugin (Yao and Nagel, 2022). As a result, at the moment, Scenario ADE data can be written and stored using both the XML and SQL encodings.

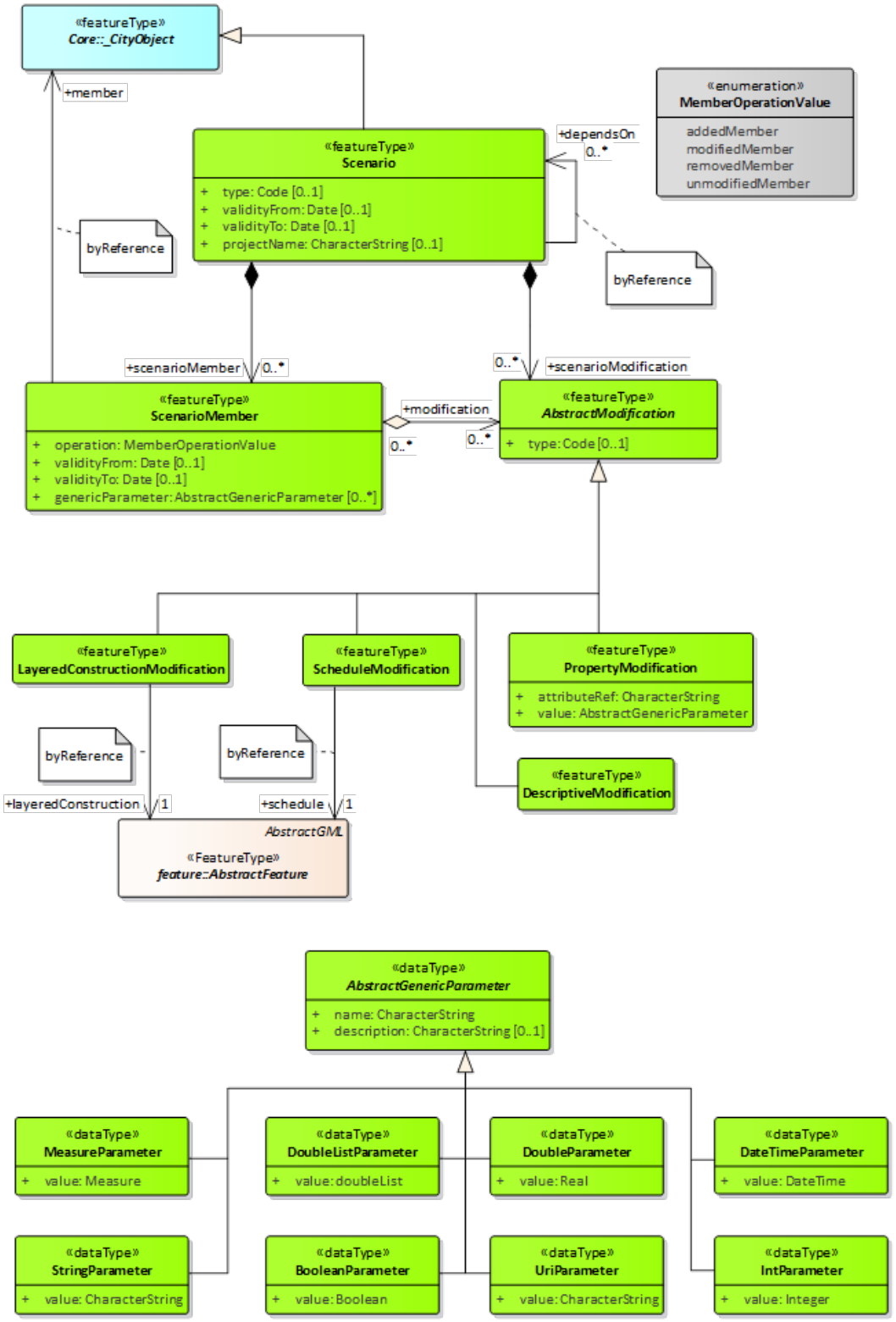


Figure 1. Overview of the Scenario ADE data model

Actual testing of the proposed data model has been carried out in the context of the European project DigiTwins4PEDs, in which strategies to foster the transformation towards Positive Energy Districts (PED) are being implemented using CityGML-compliant Urban Digital Twins of case studies in four cities: Rotterdam in the Netherlands, Stuttgart in Germany, Vienna in Austria and Wroclaw in Poland. In the case of Rotterdam, the case studies are located in the

districts of Feijenoord and Prinsenland (Figure 2). Key open-source data have been collected and processed for these districts (Gao et al., 2025). First, these data are used to perform several energy-related simulations. Then the outcomes of these simulations serve as a baseline for comparing changes in the district elements.

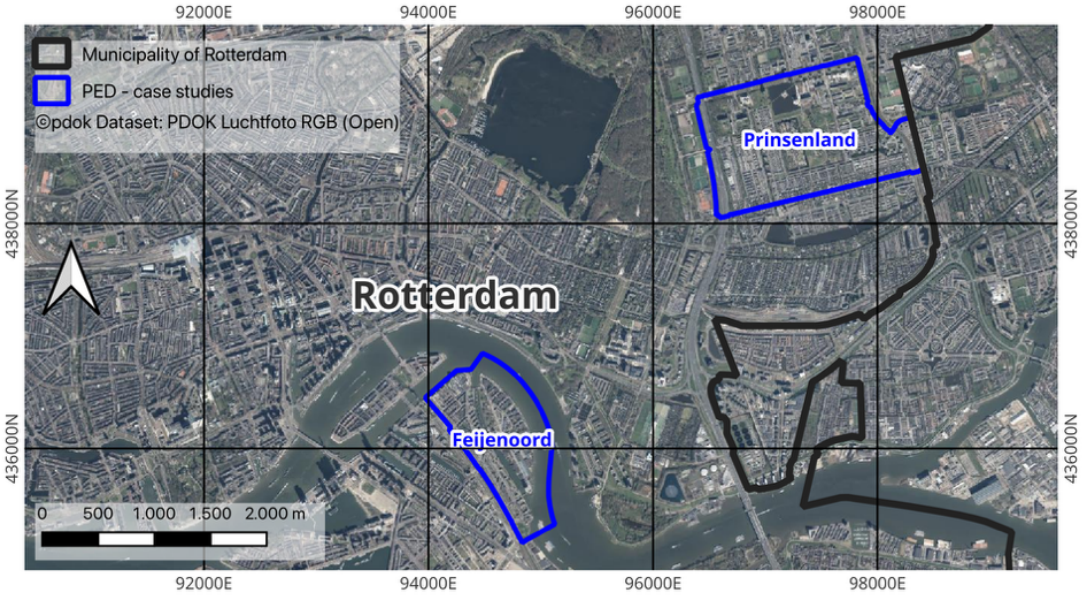


Figure 2. Location of Rotterdam districts Feijenoord and Prinsenland

Energy simulations can vary significantly based just on parameter selection. Such a situation might significantly impact the results. Therefore, to test the Scenario ADE data model, we used parameters and outputs from several SimStadt workflows as input to the proposed Scenario ADE data model for the case studies. Our tests include using two solar irradiance models for the PV potential analysis workflow and either a fixed window-to-wall ratio for all buildings or specific values per surface to define the building's thermal envelope.

To explicitly demonstrate the model's applicability and evaluate its functionality, tests were conducted using both previously mentioned encodings: XML and SQL. For the XML encoding, a data transformation workflow was developed using Safe Software's FME tool to map and write the scenario parameters into a standard CityGML file. As shown in the XML excerpt shown in Figure 3, the XML structure encapsulates two scenario objects within the same city model.



Figure 3. XML excerpt of a test file with Scenario ADE data.

In parallel with the XML encoding, the SQL encoding was tested directly in the database environment. We have created several Python scripts to store simulation results in a 3DCityDB instance that contains both the Energy ADE 3.0[2] and the current development version of the Scenario ADE. The scripts support the output of the following SimStadt workflows: PV potential analysis, Heat demand analysis and Load profile workflows. Once the Scenario ADE reaches a sufficient maturity, the corresponding Java libraries to support the 3DCityDB Importer/Exporter software are planned to be developed, eventually facilitating the usage of this ADE.

This work has presented a proposal for a data model to extend the CityGML 2.0 standard by means of an Application Domain Extension (ADE) with the purpose of facilitating the modelling of "what-if" scenarios and the results of different simulations (in our case, energy simulation results on the building stock at the urban level). Although still in active development, the current version of the Scenario ADE has proven to be a good starting point. Further testing and additional investigation are underway to define a more detailed data model that allows the inclusion of additional elements from the CityGML data model, such as for example Appearances.

[2] https://github.com/tudelft3d/Energy_ADE

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The work presented in this paper has been developed in the framework of the European project DigiTwins4PEDs (Utilisation of urban digital twins to co-create flexible positive energy systems for districts). The European Commission funds the project under the Horizon Europe Partnership scheme (Funding Indicator: 03EN3081A). The DUT Call 2022 also contributes to the Urban Transition Mission of Mission Innovation as part of the MICall 2022 initiative.

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Ontology for Verified Test Trench Data in Underground Infrastructure Management

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Keywords: Test trenches, 3D modelling, IMKL, Linked Data, Subsurface digitalization

Extended abstract

Test trench excavations produce centimetre-accurate three-dimensional measurements of underground utility positions, yet this verified ground truth is seldom preserved beyond the project that generated it. The absence of a shared semantic framework results in a cyclical verification process where each excavation project must independently rediscover subsurface conditions. This extended abstract presents the Universal Test Trench (UTT) ontology, a semantic data model developed as an OWL/RDF extension to the Dutch IMKL standard. UTT integrates linked data principles with three-dimensional geometric modelling to formalize concepts for trench geometry, field observations, position deviations, measurement quality, and verification provenance. The design enables cross-organizational data exchange within a distributed architecture that preserves data ownership. This paper describes the problem context, the ontology design rationale, the resulting model structure, and the planned trajectory toward prototype implementation.

Introduction

Despite the Netherlands having a regulatory and digital framework for underground infrastructure management, excavation damage remains structurally persistent. The KLIC system facilitates the exchange of underground asset data, while the Information Model for Cables and Pipelines (IMKL) provides the standard for representing this information. However, these frameworks do not systematically integrate field-verified observations obtained during test trench excavations. As a result, high-value ground truth data is generated repeatedly across projects but rarely reused beyond its immediate contractual context.

A test trench *(proefsleuf)* is a narrow, controlled excavation dug to physically expose and inspect buried utilities before construction or maintenance activities commence. Test trenches are routinely excavated to physically verify the presence, depth, and position of underground utilities prior to construction activities. These excavations produce precise spatial and attribute information, often revealing deviations between registered asset data and actual in-situ conditions. However, the resulting datasets are heterogeneous in format and fragmented in storage, ranging from PDF reports and sketches to GIS files and increasingly 3D LiDAR or GPR scans (Verhagen & Borsboom, 2009). The absence of a structured semantic framework prevents these verified observations from contributing to a cumulative and interoperable

knowledge base, resulting in a cyclical verification process where each project effectively "rediscovers" the subsurface (COB, 2023, 2024).
This research addresses the standardisation gap through the Universal Test Trench (UTT) ontology, a semantic extension to IMKL 3.0 that formalises verified trench observations within a linked data framework. The guiding research question is: *How can verified 3D trial trench data be semantically structured and shared in a distributed environment while preserving data ownership?*

Methodology
The ontology was developed following a design science methodology (Wieringa, 2014), treating the semantic model as the primary design artefact. Ontology engineering follows the Linked Open Terms (LOT) methodology (Poveda-Villalón et al., 2022), which integrates competency question formulation with iterative development and validation. Requirements were elicited through analysis of COB feasibility study reports; systematic review of IMKL 3.0 and NEN 3610 documentation to establish alignment constraints with national geo-information standards; and iterative consultation with industry partners to ground the model in operational practice. For example, stakeholders identified the need to query whether a specific location had been previously excavated, to compare registered utility positions against field-verified measurements, and to trace which organisation conducted a given verification and with what measurement method. These operational requirements were formalised as competency questions that directly shaped the ontology's modular structure.

UTT is encoded in OWL/RDF, which enables organisations to publish and interconnect test trench data through shared vocabularies while retaining ownership of their datasets (Berners-Lee, 2006). Spatial representation relies on GeoSPARQL, through which trench geometries and observed utility positions are represented as three-dimensional features in the Rijksdriehoek coordinate system (EPSG:28992) with NAP-referenced heights. This ensures compatibility with Dutch geo-information infrastructure and standard GIS tooling.

The choice of OWL/RDF over extending IMKL through a UML Application Schema, as prescribed by the INSPIRE framework for geospatial data harmonisation (European Commission, 2007), was driven by the requirements of the use case. The national test trench database must support distributed data exchange across organisational boundaries, where each organisation retains ownership and governance of its own data. The INSPIRE methodology employs UML application schemas with GML encoding (ISO 19136) for data exchange, an approach designed primarily for file-based transfer between known parties through Web Feature Services (Tschirner et al., 2011). In the test trench use case, however, dozens of organisations including utility owners, contractors, surveyors, and municipalities must independently publish, query, and interlink verification data without pre-coordinated bilateral exchange agreements. OWL/RDF natively supports this through URI-based resource identification and federated SPARQL querying, enabling organisations to publish interlinked datasets without requiring a centralised data store or schema-level coordination between parties (Schade & Lutz, 2011). Combining semantic and spatial queries within a single framework, for example retrieving all observations within a given geographic area where the measured deviation exceeds a specified threshold, is supported through GeoSPARQL integration with SPARQL endpoints. The transformation from IMKL's UML-based model to OWL follows ISO

19150-2 (ISO, 2015), which provides a standardised mapping between geographic information conceptual schemas and OWL ontologies, ensuring that this approach remains aligned with geospatial standards rather than departing from them. The decision was therefore grounded in the architectural requirements of distributed data exchange rather than in modelling paradigm preference. It should be noted that while the methodology to publish INSPIRE data as GML is well-defined, a corresponding methodology for INSPIRE data as linked data has not yet been fully established (INSPIRE-EU-RDF, 2024), which represents a recognised challenge for broader adoption of this approach.

The UTT Ontology

UTT extends IMKL by formalizing concepts for test trench verification that are outside the scope of the current standard. Table 1 presents the seven modules constituting the ontology.

Table 1. UTT ontology modules

Module	Core Class	Functional Role
Trench	utt:Proefsleuf	3D excavation volume (subclass of geo:Feature)
Observation	utt:Waarneming	Field-observed utility record linked to IMKL registry
Deviation	utt:PositieAfwijking	Vector difference between observed and registered positions
Verification	utt:VerificatieActiviteit	Provenance of the verification event (subclass of prov:Activity)
Quality	utt:Nauwkeurigheid	Quantified horizontal and vertical measurement uncertainty
Supporting Data	utt:OndersteunendeData	References to point clouds, photographs, and CAD files
Project Context	utt:Project	Link to the broader construction project

The test trench is modelled as a subclass of `geo:Feature` from GeoSPARQL, with its geometry linked through `utt:sleufGeometrie` property as a sub-property of `geo:hasGeometry`. The geometry is defined in three-dimensional coordinate space while the physical extent of the excavation is further described through explicit properties for trench length, width and depth. This representation is independent of the utilities observed within the trench.

Each observation within a trench records the observed utility type, its verified three-dimensional position, and optionally its physical characteristics such as diameter, material, and colour. When the observed utility can be matched to a registered KLIC asset, an explicit link is established through the `utt:komtOvereenMet` property. This also enables deviation tracking: the `utt:PositieAfwijking` class captures horizontal shift, vertical shift, and directionality as separate properties, supporting systematic accuracy analysis across utility types and geographic areas. Verification provenance follows W3C PROV-O patterns, to record the surveyor, the measurement method, the date, and the commissioning organisation. A dedicated supporting data module maintains references to underlying three-dimensional source files such as point clouds, photogrammetric models, and CAD drawings.

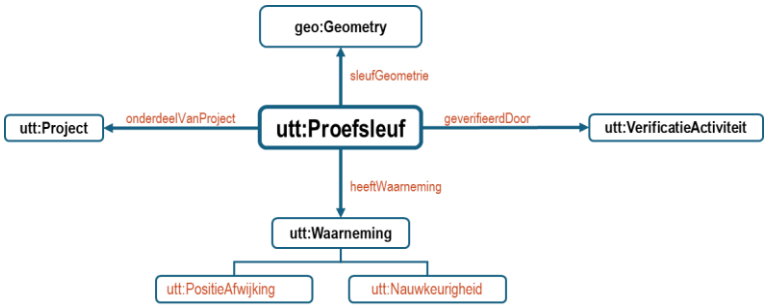


Figure 1:Semantic relationships in the UTT ontology

UTT imports an OWL subset of IMKL classes transformed following ISO 19150-2 patterns and reuses IMKL code lists for utility types, accuracy classifications, and pipe materials without modifying the base standard. This ensures that field classifications remain semantically identical to KLIC registry entries, enabling automatic correspondence between verified observations and registered assets.

Current Status and Verification

The ontology was implemented in OWL 2 DL using Protégé 5.5 and verified through logical consistency checking with HermiT reasoner, SPARQL-based competency question testing, and SHACL constraint enforcement for data quality. These activities constitute verification of internal consistency and functional completeness against the specified requirements. The assessment of whether the ontology adequately represents real-world test trench workflows and supports operational decision-making is planned as part of the next research phase. This will involve deploying UTT within a triple store using production datasets from partner organizations, followed by structured evaluation workshops with domain stakeholders to assess the model's fitness for purpose. The ontology is published under a Creative Commons Attribution 4.0 license.

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Thematic session:

Scenarios and Simulation

Digital Platform 'Public Dialogues' as Enabler for Collaborative Climate Action in The Hague

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Keywords: Climate Action, Digital Platform, Citizen Participation, Knowledge Sharing, EU Mission Cities

Research Context

The HK-ACT (The Hague Climate Agreement – Collaborative Transformation) is co-funded under the NetZeroCities Enabling City Transitions programme in Horizon Europe, and is situated within the framework of the European Commission's mission *"100 Climate-Neutral and Smart Cities by 2030."* The City of The Hague is the first in the Netherlands to receive this designation, positioning it strongly for continued EU support for climate-related innovation and research.

To accelerate its transition towards climate neutrality, The Hague Climate Agreement (in Dutch: *Haags Klimaatakkoord* – HKA) was launched in 2024. The HKA currently consists of 44 climate deals, each initiated and implemented by local stakeholders and focused on specific aspects of climate action, such as energy transition, mobility, urban greening, and knowledge exchange. Collectively, these deals are intended to contribute to the city's climate-neutrality goals.

However, the scale and diversity of the HKA present significant challenges. More than 150 partners and stakeholders operate across multiple thematic domains, with new climate deals and actors joining over time. This complexity complicates communication, coordination, and knowledge sharing. In parallel, multiple research initiatives are conducted across similar domains, often without mutual awareness, resulting in duplicated efforts.

To address these challenges, the HK-ACT project further develops, deploys, and scales up an existing digital participation platform named *Public Dialogues* (*PubliekeDialogen.nl*) developed by the research group Civic Technology of The Hague University of Applied Sciences, as a shared infrastructure to support collaboration, citizen participation, and knowledge exchange across the HKA ecosystem.

Research Objective

The primary objective of this research is to further develop, test, and implement the *Public Dialogues* platform as a digital backbone for collaboration and participation within the HKA. The project aims to evaluate how a civic technology platform can:

- Support communication and coordination across diverse climate deals;
- Facilitate inclusive participation, including hard-to-reach populations;
- Enable structured knowledge sharing and reduce duplication of research efforts;
- Strengthen continuity and transparency in long-term, multi-actor climate initiatives.

Research Question

How can a civic technology platform be adapted and implemented to effectively support collaboration, citizen participation, and knowledge sharing within a large-scale, multi-actor urban climate governance ecosystem?

The sub-questions focus on:

- What functionalities are most valuable to local climate initiatives?
- How do users experience digital participation alongside existing offline collaboration?
- How can platform-based knowledge sharing support continuity in projects with changing participants?

Research Methodology

Several existing functions of the *Public Dialogues* platform were used as the starting point for user testing. These include, amongst others, a chat function, list, for/against list, SWOT analysis, Kanban board, survey, document editing, and a library for various file formats. Additionally, users could participate anonymously. Key methodological components include:

1. Use-case-driven development
   From the HKA, climate deal #E9 - Mini Heat Networks *(Mini Warmtenetten)* was selected as a primary use case. In collaboration with consortium partner *Duurzaam Den Haag*, multiple dialogues were created on the platform to support neighbourhood-based initiatives developing small-scale heat networks. Each neighbourhood faces distinct organizational and technical challenges, making this a suitable context for testing flexible yet standardized digital support. Feedback from users in this pilot is continually collected by the research team responsible for the platform's technical development. This team assesses the required adaptations based on user demand, projected impact, and budget allowance.
2. User testing and feedback collection
   At The Hague's Climate Café in March 2025, four parallel user testing sessions were conducted with approximately 60 participants from across the HKA. These sessions were facilitated around different thematic clusters and allowed participants to trial the existing functionalities of the platform based on their own climate deals. The sessions were recorded and analyzed by the user experience designer. An in-depth analysis of the results was made, using industry standard usability metrics in user testing

research. Recommendations based on these findings were made to the development team, and subsequent changes to the platform were implemented.

3. Scaling through ecosystem-wide pilot
   Building on insights from the #E9 use case, a pilot is currently being rolled out across the entire HKA ecosystem, enabling each deal to create its own dialogue while also connecting to a shared network for cross-deal exchange.
4. Sub-study on offline collaboration practices
   As part of the local heat networks use case, a focused sub-study examines existing offline collaboration practices within neighbourhood-based heat network initiatives. This sub-research investigates what forms of in-person coordination and knowledge exchange currently take place and why this is not yet occurring on the platform.

Integrating findings from these four methods allows the optimal customization and upscaling of the platform for use in this, and other, large-scale urban climate initiatives.

Preliminary Results

Preliminary findings indicate a strong demand for structured, accessible, and continuous information sharing across climate initiatives. The Climate Café workshops sparked a surge of interest and requests for support from participants, highlighting the need for this platform not only for individual deals, but also for cross-deal information sharing. Preliminary results show:

- Participants value having a centralized space where progress and needs can be made visible across the ecosystem. Participation continues to grow, and there are currently more than 200 homes involved in the combined dialogues for local heat networks.
- More than 100 documents and links have been added to the Backoffice library for the local heat network initiatives. With the new bullet-in board function, details about upcoming workshops were shared with the whole community, and will soon become the main mode of digital communication about events.
- A new AI summarizing function significantly improved clarity and efficiency, allowing users to quickly grasp the latest developments from documents in the library.
- Feedback from the Climate Café session and mini heat networks dialogues were implemented in a user guide, and new opportunities for making the platform available in other deals are currently being explored.
- Asynchronous participation has allowed previous non-users to contribute to the latest developments and dialogues, increasing overall engagement with initiatives.
- Digital dialogues complement rather than replace offline collaboration, providing alternative and supportive ways of collaborating and brainstorming.

These findings demonstrate that digital civic platforms can play a crucial role in strengthening collaboration and inclusivity in urban climate transitions, particularly when embedded within existing participatory structures such as the HKA.

Acknowledgements

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Simulation-based evaluation of tree planting strategies to reduce energy demand of buildings under 2050 climate conditions

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Keywords: Urban Building Energy Modelling, Positive Energy Districts, SimStadt, Heating and Cooling Demand, Vegetation

Extended abstract

Urban areas account for 67–76% of total global energy use and approximately 71–76% of CO_2 emissions from final energy consumption (Seto *et al*., 2014). As a result, they have become central targets for efforts to reduce energy demand and address climate- and heat-related impacts. These challenges have driven growing interest in district-scale strategies such as Positive Energy Districts (PEDs), which rely on analytical methods capable of assessing urban building energy performance under changing environmental conditions (IEA 2021; Smart Cities Marketplace, 2021). To this end, Urban Building Energy Modelling (UBEM) provides an analytical basis for such evaluation by simulating power consumption and production across multiple buildings based on inputs such as geometry, construction, occupancy, and climate (Reinhart and Cerezo, 2016).

UBEM approaches are generally classified into top-down and bottom-up models (Swan and Ugursal, 2009). Within the bottom-up approach, physics-based UBEM enables systematic assessment of building typologies and operational behaviours even when empirical data are limited, providing robust results for district-scale heating and cooling simulations (García López *et al*., 2024). However, most physics-based UBEM applications have focused chiefly on building-related parameters and have given limited attention to environmental factors such as vegetation, although this element affects building energy demand under changing climate conditions.

Several methods have been developed to incorporate vegetation into UBEM. These include coupling UBEM with microclimate tools such as ENVI-met and EnergyPlus to capture local temperature and shading effects (Tsoka *et al*., 2021), as well as incorporating tree inventory data directly into UBEM workflows through GIS-based or semantic 3D city models (Hashemi *et al*., 2018). However, these studies remain limited in spatial scale, rely on coupled tools, and rarely integrate projected climate conditions.

In order to understand which method to follow, also based on the availability of existing software solutions, a preliminary study has been conducted to identify the most commonly used

tools, as well as to better understand their strengths and weaknesses. Some of the principal findings are reported in Table 1.

Table 1. Strengths and weaknesses of selected physics-based UBEM tools for vegetation modelling.

Tool	Strengths	Weaknesses
CityBES	– Mature web platform; EnergyPlus-based detail – Good documentation; supports Energy ADE	– No native vegetation module; vegetation typically via custom shading objects or external coupling – Heavier setup to represent microclimate effects
URBANopt	– Modular pipelines; HPC support for scale – EnergyPlus/OpenStudio ecosystem	– Vegetation requires external pre/post-processing or custom measures – Workflow complexity increases for city-wide runs with vegetation
SimStadt	– ISO 13790 heat-balance model scaled to city – Native CityGML ingestion and Energy ADE interoperability – Workflow modularity for batch analyses	– Vegetation may be represented as building-like objects – Limited direct representation of evapo-transpiration and wind effects without coupling
TEASER/ OpenIDEAS	– Python/Modelica openness; archetype flexibility – Useful for prototyping	– Weaker native GIS workflows at very large scale – Vegetation/microclimate needs external models or custom code

Based on the results of this preliminary research, this study develops and applies a simulation-based workflow that evaluates how urban tree-planting strategies influence building heating and cooling demand under current and projected 2050 climate conditions. Specifically, the workflow extends the simulation-based UBEM platform SimStadt (Nouvel *et al.*, 2015) by embedding vegetation effects directly within a single modelling environment, removing the need for external microclimate coupling or additional simulation tools. Our method is based on standardised CityGML building models, simplified yet seasonally dynamic vegetation representations, and a unified modelling environment that allows consistent comparison of cooling and heating demand under both current and projected climate conditions. This integration allows the quantitative evaluation of tree-planting strategies for both heating and cooling demand at the district scale.

The methodology comprises five stages that are summarised here:

1) Six scenarios were defined to isolate the effects of vegetation from those of climate change. When it comes to the climate conditions, climate data were retrieved from the Royal Netherlands Meteorological Institute (KNMI) and consist of typical year's values representing current data and forecasts for 2050, for which an increase of average temperatures is expected;
2) Building geometries, existing tree inventories, and potential planting locations were compiled and converted into CityGML to ensure consistency with the simulation environment;
3) In particular, simplified modelling assumptions were applied to trees. They are:

a. In terms of geometrical representation, trees were modelled as cylindrical geometries (Figure 1). This decision is driven by the computational and algorithmic constraints of the *Simplified Radiosity Algorithm* used in the *IrradianceProcessor* of the simulation software (see later);
b. Regarding the seasonal canopy variation, all trees were assumed to be deciduous. Different sizes of their crown diameter (D_c) were used to represent foliage variation. The diameter D_c of the cylinder was used *as is* in summer, while a reduced size ($0.64 \cdot D_c$) was used to account for the reduced foliage in winter. This simplified approach, and the accompanying values, were taken from literature as no real measured values were otherwise available;
c. For the 2050 scenario, tree growth was modelled applying parameters taken from literature and resulting in larger D_c values for existing trees.
d. When it comes to the potential planting locations, they were identified within available open spaces according to land-use suitability, while areas overlapping with infrastructure, water bodies, buildings, or roads were excluded using predefined distance rules. The remaining suitable areas were then populated with evenly spaced planting points to represent possible future tree locations. Again, distance values were taken from literature of from exiting urban planning norms;

4) The different input models were simulated using SimStadt's *Heat Demand Analysis* workflow to estimate heating and cooling demand, using the *Simplified Radiosity Algorithm* which allows to include shading from vegetation and surrounding structures into the simulation;
5) Post-processing integrated seasonal outputs into annual values, normalised energy use by floor area, and aggregated results at neighbourhood-scale. The building-scale and neighbourhood-scale outputs were compared across scenarios to quantify changes in heating and cooling demand attributable to vegetation and climate change, and spatial analysis identified locations where vegetation has a strong influence on thermal performance and potential energy reductions.

More details about each of these steps and about the characteristics of each scenario can be found in (Rahmawati, 2025).

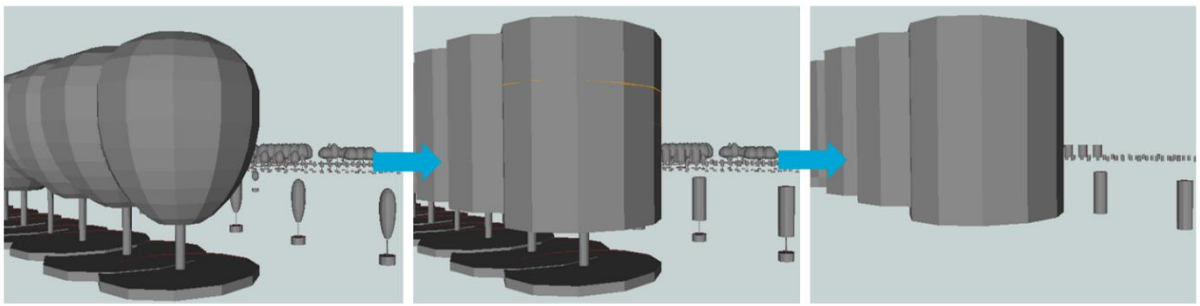


Figure 1. Example of the geometrical simplification process for the trees: from CityGML Implicit Geometries (in LoD3), available in the 3D Rotterdam[1] model, to simpler, pseudo-LoD1 explicit geometries (cylinders) without roots and trunk. Image source: (Rahmawati, 2025)

[1] https://www.3drotterdam.nl

To demonstrate the approach, the methodology was applied to the Kop van Zuid and Afrikaanderwijk neighbourhoods in Rotterdam's Feijenoord District. The workflow produces spatially explicit maps and scenario comparisons to support energy-aware, location-specific planting strategies. The spatial distribution of these effects in the Afrikaanderwijk neighbourhood is illustrated in Figure 2.

Results show that, between 2023 and 2050, cooling demand is expected to increase by 32–39%, while heating demand is expected to decrease by about 12%. Adding deciduous trees reduces neighbourhood cooling demand by 3–10%, depending on location and climate scenario. However, additional shading during winter introduces heating penalties of up to 2%, resulting in small net annual changes at the neighbourhood scale (-0.9% to -0.4%). At building level, impacts are more heterogeneous: in compact districts, added trees can block the limited winter solar gains, while in open areas with high cooling exposure, they consistently reduce peak summer loads. Orientation and façade exposure play a major role as key factors that shape the balance between summer benefits and winter penalties.

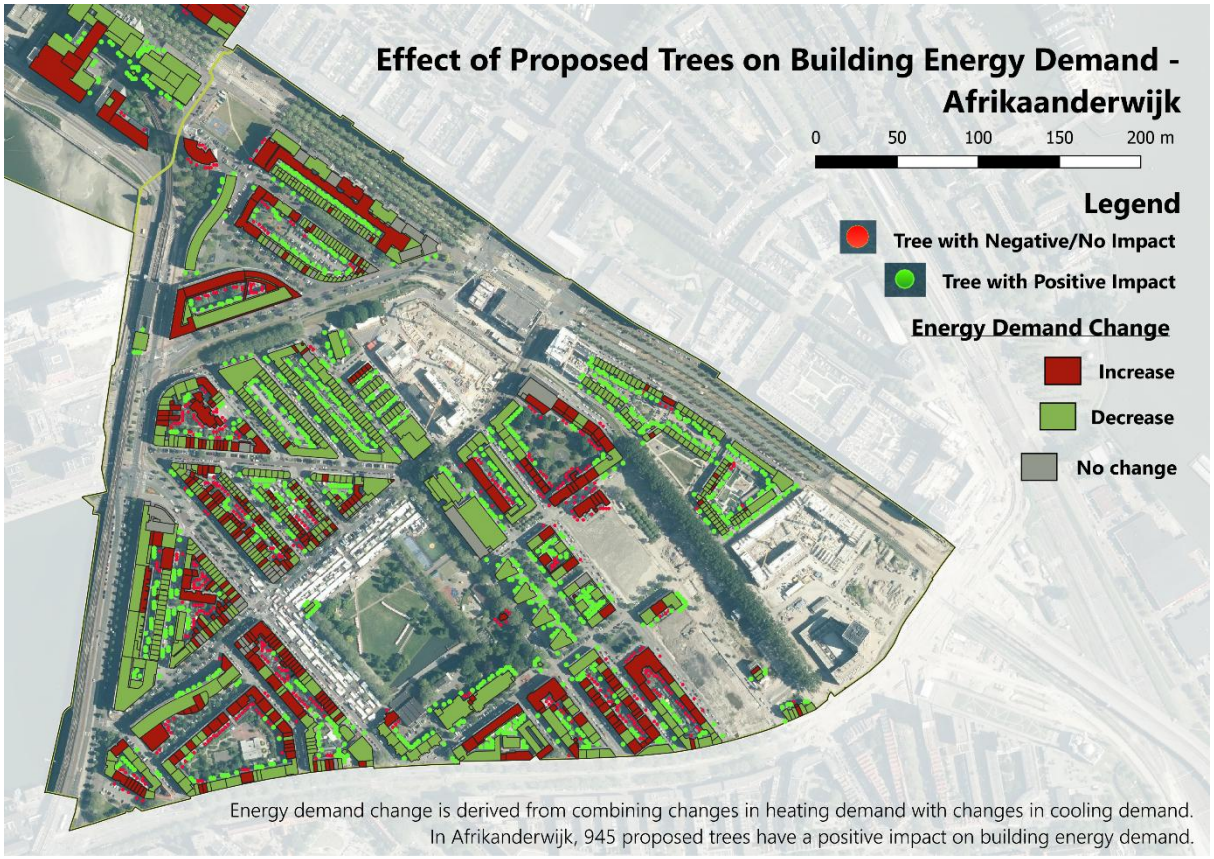


Figure 2. Effect of proposed tree planting on total energy demand (heating + cooling) in Rotterdam's Afrikaanderwijk neighbourhood. Image source: (Rahmawati, 2025)

Overall, this study demonstrates how integrating vegetation into UBEM at the neighbourhood level can bridge the gap between energy modelling, urban greening, and Positive Energy District objectives. By capturing how tree placement and orientation influence heating and cooling demand under current and future climate conditions, the proposed workflow provides a methodology for designing energy-aware planting strategies. At the same time, it allows to quantify the annual impact of such tree planting interventions, which, depending on the size

and orientation of the buildings, and the respective distance to the tree(s) (and their type) can result in rather modest differences. For example, the effect of additional trees is rather limited in areas with predominantly high-rise buildings, as the shadowing effect of the vegetation is limited to the height of trees, as it can be significantly less than the height of the buildings. Nevertheless, it must be noted that the effect of trees regarding the energy demand of the buildings is only one of the factors that must be considered. Although this study has focused on the effects in terms of energy demand, other aspects such as the influence of vegetation when it comes to microclimate, or the overall sense of well-being in terms of perceived human well-being must not be neglected (Van Veghel *et al.*, 2024).Furthermore, the possibility to compare quantitative results allows to perceive the magnitude of the modelled phenomena with respect to each other, but all results must still be interpreted critically and taken *cum grano salis* due to the simplifications and assumptions needed as a result of lack of more detailed information.

Keeping this in mind, the findings underscore the importance of spatial context and demonstrate that targeted, orientation-sensitive planting can support climate adaptation and long-term energy efficiency goals, although tree planting alone may be far from sufficient to contribute significantly to the reduction of the overall energy demand of buildings. In this hindsight, further investigation is being carried out to evaluate the effect of other mitigation strategies (e.g. adoption of shading devices). More details about this study can be found in (Rahmawati, 2025).

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Comparative study of extreme sustainable energy systems for the Netherlands in 2050

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Keywords: Nuclear Energy Pathway, 100% Renewable Energy Systems, Energy Transition Model (ETM), Net-Zero Electricity Supply, Digitalization in Energy Systems.

Extended Abstract

Problem statement: Research on 100% renewable electricity systems has expanded in the academic literature, driven by the need for deep decarbonization and concerns over supply security and resource flexibility (Denholm et.al, 2021; Khalili et.al, 2025). Peer-reviewed assessments highlight persistent challenges related to long-duration storage, system stability and balancing, as well as socio-economic challenges (Breyer et.al, 2022, Khalili et.al, 2025). Ruhnau and Qvist (2022) show that multi-week periods of low wind and solar output can impose storage requirements far exceeding conventional model assumptions. In terms of system challenges, a critical meta-review by Heard et al. (2017) argues that many 100% renewable scenarios lack robust feasibility assessments, particularly regarding dispatchable capacity, ancillary services, and realistic transmission needs, often motivating consideration of nuclear energy as a low-carbon alternative. On the other hand, other analyses responding to the *Burden of Proof* critique highlight that, unlike nuclear power, which faces feasibility issues such as finite uranium resources and reliance on unproven future technologies, renewable systems based on wind and solar are already technically viable and steadily decreasing in cost (Brown et al., 2018). Furthermore, the core socio-economic challenge of renewables is that they require huge domestic investment and construction capacity which is economically positive but socially demanding, whereas the core challenge of nuclear is that it delivers relatively low domestic economic benefit, while increasing import dependency and limiting employment creation (Koelbl et al., 2016). Parallel to this, studies comparing renewable-only and nuclear-inclusive systems remain limited. Most national-level analyses examine mixed portfolios rather than deliberately extreme, single-technology systems. In the Dutch context, the II3050 Integrated Infrastructure Outlook provides one of the most comprehensive national assessments of future energy system configurations, quantifying the implications of divergent pathways for grid capacity, flexibility needs, storage volumes, and spatial requirements (Netbeheer Nederland, 2023). However, II3050 does not explicitly compare *exclusive* wind-only, solar-only, or nuclear-only electricity systems.
Therefore, the present study addresses the research gap by evaluating whether a 100% renewable electricity supply based solely on wind or solar, supported by hydrogen and battery

storage, can meet Dutch 2050 demand with full security of supply, and by contrast assessing a nuclear-only low-carbon configuration. We contribute to the societal question of whether fully green electricity with full security of supply is feasible for the Netherlands and how consequences compare with a nuclear pathway for meeting 2050 climate-neutrality goals. This study also contributes to digitalization in the built environment by applying a national-scale, data-driven energy system model to explore infrastructure-intensive energy futures and their implications for spatial and system design.

Methodology and scenario development*:* This study develops three future energy scenarios for solar, wind and nuclear energy using energy transition model (ETM) as the main modelling tool. The methodology framework is based on the integrated infrastructure outlook 2030-2050, which was selected because it provides a comprehensive outlook on the infrastructure and flexibility resources needed to reach net -zero emissions by 2050. The outlook highlights the importance of large-scale renewable deployment and supporting infrastructure. The scenarios were developed from national leadership pathways and scaled to represent extreme supply configurations. The ETM was originally developed from the Netherlands environmental assessment agency (PBL), enables the digitalization of future energy systems by linking energy demand, supply, infrastructure, emission and costs a cross sector. The ETM couples scenario-based energy transitions to material in- and outflows and material stock dynamics through dynamic material flow analysis (MFA), enabling a system-level assessment of infrastructure and resource implications. The model applies a primary energy-based accounting method using a bottom-up allocation approach, in which each energy conversion process traces inputs upstream to their primary sources. The scenarios in this study are structured around five key modelling components: energy demand, energy supply, system flexibility, emissions and system costs and efficiency. The modelling includes: (i) ETM accounting for emissions associated with imported energy carriers and hydrogen, plus conversion and transport losses; (ii) inclusion of industrial feedstock emissions and emissions related to non-energetic hydrogen final demand; and (iii) a focus on hydrogen as an energy carrier produced via electrolysis, where excess renewable electricity is converted and stored for long-term balancing depend on digitalized monitoring and control architectures. Furthermore, In the solar and wind scenarios, electrolyzers convert surplus renewable electricity into hydrogen to support seasonal adequacy and sector coupling. Battery storage complements hydrogen to manage diurnal variability.

Results: As shown in Figure 1, we compared primary energy demand (PJ) for the Netherlands in a historical reference year (2019) and three extreme 2050 pathways: wind, solar (both coupled with battery storage system and hydrogen), and nuclear only. The 2019 scenario is dominated by oil and natural gas, reflecting a fossil-based energy system with substantial conversion losses. In all 2050 cases, the mix shifts strongly toward a single low-carbon primary source, while fossil fuels become residual. The wind scenario pathway is largely supplied by wind electricity, with a visible contribution of hydrogen carriers indicating sector coupling and storage/balancing via electrolysis and hydrogen use. The solar pathway is dominated by solar electricity and shows a comparable hydrogen role, but a lower total primary demand, consistent with different balancing needs and potential curtailment. The nuclear-only pathway is dominated by nuclear energy and yields the highest total primary demand, partly because primary-energy accounting includes thermal conversion in nuclear supply.

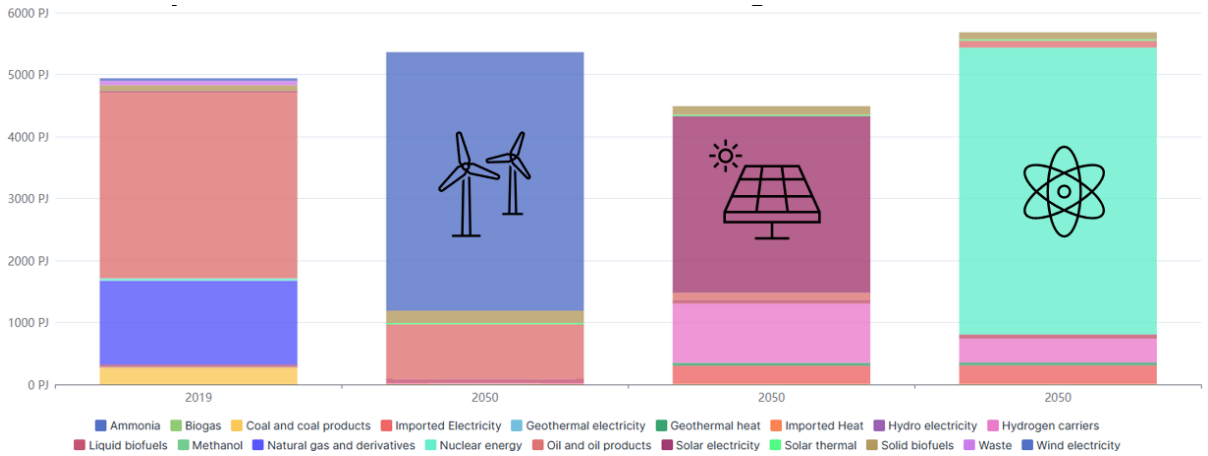


Figure 1: Primary energy demand of the nuclear, solar, and wind scenarios (from right to left), compared to the 2019 reference year.

Figure 2 shows the contribution of renewable energy carriers (PJ) in the reference year (2019) and in the three 2050 extreme pathways (wind, solar, and nuclear-only). In 2019, renewables provide only a minor share of total supply, distributed across small contributions from biomass-based heat and fuels, limited renewable electricity, and biogenic waste. In the 2050 wind pathway, renewable supply increases strongly and is dominated by wind electricity, accompanied by a substantial contribution from renewable hydrogen, reflecting large-scale sector coupling (power-to-hydrogen) for balancing and hard-to-electrify end uses. In the 2050 solar pathway, the renewable portfolio is instead dominated by solar PV electricity, again complemented by renewable hydrogen and smaller shares of renewable fuels and biomass/ambient heat. In the nuclear-only pathway, total renewables remain comparatively low, with only residual contributions from biomass, ambient/geothermal heat, and renewable fuels, consistent with nuclear providing most primary energy.

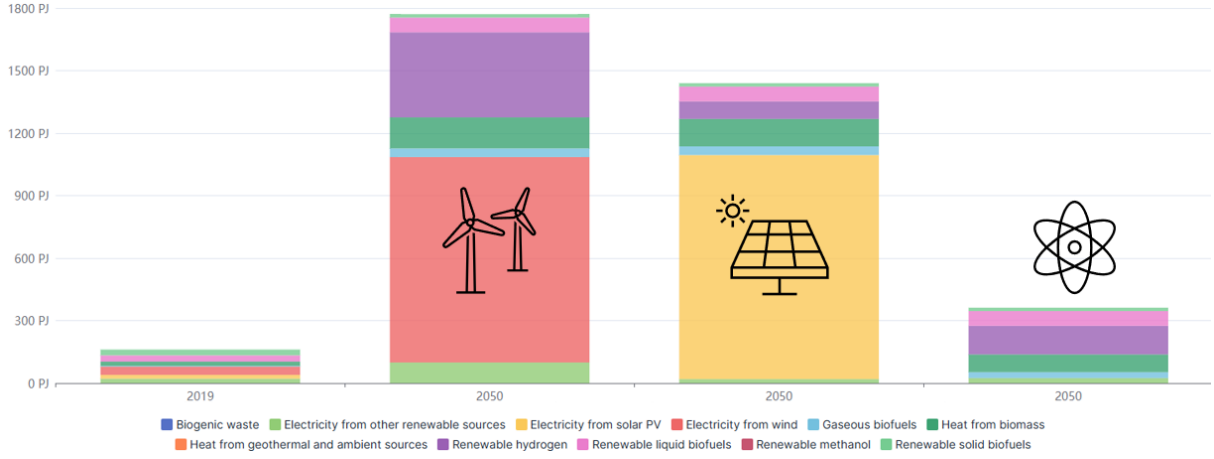


Figure 2: Share of renewable energy across the three scenarios of nuclear, solar and wind, compared with the 2019 reference year.

We also compared the electricity generation (installed capacity, GW) in the reference year (2019) and in the three 2050 extreme pathways (wind, solar, and nuclear-only) as show in Figure 3. The 2019 system shows a relatively small and mixed portfolio, reflecting a conventional dispatchable backbone complemented by limited renewables. In the wind pathway, total capacity increases markedly and is dominated by onshore/offshore wind,

complemented by dispatchable hydrogen-based power plants and limited storage to cover low-wind periods. The solar pathway requires the largest nameplate capacity: PV dominates the mix and substantial overcapacity is needed to compensate for low-capacity factors and strong diurnal/seasonal variability, with hydrogen-based dispatchable units and storage providing adequacy during low-solar periods. In the nuclear-only pathway, total capacity remains comparatively modest and is primarily nuclear, with smaller contributions from renewables and backup units. Overall, the figure highlights that extreme variable renewable energy pathways shift system needs from fuel supply to large-scale capacity and flexibility infrastructure.

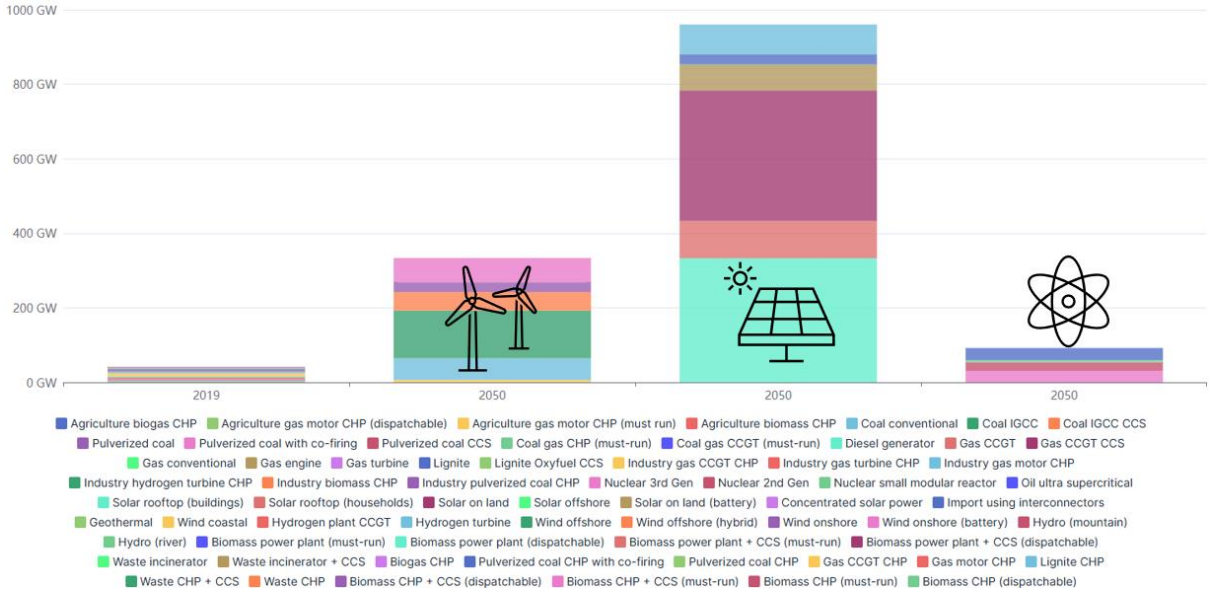


Figure 3: Electricity production capacity of the nuclear, solar, and wind scenarios (from right to left), compared to the 2019 reference year.

Discussion and conclusion: In this study, three extreme scenarios for Dutch energy supply in 2050 are analyzed using the ETM. Each scenario assumed use of one single energy source to be used: wind energy, solar energy or nuclear energy. The model reveals distinct electricity production capacity requirements across energy sources. Solar demands the largest system due to additional installations needed for adequate production and storage capacity. Nuclear, being centralized and predictable, requires a significantly smaller system to meet demand. Wind energy similarly needs a larger system for flexibility to match production profiles with consumption, though smaller than solar.

Cost comparisons show important distinctions between total yearly costs and costs per gigawatt. Total costs peak for solar (€110 billion), followed by wind (€90 billion) and nuclear (€55 billion). Per installed power, however, nuclear ranks highest (€1.20 billion/GW), with solar (€0.40 billion/GW) second and wind (€0.10 billion/GW) third. Flexibility requirements drive this divergence: both solar and wind need greater installed capacity with battery/hydrogen storage backup, increasing total costs despite lower per-GW prices.

Land requirements further differentiate scenarios. Wind requires 6,500 km² versus 3,250 km² for solar, respectively twice and similar to the area of Zuid-Holland province (3,300 km²). This underscores the spatial-planning implications of large-scale renewables. Nuclear plant surface area remains undefined in the model, though strict safety regulations similarly necessitate dedicated spatial consideration.

This study presents an assessment methodology with several limitations. The cost framework captures only direct energy value chain expenses without accounting for end-user or broader stakeholder expenditures. Furthermore, the analysis underestimates critical constraints such as land availability for renewable deployment, supply chain bottlenecks, and labor cost variability. Environmental impacts beyond carbon neutrality were also excluded, as these fell outside the scope of the ETM. Despite these constraints, the study's reliance on extreme scenarios provides insight into the potential and operational flexibility of each energy source, demonstrating their reliability under stress conditions. Future work will include sensitivity analyses on storage sizing and curtailment to strengthen real-world feasibility assessments.

Acknowledgements

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Thematic session:

Data Driven Prediction

Continuous Learning Digital Twin for Predictive Building Energy Management.

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Keywords: Digital Twins, Building Energy Management, Energy Forecasting, Smart Buildings, Machine Learning, Building Information Modelling

Extended abstract

Digital Twins are increasingly being adopted to support the monitoring and optimization of buildings. Recent studies highlight both the growing importance of digital twins in urban and building contexts and the need for tighter integration with operational data workflows, more so with building energy data. However, many current implementations still rely on static or loosely connected analytical components, limiting their value for operational use and decision support. This restricts their usefulness for building energy management, where energy forecasting, subsystem-level interpretation, and prospective scenario evaluation are essential (Argota Sánchez-Vaquerizo, 2024; Arsecularatne et al., 2024; Boukaf et al., 2024).

This research presents a sensor-driven digital twin framework for smart building energy management, demonstrated on the building of the Big Data for Smart Society (GATE) Institute in Sofia, Bulgaria. The proposed framework integrates four main components within a unified operational workflow: (1) circuit-level electricity measurements, which are electrical measurements collected at smart meters installed at individual circuits (2) data-driven energy forecasting using machine learning (ML)-based global and local forecasting models, (3) scenario simulation, where predicted electricity demand can be evaluated under different operational conditions and (4) a semantically enriched 3D building information model (BIM) that links energy measurements to building systems. Unlike many digital twin approaches that depend on static simulations, this approach allows continuously updated energy analysis driven by incoming sensor data.

The digital twin framework operates using high-resolution sensor data extracted and maintained for the GATE building. The circuit-level electrical measurements are linked to a semantically enriched three-dimensional building information model (BIM) that integrates energy data with the corresponding building infrastructure. This data is used to train time-series prediction models integrated into the digital twin architecture, producing short- and medium-term forecasts to support scenario testing and iterative system refinement.

A two-level modelling strategy is adopted. At the global level, a forecasting model captures the whole-building electricity consumption behaviour using circuit-level measurements, temporal variables, seasonality indicators, and external temperature as input features. At the local level, separate models are trained to predict electricity demand for individual circuits, enabling a more granular analysis. Candidate models are trained and evaluated by comparing predicted electricity demand against observed sensor measurements, with the best-performing model selected based on Mean Absolute Error and Root Mean Square Error (RMSE). The data is split into 80% training data, 5% validation data, and 15% testing dataset.
Preliminary results demonstrate that for short-term forecasting, LSTM reduces forecasting error by 18%, compared to the baseline(persistence), and performs 57% better than ARIMA, a statistical model. To support continuous learning, the models are retrained on new sensor data, enabling the system to adapt to evolving usage patterns. This approach builds upon developments in smart building performance monitoring and predictive energy modelling (Al Dakheel et al., 2020; Misiurek et al., 2025). The main contribution of this work is a digital twin architecture that integrates circuit-level data, machine learning forecast models, and BIM representation to enable continuous predictive energy monitoring.

Figure 1 shows the landing page of the developed web application.

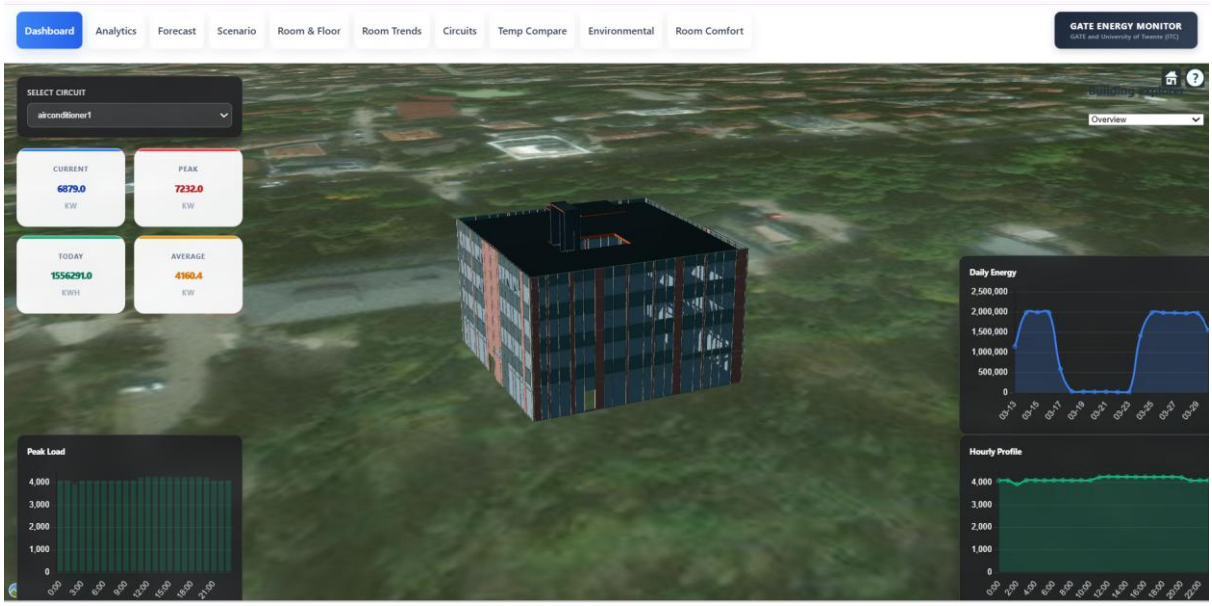


Figure 1. Landing page of the energy monitoring platform.

Figure 2 shows a seven-day historical load of the main circuit of the building and the 24-hour forecast generated by the LSTM model.

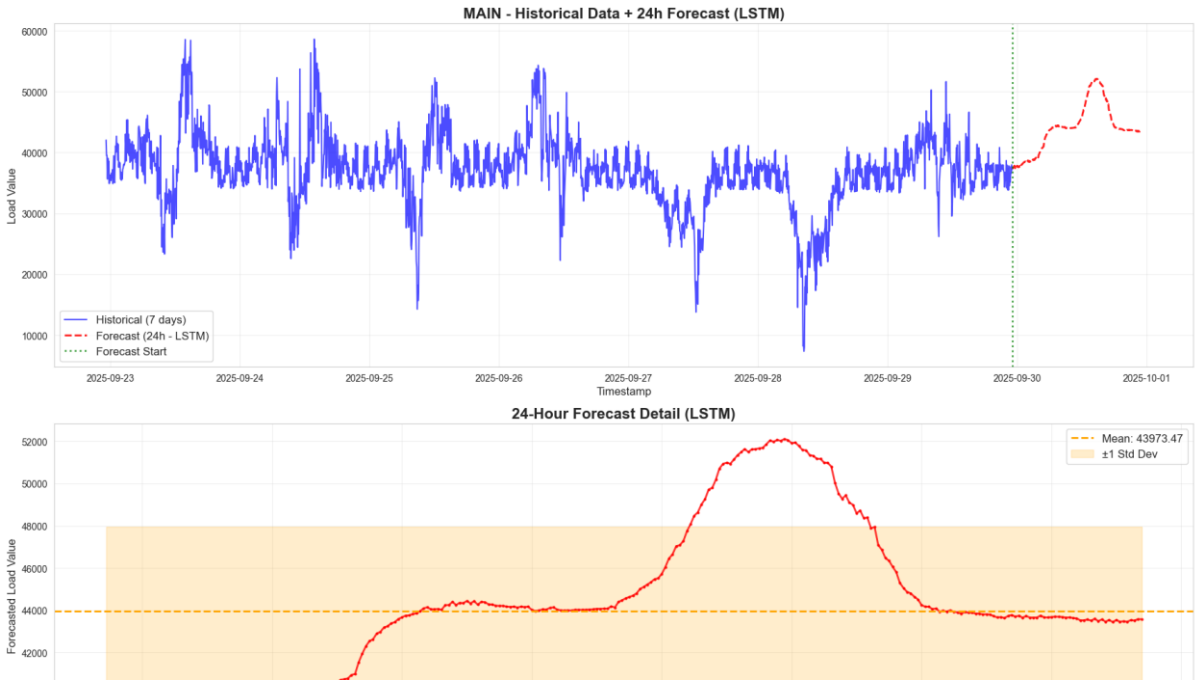


Figure 2. Seven-day historical circuit-level electricity and a 24-hour forecast generated by the LSTM model of the main electrical circuit.

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Metamodel-based Temperature Sensitive Warm Mix Asphalt Compaction Modelling

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Keywords: Metamodel, Machine learning, Physics-based simulation, Warm mix asphalt, Compactability

Extended Abstract

Warm Mix Asphalt (WMA) is increasingly used to reduce emissions and energy consumption compared with Hot Mix Asphalt (HMA), but knowledge on achieving optimal pavement quality remains limited. Differences in material behaviour hinder the transfer of HMA experience, creating uncertainty in construction planning. Developing reliable knowledge and planning tools is therefore essential for consistent and sustainable WMA construction.
Accurate modelling of asphalt compaction, particularly its response to compaction temperature, is key for informed planning. However, high-fidelity methods such as the Finite Element Method (FEM) and Discrete Element Method (DEM) are computationally expensive and require temperature-specific calibration, limiting practical use, where data-driven models are more efficient but often lack physical interpretability (Shen et al., 2022). Therefore, a physics-aware metamodelling framework combining physics-based simulations and machine learning is proposed to model WMA compaction through two metamodeling layers (Figure 1).

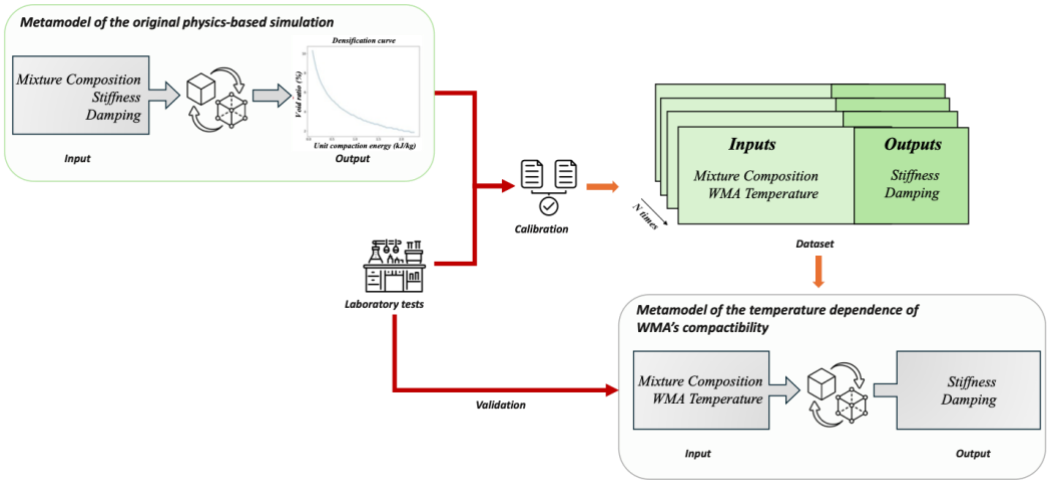


Figure 1. The overview of the proposed framework

The first metamodel predicts densification behaviour from mixture composition and physically meaningful contact parameters (stiffness and damping) representing temperature-dependent

viscoelastic response. It was developed using a dataset generated from physics-based simulations of laboratory-scale WMA compaction with the Bullet Physics engine, adapted from existing models to construct digital mixtures using 3D aggregate models and simulate particle contact behaviour (Komaragiri et al., 2021a, 2021b). Using a Random Forest model, the metamodel achieved high accuracy ($R^2 = 0.83$) and a computational speed-up exceeding 420000 times compared to the original simulation model. To avoid the high dimensionality of directly predicting densification curves, the curves were instead represented by logarithmic functions (Equation 1), with parameters a and b used as simplified outputs (Komaragiri et al., 2021b).

$$v = a + bln\,(E) \tag{5}$$

where v stands for the void ratio in the densification curve, E refers to the unit compaction energy, a is the intercept of the logarithmic function, and b stands for the slope of the logarithmic function.

Although the first metamodel accurately predicts asphalt densification from mixture composition and contact parameters (stiffness and damping), temperature-dependent viscoelastic behaviour is only represented indirectly. The framework therefore relies on laboratory densification data at each temperature to calibrate these parameters, limiting its applicability when temperatures vary continuously. To address this, a second-layer metamodel is proposed to directly map temperature and mixture composition to the contact parameters. By combining experimental compaction data at selected temperatures with outputs from the first metamodel, temperature-dependent functions can be derived and embedded in the model. This removes the need for manual calibration and enables continuous, temperature-aware prediction of WMA compaction behaviour.

Specifically, experimental densification curves at several temperatures are matched with predictions from the first metamodel to infer the corresponding contact parameters and derive temperature-dependent functions: (1) gyratory compaction data at selected temperatures (e.g., 40°C, 60°C, 80°C, 100°C, 120°C) are used to determine stiffness and damping values; (2) temperature-dependent functions (e.g., exponential decay) are fitted to predict parameters at intermediate temperatures (e.g., 50°C, 70°C, 90°C, 110°C) and validated with additional experiments; (3) the resulting functions enable prediction of compaction behaviour at untested temperatures without additional experimental data, capturing how contact behaviour evolves with temperature.

The fitted temperature-dependent decay functions will then be the main form of the second layer of metamodel. Figure 2 showcases the validation of this approach using a pre-selected WMA mixture type, where Figure 2 (a) represents the obtained exponential-decay-function-based metamodel, and Figure 2 (b) to (e) demonstrate the comparisons between the predicted densification curves against the laboratory results. With this extension, the final framework will enable practical prediction of temperature-dependent compactability for any WMA mixture based solely on its composition.

Together, the two metamodeling layers that have been presented would create a generalisable and practically applicable framework that can quantify and predict the temperature-sensitive compaction behaviour of WMA mixtures under a variety of temperature conditions. This would close the gap between the strategic planning of the compaction process and the required laboratory-scaled compaction tests.

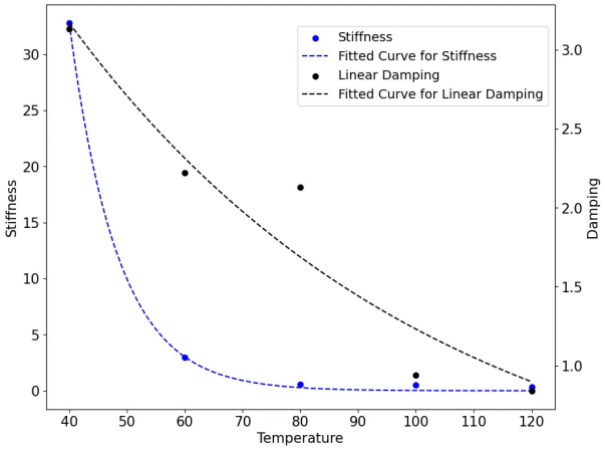


Figure 2 (a) The obtained decay functions

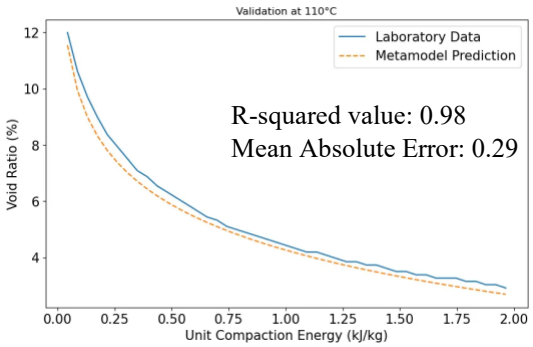


Figure 2 (b) Validation at 110°C

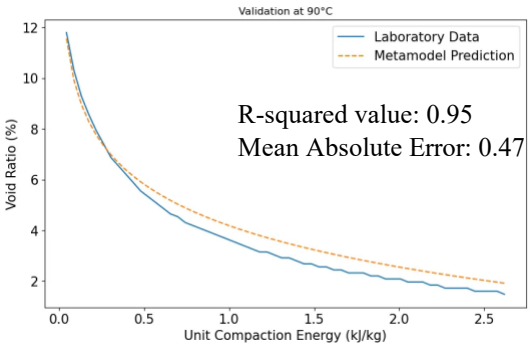


Figure 2 (c) Validation at 90°C

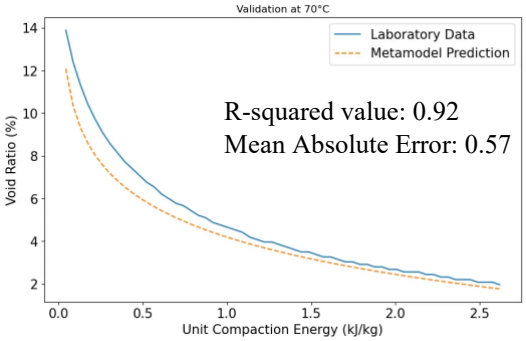


Figure 2 (d) Validation at 70°C

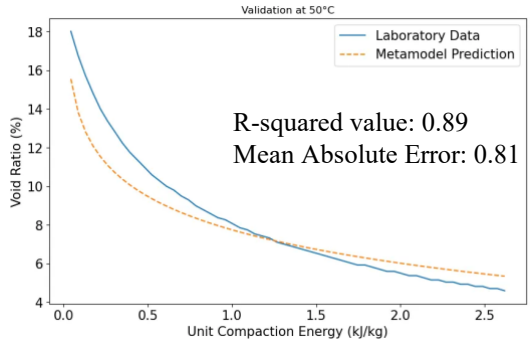


Figure 2 (e) Validation at 50°C

Figure 2. The validation results

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Towards Human-Centred and Neuro-Symbolic AI-Based Digital Twins for Industrial Built Environments

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Keywords: Decision Support Systems, Linked Data, Industry 5.0, Human-data interaction

Extended abstract

Industrial indoor built environments, such as factories, need holistic solutions to improve their operational efficiency and facility management. Digitalising processes, assets and spaces through sensors and Digital Twins (DTs) is among the promising interventions (Lyu & Fridenfalk, 2023). Yet, their use often remains limited to visualisation and isolated performance dashboards. While these systems provide spatial visibility, they rarely support an integrated understanding of ongoing processes in those spaces, human factors and responsibilities, and system state in real time. As a result, decision-making remains reactive, knowledge is fragmented across tools and people, and operational inefficiencies persist. This study aims to address this gap by exploring how a DT of an industrial indoor built environment can be extended with semantic modelling and neuro-symbolic AI interaction, and integrated with IoT networks to enable real-time, context-aware, query-based understanding of spaces, processes, products, equipment and humans in line with Industry 5.0 principles. Enabling semantic, query-based interaction with DTs supports informed decision-making, as the integration of ontologies enables reasoning and exploration through the DT rather than relying on conventional prescriptive approaches. The system combines historical and real-time data to support predictive and forecasting analyses. Based on these insights, it can suggest potential actions or improvements. However, it functions as a decision-support tool, and the final decisions remain with human operators. Overall, the system architecture aims to improve efficiency, anticipate risks, and support more sustainable and resilient management of complex environments. This abstract discusses the system architecture and integration steps of the MOAF-DiT project, which employs several digital methods to develop an advanced DT.

The project uses a case study in an industrial factory environment (called Karel), which produces Printed Circuit Boards (PCBs). The case study focused on the factory's second floor, which comprises eight departments with tightly coupled spatial configurations, worker activities, and processes. The factory layout was initially provided in DWG format and subsequently transformed into a DT using the Unity software. The spatial model was iteratively

refined through multiple site visits. The resulting 3D model represents a navigable space including production lines, equipment, and a human avatar that walks through the spaces. This allows users to explore the environment from an operational rather than purely geometric perspective. In addition to the 3D environment, there are dashboards that let users monitor the real-time status and movements of sensor-equipped tools and spaces (Baghaee & Eren, 2025). The DT is deployed through a web-based platform (Figure 1).

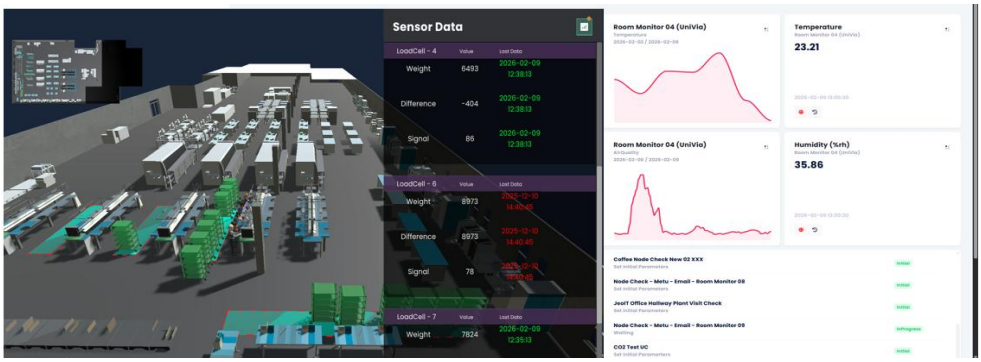


Figure 1. An overview of the digital twin platform and IoT data

To provide semantic reasoning and interoperable exchanges, Linked Data and ontologies are frequently used in the built environment domain (Akbarieh et al., 2025). Thus, a new ontology is developed to holistically represent interconnected layers of relevance to the MOAF-DiT project, including production routes, tasks, products, machines, departments, and human roles. The ontology was informed by Exploratory Data Analysis (EDA) of production data from the case study's operations. After further analysis of the case study's industrial processes and layout, a series of BPMN diagrams of multi-layer processes of the factory was developed to complement the ontology development steps. The novelty of the developed ontology lies in its semantic capacity to distinguish between process steps within departments (supporting BPMN-based modelling of multiple production lines across departments) and in its set of classes and properties that enable real-time traceability across the production flow.

Then, neuro-symbolic AI was used, a method to create credible AI systems with retrieved and reasonable semantics (Luo et al., 2023). Thus, building on the ontology layer, a neuro-symbolic interaction layer was implemented that allows users to ask natural language questions, which are translated into SPARQL queries. SPARQL generation is a difficult task that needs expert knowledge of ontologies. This workflow lowers this technical barrier and enhances human-data interactions with the twin. This pipeline enables questions such as where a specific PCB type is in the process, which department or equipment is currently responsible for it, or which role is associated with a given task or shift. This interaction paradigm enables users to explore the environment visually and, when needed, ask questions directly in the DT. In this way, the DT evolves from a passive visualisation into an active interface for understanding and reasoning about the indoor built environment. While full real-time instance population and validation are ongoing, the approach demonstrates how semantic models can serve as intermediaries between user intent and operational data.

The project uses the AI-Core system developed by Univia, which provides an infrastructure for hosting AI models via secure APIs. Within this system, the neuro-symbolic AI model is deployed on the AI-Core, enabling scalable execution, load balancing, and secure access without requiring local hosting of AI models. The DT exchanges semantic and sensor-derived data with the AI-Core, where model inference and reasoning are performed, after which results

are returned via API calls and secure encrypted communication protocols to the DT. In this solution, ethical implementation and privacy are ensured through the system architecture: AI-Core hosts only the AI model, while user data remain stored on the client's server. Figure 2 shows the system architecture and exchanges using the AI-Core.

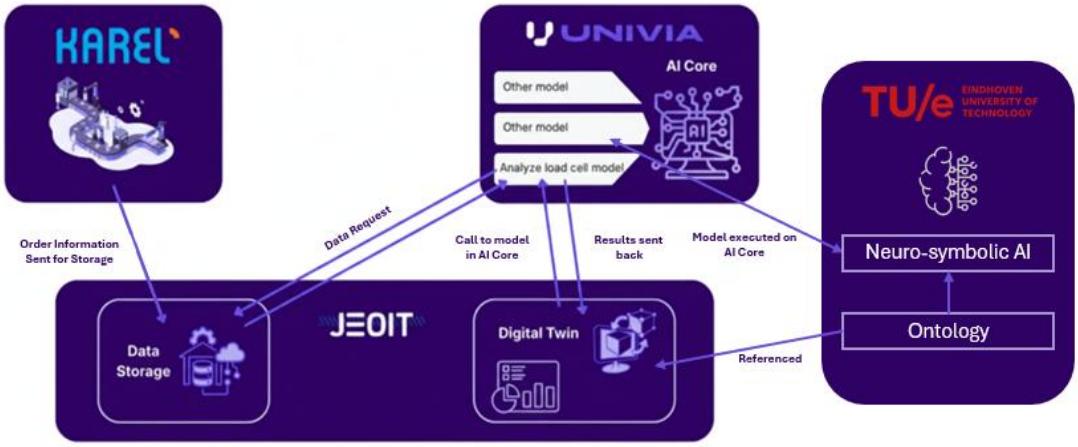


Figure 2. MOAF-DiT system architecture

The MOAF-DiT project is still ongoing, and further optimisation is needed. Early implementation results show that the system architecture successfully integrates 3D representations, IoT-enabled data, semantic modelling, and connects them to API of the case study's Enterprise Resource Planning (ERP). This work presents an integration architecture for developing queryable, human-centred systems that support DTs of indoor built environments. The DT provides visualisations, analytics, and interaction methods to monitor and improve efficiency, transparency, and decision-making in complex operational spaces. The lessons learned and the methodology developed are applicable to other built environment projects where spatial context, human activity, materials, and processes must be understood together.

Acknowledgements

The Multi-Ontology AI-based Facility Digital Twin (5902 MOAF-DiT) project has received funding from TÜBITAK and Rijksdienst voor Ondernemend (RVO) through Eureka and the Eurostars programme (estar24226 E! 5902), which is co-funded by the European Union through Horizon Europe as part of the European Partnership on Innovative SMEs.

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GreenVision – Classifying green roof typologies from aerial imagery

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Keywords: Nature inclusive building, Biodiversity, Green roofs, Computer vision, Urban ecology

Extended Abstract

Given the fierce competition for space in rapidly urbanising landscapes, green roofs are increasingly posed to either expands or compensates vegetated surfaces. This new ecotope is meant to promote biodiversity, water storage, energy regulation and human wellbeing within the built environment. Green roofs differ significantly in ecological potential, depending on their design history and location, where increased vegetation complexity generally comes with higher insect diversity (Drukker et al., 2025; Figure 1). The Dutch policy guideline *Basiskwaliteit Natuur* (BKN) states under which conditions the surface area of green roofs contribute to a minimal urban nature quality: if it is rich in herbs (herbaceous) and has a substrate depth thicker than 6 cm. In practice this definition corresponds to a 'nature roof', which is heavier than a regular sedum roof (Edixhoven & Hofhuis, 2024). Despite mentioned interest and broad urban biodiversity goals, Dutch municipalities mostly lack measurable targets of how many green roofs of which typology should be installed where to contribute to urban biodiversity. Studies have explored the current number of green roofs in the Netherlands, as well as suitable locations for novel ones (Slootweg et al., 2023) but the distinction of green roofs with major or minor ecological potential currently and in the future remains unexplored.

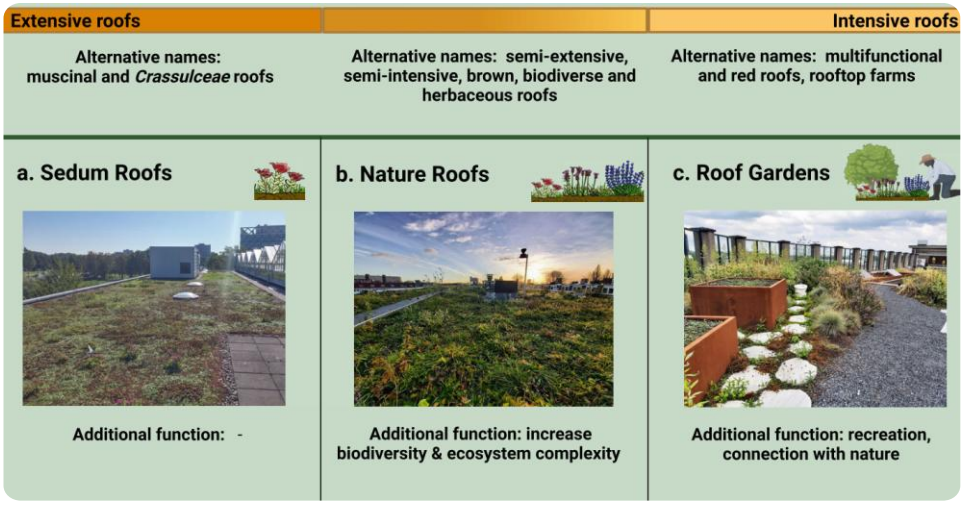


Figure 1. Example of green roof typologies. Source: Drukker et al. 2025

We develop GreenVision, where we explore how a computer vision model can not only detect green roofs on open aerial imagery but also classify them into three vegetation types: sedum, nature roofs or roof gardens. Greenvision is a pipeline that consists of two separate convolutional neural network models (CNN) trained to detect green roof presence (ResNet-50) and subsequently classify green roof vegetation type (EfficientNet-80). Attention is paid to annotation practices, data pre-processing and generalizability so far.

For training data green roof locations and descriptions in Amsterdam and The Hague were collected and harmonised at building level (Kadaster, 2025). Citizen science, municipal and commercial records of green roof locations were combined (Gemeente Amsterdam, n.d.; Gemeente Den Haag, 2022; Readar, 2024). Temporal inconsistencies were manually removed during validation. Class annotations were generated through manual photointerpretation of aerial imagery which were centred on and masked by building footprints (*Beeldmateriaal Nederland*, n.d., False color, 8cm resolution, 2024 winter collection). If present, the 'Description' attribute in green roof datasets served as an initial modality to facilitate the semantic mapping of green roof typologies, after which labels were still manually validated. Annotation rules ensured aggregation to three vegetation types meaning that nature roofs included all non-sedum herbaceous vegetation, including lawn and dune grass. Roof gardens were interpreted as any roof that included one or more elevated trees. For the detection model both 1441 green roof and grey roofs were selected as training data. For classification, in total 1859 roofs were annotated, of which 1502 turned out to be sedum roofs, 292 nature roofs and 65 roof gardens. To make up for the severe class disbalance, trimming and image augmentation resulted in 300 sedum, 292 nature roofs and 200 roof gardens.

Preliminary results show that beyond the detection of green roofs (97% class average precision and recall), classifying their vegetation complexity is technically feasible. In the context of a 10% test dataset of the Hague and Amsterdam 2024 the model reached a class average precision of 85%. However, running inference on an unseen dataset of 1682 green roofs, validation shows an average precision of 49%, with 77% on sedum roofs, 65% roof garden and only 5% for nature roofs. Larger datasets with a higher number of roof gardens and nature roofs are necessary to resolve this imbalance.

Annotation was performed again on the The Hague dataset by a second researcher with more experience on green roofs as well as a second modality access to 5cm aerial imagery and oblique imagery in similar time periods (Cyclomedia). This validation revealed an overall agreement of 89%, with the lowest agreement on herbaceous roofs (71%), where sedum roofs were seemingly mistaken for nature roofs.
This means the current model is not yet generalizable across different urban contexts in the Netherlands, and model improvement is necessary before policy informing or accurate mapping of green roof typologies can occur.
In the studied records of green roof locations in the Hague and Amsterdam we find strong hints that currently green roofs are predominantly sedum-based, whilst green roofs with a more complex vegetation structure are of very minor occurrence.
The low agreement on annotation, especially for herbaceous roofs may be resolved through several factors:

- The heterogenous appearance of sedum roofs (flowering yellow and dead brown patches) is confused with the occurrence of herbaceous vegetation. Conversely, the uniform character of lawn grass is confused with sedum. A focus session amongst annotators can help to relieve this barrier.
- Vegetation is not sufficiently distinguishable on 8cm aerial imagery. This ties in to point (i) as especially oblique imagery reveals more detail about the vegetation type. Future advancement of publicly available imagery can relieve this barrier. While commercial imagery can temporarily mitigate the issue unless integrated into long-term data acquisition strategies.
- The definition of sedum, herbaceous and roof garden does not allow for a full distinction in practice on the building level, since one building can hold multiple roofs with multiple vegetation types.
- The aerial imagery only shows one snapshot throughout the year, meaning that many flowering plants that characterise herbaceous vegetation might be invisible.

Further work includes refining the typology scheme to capture a distinctive range of green roof subtypes, all unique in the biotic conditions and increased ecosystem services they provide, such as recreation, energy generation and water retention. Another possible refinement is moving toward semantic segmentation to capture intra-roof variation of typologies or vegetation characteristics.
In ongoing research, we hope to inform municipalities, planners, and the green roof industry on the national extent, diversity and biodiversity value of this new urban ecotope, enabling decision-making on current and future developments in nature inclusive design in cities.

Acknowledgements

This study is part of the exploratory KIEM-groen project Kwaliteit van Web van Leven op Hoogte, a SIA-funded collaboration between Lectoraat Nieuwe Energie in de Stad (University of Applied Sciences Utrecht), Practoraat Groene Leefbare Stad (Yuverta), Rooftop Revolution, Readar and Municipality of Amsterdam.

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Demonstrations and Posters

Thematic session:

Demonstrations

PDF2GIS: from old blueprints to 3D city models

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Demo description

PDF2GIS is a software solution that transforms architectural drawings—such as floor plans and technical blueprints—into structured geospatial data and detailed 3D building models. In this demonstration, we present a live walkthrough of the application (see Figure 1), showing how machine learning techniques and human validation are combined in a *human-in-the-loop* workflow. This combination enables the system to achieve high levels of accuracy while significantly reducing the cost and effort associated with manual data extraction.

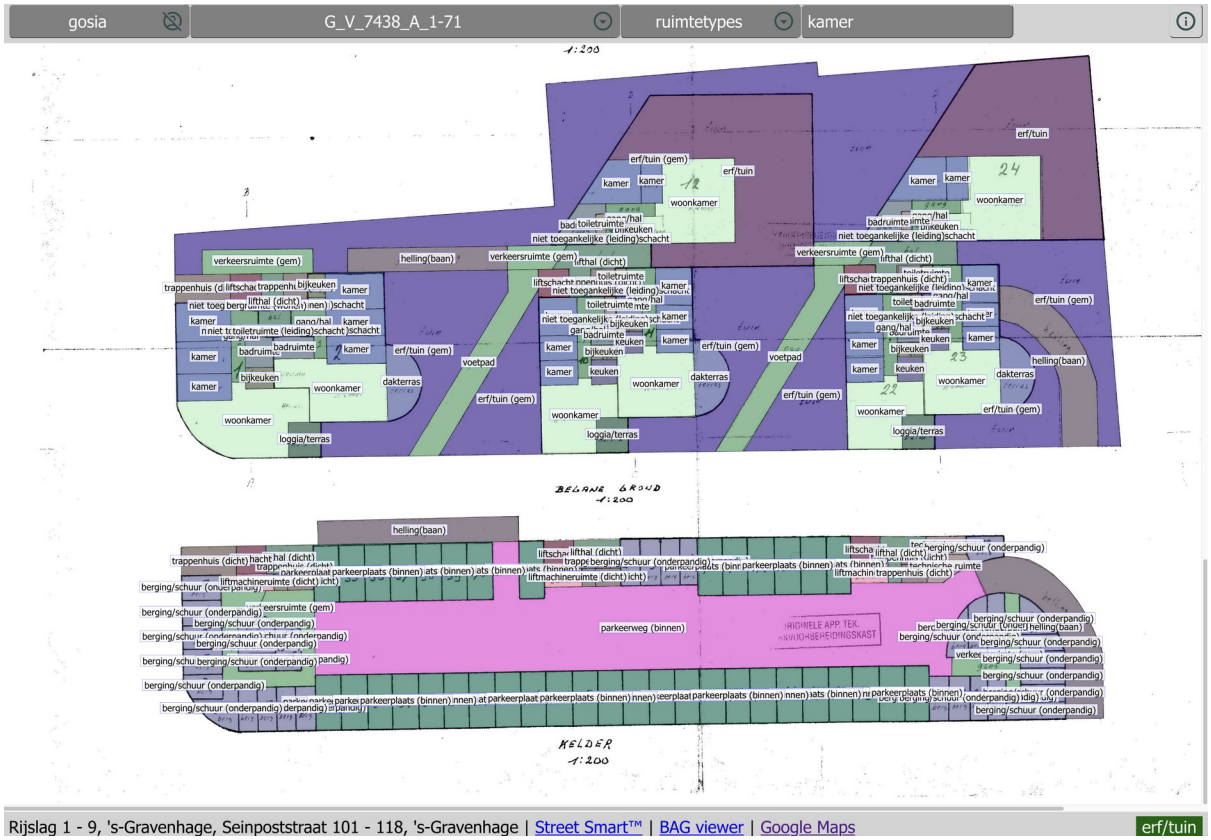


Figure 1. Example PDF2GIS screen: room-type detection

The system is designed for organizations that manage large archives of technical drawings, including municipalities, housing corporations, and other public-sector institutions. Many of these organizations possess extensive collections of architectural drawings that exist only as PDF files or scanned documents. Although these drawings contain valuable information about buildings and infrastructure, they are difficult to integrate into modern digital

information systems. By automatically converting these legacy PDFs into GIS-ready datasets and 3D models (see Figure 2), PDF2GIS makes it possible to unlock the information stored in these archives and integrate it with contemporary geospatial platforms.

The resulting datasets support a range of important applications. These include urban planning, property and asset management, building maintenance planning, and integration with digital city platforms and digital twin environments. By providing accurate geometric data and additional building information, the system enables organizations to make better-informed decisions and improve the quality of their urban data infrastructures.

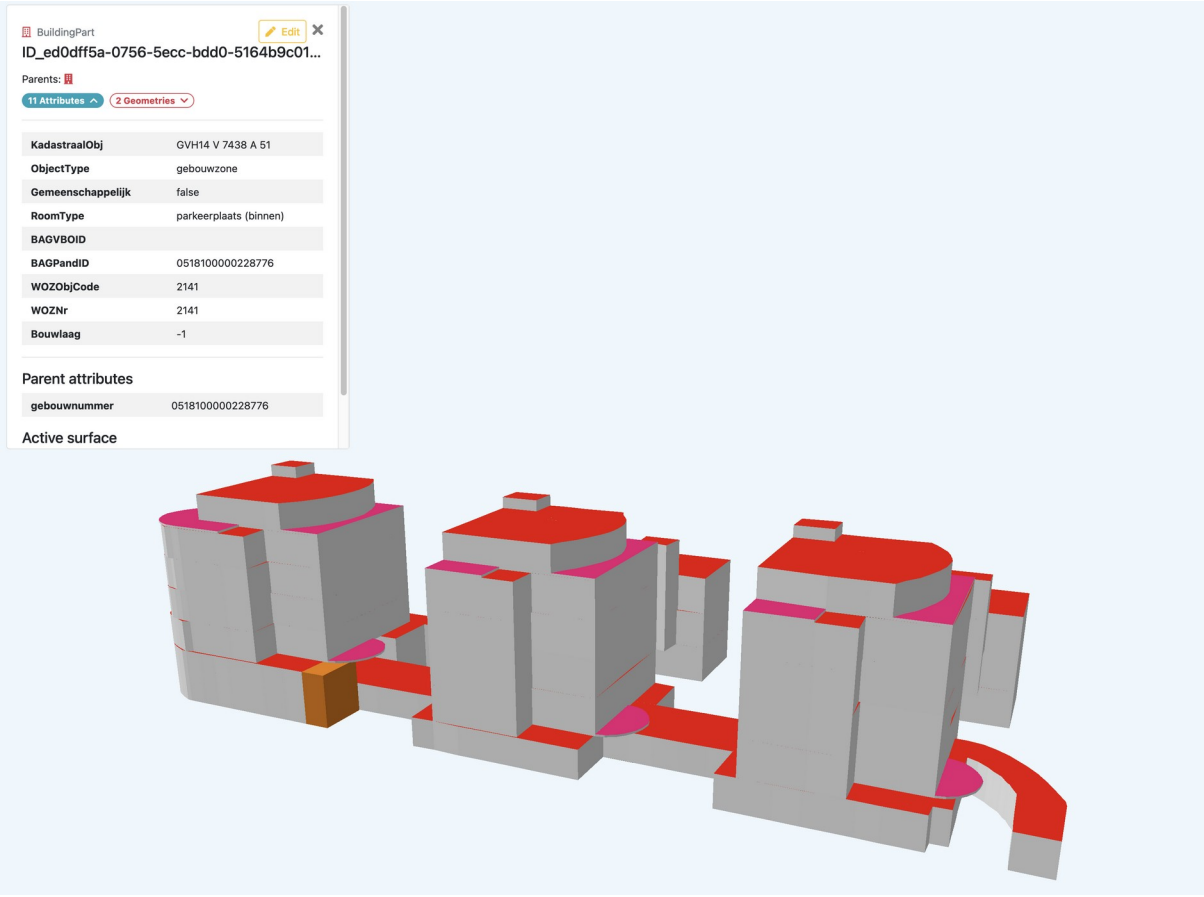


Figure 2. Example 3D-model generated by PDF2GIS visualised in the Ninja viewer (https://ninja.cityjson.org/)

Alongside the live demonstration of the system, we also present real-world results from a large-scale deployment in the City of The Hague.

The municipality of The Hague has processed more than 1,200 architectural drawings using PDF2GIS. The information extracted from these drawings has been used to improve and enrich several municipal databases.

First, the quality of the WOZ (property valuation) database has been significantly improved. Through the analysis of the architectural drawings, surface areas of various building elements could be corrected or added, including balconies, storage units, and other auxiliary structures. In addition, many previously missing objects were identified and incorporated into the

database. These improvements contribute to a more efficient property taxation process and help reduce the number of valuation disputes submitted by citizens.

In addition, the national land administration datasets BAG (Buildings and Addresses Register) and BGT (Large-Scale Topography Register) were enhanced with more accurate geometric information and improved surface area measurements. In particular, underground parts of buildings—such as basements and underground parking structures—could be identified and documented, while these were previously often unknown or only partially recorded. This results in a more complete and consistent representation of the built environment.

Finally, the city's 3D model has been enriched with detailed information about the internal structure of buildings as well as their underground components. This creates a more detailed and realistic digital representation of the city, which can be used for various purposes such as routing for emergency services, energy modeling, noise simulations, renovation planning and many more.

In addition to demonstrating the end-user workflow, we also provide insights into the technical implementation of the system.

The processing of an architectural drawing consists of a sequence of stages. At each stage, a specific algorithm is applied. These algorithms may be based on machine learning techniques or on more traditional computational methods. The output produced at each stage can be reviewed and corrected by a human operator when necessary. These human corrections are subsequently used as training data for the machine-learning models, allowing the system to improve its performance over time. During the demonstration, we will show how this iterative training process has led to measurable improvements in both accuracy and efficiency.

After all relevant elements have been extracted from the drawing—such as walls, doors, windows, staircases, and elevators—the 3D building model is constructed in multiple stages using several novel algorithms. An important part of this process is determining the correct vertical stacking of the different building floors. For this purpose, we use a heuristic algorithm that automatically stacks the floors on top of each other.

To ensure correct alignment between floors, the algorithm uses distinctive building elements such as elevator shafts and staircases as reference structures. These elements typically span multiple floors and therefore provide reliable anchors for aligning the different layers of the building model.

Another crucial step in the workflow is the georeferencing of the extracted building data. In this step, the geometry derived from the architectural drawing is aligned with existing geometries in official land administration datasets such as the BGT or BAG. The system automatically computes the best spatial fit between the drawing data and the reference data. However, in some cases manual corrections are required, for example when the building has been modified after the original drawing was created and therefore differs from the geometry recorded in the drawing.

An additional challenge in aligning architectural drawings with existing geospatial data is the variable quality of the drawings themselves. Many drawings originate from scanned paper documents and may therefore be slightly skewed or distorted. In other cases, the drawings may not be perfectly to scale.

To address these issues, we implemented a variant of the *rubber-sheeting* algorithm. Rubber-sheeting is a technique commonly used in geospatial data processing to locally adjust geometries so that they match reference data. Interestingly, similar techniques are also used in astronomical image processing—for example when correcting images captured by the Hubble Space Telescope. Using this approach, the geometry of a drawing can be locally deformed so that it better fits the reference geometry from the BGT while still preserving the overall structure of the building.

The final stage of the workflow involves generating the complete 3D building model from the extracted 2D drawing data. Architectural drawings do not always contain sufficient information about the exact shape of the roof. To overcome this limitation, we combine the information extracted from the drawings with existing 3D datasets, such as the city's 3D model or data from the national 3D BAG dataset. These datasets typically contain a 3D representation of the exterior geometry of buildings.

By integrating these external datasets with the drawing-derived information, we can estimate the heights of individual building storeys and construct a realistic 3D representation of the building. Furthermore, these datasets allow us to reconstruct the correct roof geometry for rooms located on the top floors. To achieve this, we developed a novel roof-cutting algorithm that automatically derives the roof shape from the existing 3D building model and integrates it with the internal floor geometry extracted from the drawings.

By combining information from architectural drawings with existing 3D city models, PDF2GIS is able to generate highly detailed and consistent 3D building models. These models capture both the external geometry of buildings and important aspects of their internal structure.

The demonstration highlights how PDF2GIS contributes to more efficient, data-driven, and sustainable city management. By unlocking the hidden value of existing drawing archives, the system enables cities and organizations to enrich their digital infrastructures and better respond to the growing demand for accurate, integrated urban data.

Digital Twin For Improvement of The Sustainability of Neighbourhoods Through Scenario Planning

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Abstract

Digital twins are increasingly used for climate adaptation and sustainability planning, yet most applications remain sector-oriented. This limits their capacity to capture interactions between domains through multiple, interrelated indicators, an issue that becomes especially visible at the neighbourhood scale, where interventions are implemented and trade-offs are negotiated. This paper aims to develop and demonstrate a neighbourhood-scale digital twin for integrated, scenario-based analysis of urban ecology and energy, and to show how it can support local sustainability decision-making by making cross-domain synergies and trade-offs more explicit. This work presents a prototype neighbourhood-scale digital twin designed for integrated, scenario-based analysis of urban ecology and energy. Implemented in the post-war residential neighbourhood of Twekkelerveld in Enschede, the Netherlands, the system addresses challenges such as an ageing building stock, limited green infrastructure, and relatively high energy demand. The framework combines open and municipal datasets, including tree inventories, green spaces, urban heat potential, building geometry, energy-use intensity, energy-demand estimation, rooftop solar electricity potential, and carbon footprint.

The digital twin enables interactive "what-if" exploration of typical urban measures across domains. Ecological scenarios, such as tree planting strategies and green facade deployment, allow users to evaluate impacts on greenness, urban heat mitigation, carbon sequestration, and investment costs. Energy scenarios include insulation upgrades, rooftop solar deployment, heat pump transitions, and local energy sharing, assessed with indicators at both building and neighbourhood levels. An interrelation module explicitly connects ecological and energy measures, enabling comparison of combined effects on cooling, energy demand, emissions, and overall performance.

By presenting baseline and scenario outcomes side by side, the prototype makes cross-domain synergies and trade-offs clearer for planning discussions, complementing Earth system-scale digital twins with decision support where local actions are debated and implemented. A web-based demonstrator of the prototype is also available for exploration.

Developing a Digital Twin for Watershed Restoration Scenario Analysis: A Case Study in Mujib basin, Jordan

Nawwar Procheta, Mila Koeva, Rosa Aguilar, Mira Haddad

Demo description

Jordan's dryland watersheds face acute water stress alongside accelerating land degradation. Intense, short-duration storms generate flash runoff that increases soil erosion and sediment delivery to downstream infrastructure, while groundwater, Jordan's primary strategic water source, remains under long-term pressure. These hydrological effects pose risks to the built environment, such as sedimentation pressure on reservoirs and the exposure of settlements downstream to flash-flow pathways. Rainwater-harvesting (RWH) interventions such as Vallerani micro-catchments on degraded hillslopes and Marab/flood-spreading and check-dam systems along ephemeral waterways are expanding, yet basin-scale planning is limited by uncertain hydrological trade-offs and the gap between model outputs and stakeholder-ready spatial decision support. This study develops a basin-scale hydrological Digital Twin (DT) for the Mujib Basin (central Jordan) by translating process-based modelling into an interactive, scenario-driven 3D dashboard. A SWAT modelling core is integrated with harmonized in-situ and Earth Observation (EO) datasets to represent coupled water and land-surface responses. Physiographic inputs (topography, soils, land use) and meteorological forcing from ERA5 reanalysis are complemented by EO time series, including Sentinel-2 vegetation indices, evapotranspiration products, and soil moisture, to provide an ecohydrological context.

Four intervention scenarios (baseline, Vallerani, Marab, and combined) are evaluated at the sub-basin scale using water restoration-relevant indicators, including surface runoff, sediment yield, groundwater recharge, and vegetation/ET-related metrics. The DT supports systematic scenario comparison and "what-if" testing by integrating suitability-based intervention targeting with climate forcing adjustments, enabling exploration of management and climate conditions under risk and operational constraints. This study shows how digital twins can bridge process-based hydrological modelling and implementation-oriented planning, demonstrating that sustainable upstream watershed management is vital for reducing downstream infrastructure risk and strengthening resilience in data-scarce dryland settings.

Early Warning System for Harmful Algae Bloom in Beautiful Indonesia (HABIBI)

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Demo description

Lake Toba, located in North Sumatra, Indonesia, is a vital freshwater resource that supports aquaculture, tourism, domestic water supply, and regional food security. In recent decades, intensified aquaculture activities, land-based nutrient inputs, and insufficient waste management have increased eutrophication levels in the lake, leading to repeated harmful algal bloom (HAB) events and large-scale fish mortality. Figure 1 presents a problem tree illustrating how declining water quality in Lake Toba is driven by eutrophication and pollution originating from aquaculture, agriculture, tourism, and domestic waste, and how these pressures translate into ecological degradation and socio-economic impacts such as fish kills, biodiversity loss, unsafe drinking water, and reduced local livelihoods (The World Bank, 2018). These developments highlight the need for proactive and data-driven monitoring solutions.

This demonstration presents HABIBI (Harmful Algae Bloom in Beautiful Indonesia), a conceptual early warning system designed to detect, monitor, and anticipate harmful algal bloom conditions in Lake Toba. The system integrates satellite remote sensing, UAV-based multispectral observations, in-situ water quality measurements, and meteorological data into a unified geospatial framework. Key indicators such as chlorophyll-a concentration, colored dissolved organic matter (CDOM), turbidity, nutrient levels, water temperature, rainfall, and wind speed are combined to assess bloom risk both spatially and temporally.

The demo showcases spatial visualizations of historical and recent water quality patterns, vulnerability zoning across Lake Toba, and a prototype risk indexing framework that translates complex environmental data into simple and actionable alert levels. The warning logic illustrates how threshold-based indicators and lead-time analysis can support early intervention, allowing fish farmers and local authorities to adapt feeding practices, increase monitoring, or prepare mitigation measures before critical bloom conditions occur.

Beyond technical monitoring, HABIBI emphasizes effective risk communication, demonstrating how warning information can be tailored to different stakeholder groups through intuitive indexing schemes. The demonstration highlights the potential of digital geospatial technologies to support sustainable lake management, reduce economic losses, and strengthen environmental governance in data-scarce regions.

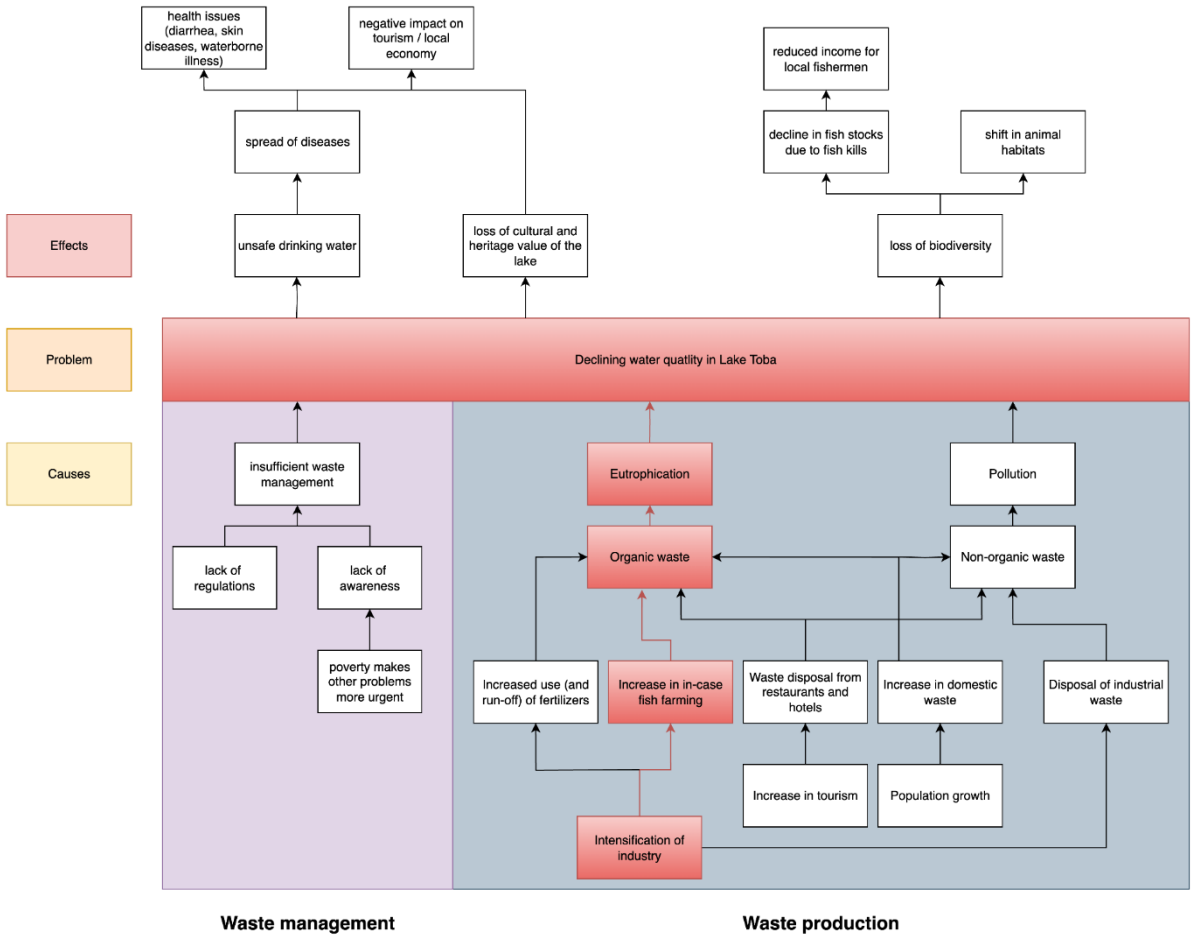


Figure 1. Problem Tree

Acknowledgements

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In addition, we acknowledge the guidance of Roelof Rietbroek (University of Twente) throughout the conceptualization of the early warning system framework and the use of satellite remote sensing data. We also recognize the European Space Agency (ESA) for access to Sentinel imagery used in our analysis.

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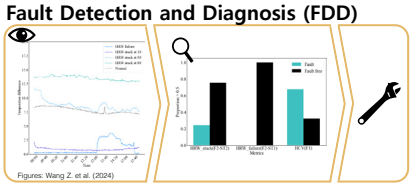
Thematic session:

Posters

Towards Human-informed Building System Resilience: Enhanced Whole-HVAC System FDD with Occupant Behavior

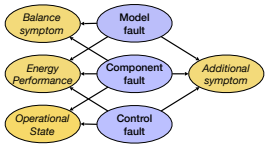
Martín MOSTEIRO-ROMERO[1], Nitant UPASANI[2], Laure ITARD[3]
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Fault Detection and Diagnosis (FDD)



Diagnostic Bayesian Networks (DBN)

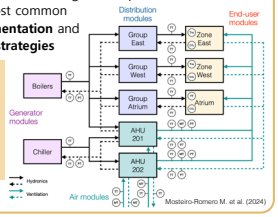
- **Probability of a fault** calculated based on the **presence and absence of symptoms**



Whole-building DBN

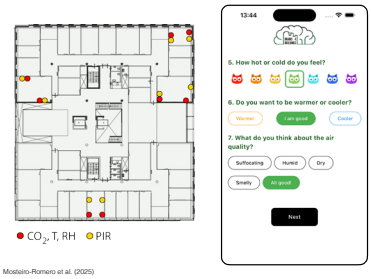
- 7-floor office building in the Netherlands
- **Classification rate 85%** during AHU experiments
- **Sensor faults** most common
- **Outdated documentation** and **unclear control strategies**

How can DBN performance be improved under operational uncertainty?

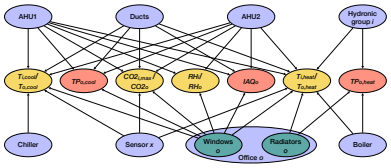


Occupant feedback and sensor data

- **Occupant feedback** → Symptom of malfunction
- **Occupant behavior** → Potential fault in building operation
  → Data collection in **September–October 2024**



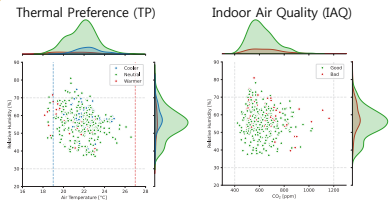
Occupant-informed DBN



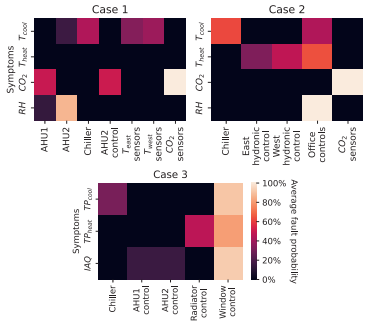
Three levels of additional data

1. **Building Management Systems (BMS) data** → zone-level
2. Additional **sensor data** → office-level
3. Additional **self-reported data** → office-level

Collected data



Fault diagnosis results



- Room-level sensors help **differentiate different potential faults**
- Occupant feedback points to potential **inadequate room-level controls**

References:
Mosteiro-Romero, M. et al. (2024) "Whole-Building HVAC Fault Detection and Diagnosis with the 4S3F Method: Towards Integrating Systems and Occupant Feedback". Proceedings of ASim 2024, Osaka, Japan.
Mosteiro-Romero, M. et al. (2025) "Occupant-driven Diagnostic Bayesian Networks: Incorporating Subjective Feedback for Resilient Operation". Proceedings of BuildSys'25, Golden, USA.
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Abstract

Automated fault detection and diagnosis (FDD) of systems can allow component and control faults to be identified and rectified early to minimize their impacts. However, most work on FDD of building systems focuses on the component scale, neglecting the interactions and cascading effects between systems. Furthermore, despite the outsized role occupants play in building energy performance, their behavior and preferences are typically neglected in FDD processes. In this paper, we present a whole-building FDD method incorporating occupant feedback as potential symptoms and occupant behaviors as potential faults in building performance. The method is based on Diagnostic Bayesian Networks (DBN), which are especially well-suited for whole building FDD due to their flexibility, scalability and ability to combine diverse, potentially-conflicting data sources. We expand our DBN by incorporating occupant feedback collected through surveys using a smartphone application. The methodology is applied on a seven-floor office building in Delft, the Netherlands. Occupants were invited to fill out surveys on their behaviors and thermal preference for four weeks in late summer through a smartphone. This information was integrated into the DBN to expand our scope to include both building performance and occupant comfort. Therefore, our work represents a promising step towards FDD methods that support energy-efficient and climate-resilient building operation.

Author Index

Agugiaro, Giorgio, 38, 85, 90, 106
Aguilar, Rosa, 137
Akbarieh, Arghavan, 62, 124
Alsahwi, Joseph, 127
Ataman, Cem, 124
Athid, Rakibun, 136
Auer, Frederick, 90

Babakhani, Amir Hosein, 112
Balaban, Özgün, 78
Berg, Marc van den, 69
Bin Khalil, Ishraque, 138
Boroushaki, Bahar, 62
Borrmann, André, 81
Bratic, Aleksandra, 66
Bravo Rivera, Mirén, 124

Dhavale, Nikita, 69
Doi, Hiba, 38
Donkers, Alex, 27
Doreé, André, 121

Ebus, Jasper, 124
Eren, Yavuz, 124
Eshuis, Rik, 3

Farnaghi, Mahdi, 118
Feldbrugge, Berend, 112

Gao, Weixiao, 106
Geerman, Quint, 48

Haddad, Mira, 137
Hartmann, Andreas, 69
Hofman, Jasper, 73
Hulst, Britt van, 13
Huurne, Ramon ter, 97

Itard, Laure, 141

Jiang, Rui, 124

Kazemzadeh, Siavash, 103
Klanken, Giel, 73
Koeva, Mila, 118, 136, 137
Kollen, Roos, 103
Kramwinkel, Philip, 138
Krämer, Ulla-Britt, 136
Kuipers, Pleun, 138

Leeuwen, Jos van, 103
León-Sánchez, Camilo, 90, 106
Lu, Chujie, 76

Mahmoud, Rima, 112
Mastenbroek, Lucas, 103
Meijer, Maarten, 127
Miller, Seirgei, 121
Molengraft, Rene van de, 81
Mosteiro-Romero, Martín, 141

Njoroge, Joan, 118
Nourian, Pirouz, 136

Padsala, Rushikesh, 85
Pantusheva, Mariya, 118
Pauwels, Pieter, 3, 13, 16, 62, 78, 81
Petrova, Ekaterina, 3, 13, 16, 27
Petrova-Antonova, Dessislava, 118
Procheta, Nawwar, 137

Rahmawati, Adhisye, 106
Ramachandruni, Avinash, 16
Rovers, Twan, 48

Sarıkan, Alper, 124
Schlosser, Daan, 38
Schluter, Margreet, 136
Scholtenhuis, Léon, 66, 97
Schröder, Torsten., 69
Sebastian, Rizal, 103
Sharma, Ravi, 16
Shen, Qinshuo, 121
Sommer, Kees, 103
Sridharan, Anish, 81
Strydom, Daniëlle, 103

Tangara, Faith, 97
Torta, Elena, 81
Tunçer, Bige, 124

Upasani, Nitant, 141

Vadacci, Luca, 73
Vahdatikhaki, Faridaddin, 66, 121
Vermulst, Lysanne, 124
Voordijk, Hans, 69, 73
Vos, Koen de, 81

Wams, Jan-Mark, 132
Wrzesińska, Gosia, 132

Zandwijk, Krista van, 3, 13
Zeeshan, Ali Agha, 112

Öztürk, Elçin Sarı, 124